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A review of offshore windfarm related underwater noise sources.

Report No. 544 R 0308

by

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COWRIE
Collaborative Offshore Wind Energy Research Into the Environment

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The reader should note that this report is a controlled document. Appendix A lists the version number, record of changes, referencing information, abstract and other documentation details.

Executive summary

Introduction

A concerted effort is currently being made by industry to minimise any undesirable effects relating to windfarm development and operation. One potential effect of offshore windfarm development is the creation of underwater noise. Although the effect of underwater noise is not fully understood, it has the potential to disturb, and in the most severe cases, harm marine wildlife. Possible effects include attraction towards a noise source, avoidance, temporary hearing damage and permanent physical injury. The Crown Estate own most of the seabed up to 12 nautical miles from the British coast and lease some of this area for windfarm development. They have set up the COWRIE (Collaborative Offshore Wind Research Into the Environment) trust to conduct research into offshore windfarm development, who have highlighted the effects of underwater noise as one of several priority areas for research. This report is a review of available information on underwater noise related to windfarm development. It is one part of a larger study into the effect of windfarm related underwater noise, which includes field surveys of underwater noise from wind turbines and windfarm construction.

The windfarm lifecycle

Knowing the length of time the marine environment is exposed to an underwater noise source is useful when assessing environmental effect. To help in this assessment, the lifecycle of an offshore windfarm is split into four phases. The first of these phases is pre-construction.

Pre-construction

Background noise may be used as a benchmark to assess the environmental impact of new sources. In shallow coastal waters, where offshore windfarms will be located in the near future, not enough is known to predict the level of background noise. Activities that occur before construction begins on a windfarm include geophysical and geotechnical survey, meteorological mast installation and an increase in vessel traffic. Offshore windfarm geophysical surveys are typically conducted using boomers and sparkers, but little is known about the level of underwater noise these emit. No measurements are available of meteorological mast installation noise, but since they have a similar foundation to wind turbines, the noise levels may be similar.

Vessel traffic will increase in the vicinity of windfarm before its construction and continue through to decommissioning. Measurements of the small vessels that are likely to be used during survey are limited. A 25 m tug pulling an empty barge, a scenario that is likely to occur during windfarm construction, has been reported to have a 170 dB re 1 μPa @ 1 m Source Level. The effect on marine wildlife from vessel noise is not clear, with both attraction and avoidance reactions having been observed.

Construction

Measurements of the noise from offshore windfarm construction are currently scarce. A significant addition to available information will shortly be made with the publication of the report on underwater noise surveys of windfarm construction, which has been funded by COWRIE as part of this study.

One of most significant activities during windfarm construction is foundation installation. While no measurements of the noise from concrete (e.g. gravity support structures and caissons) foundation installation are available. Measurements are available of pile installation using both impact and vibro pile hammers. The most relevant of these is a measurement of wind turbine monopile foundation installation, giving Source Levels of 215 dB re 1 μPa @ 1 m. During this and other studies, marine wildlife monitoring and injury mitigation strategies have been put in place during pile driving. Both physical and behavioural effects on marine wildlife have been noted. Drilling may be required during piled foundation installation. However, measurements are only available of offshore oil and gas drilling operations, which will differ significantly from windfarm related drilling.

Dredging and rock laying may be undertaken during windfarm construction. Applications include scour protection, cable protection and modifying non-ideal bathymetry (water depth). Some measurements of suction and hopper dredgers have been taken, and show a peak spectral Source Level of up to 177 dB re 1 μPa @ 1 m between 80-200 Hz. The measurements were conducted in shallow water and, where similar techniques are used in windfarm development, these measurements may be used for comparison.

Other construction activities include cable laying, turbine and turbine tower installation, and ancillary structure (e.g. offshore transformers) installation, but no measurements of the noise from these processes are available. In addition to this, divers will be used throughout windfarm construction to carry out underwater activities, and they may use a variety of tools. One set of measurements exists of diver tools, and these show peak Source Levels of up to 200 dB re 1 μPa @ 1 m.

Operation

By far the longest phase of a windfarm's lifecycle is the operational phase. Two measurements of offshore wind turbine noise are available. These show low frequency sound levels, with a Source Level spectra showing a maximum of 153 dB re 1 μPa @ 1 m at 16 Hz. The measurements are of individual turbines of a relatively low power (less than 1 MW). Despite the low level, low frequency nature of the sound, behavioural reactions have been observed in a study of harbour porpoise (*Phocoena phocoena*) response to the reproduction of wind turbine noise.

Decommissioning

The final stage of a windfarm's lifecycle is its decommissioning, the majority of which will be a reflection of the installation process. However, the wind turbine foundation decommissioning process is unclear. Options for pile foundation removal include jet and explosive cutting below the seabed. While the process for concrete foundation decommission is not known, it may include explosive break up followed by dredging. No measurements of jet cutting noise are known to the authors, but underwater blast has received significant attention. Well used models exist for both predicting the sound level from underwater blast, and its physical effect on marine wildlife. These models require knowledge of the charge weight, and this is as yet unknown, but given this knowledge a reasonable assessment may be made of the physical effect of underwater blast. Behavioural reactions to blast are less well understood.

The reviewed noise sources are summarised in Table I for comparison. There are significant gaps in knowledge, and where research has been conducted, it is not often in an easily comparable form. Where possible, the minimum and maximum Source Levels for specified measurement quantities are given for each source. All the data is taken from the body of the report although, where appropriate, measured levels are adjusted using a $20\log_{10}(r)$ Transmission Loss to give Source Level. A brief note summarising the knowledge which has led to these levels is given along with a summary of reviewed behavioural observations.

Recommendations

Based on the available information and the authors' experience, recommendations made for priority areas for investigation into underwater noise levels and its effect on marine wildlife are as follows (greatest priority first):

- Foundation decommissioning using explosives.
- Piled foundation installation and windfarm related geophysical survey.
- Drilling, rock laying, cable trenching, diver tools.
- Vessel and machinery, wind turbine operation.

This assessment does not include the cumulative effects of noise, which would emphasise wind turbine and vessel noise because of the exposure the marine environment has to these sources. An assessment cannot be made of jet cutting, turbine structure installation and gravity support structure installation, as no measurements are available of these sources.

Amongst the sources of underwater noise, the authors believe the following areas are priority areas for investigation (greatest priority first):

- Piled foundation installation, wind turbine operation, and windfarm related geophysical survey.
- Cable trenching, drilling, rock laying, diver tools, jet cutting, gravity foundation installation, vessel and machinery, turbine structure installation.

Windfarm related noise source	Measurement quantity	Source Level		State of knowledge	
		Min	Max	SL & TL	Behavioural response
Background Noise	SPL	Highly variable. Frequency dependent.		Good knowledge of deep water ambient noise. Poor knowledge of shallow water ambient noise.	Concern about the effects of increasing background noise on marine wildlife.
Shipping and Machinery	Linear SPL dBht(*Salmo salar*)	152 30	192 60	Poor for small craft, otherwise realtively good.	Mixed observations including attraction and avoidance.
Geophysical Survey	Linear Peak SPL Peak dBht(*Gadus morhua*) Peak dBht(*Orcinus orca*) Peak dBht(*Phocoena phocoena*)	215 142 159 144	260 195 216 203	Good for airguns, very poor for typical windfarm survey sources such as boomers and sparkers.	Some cetacean airgun avoidance observations.
Pile Driving	Linear Peak SPL SEL Peak dBht(*Salmo salar*)	192 210 40	261 215	Limited set of measurements with a large variation in results. SL possibly related to pile diameter.	Observation of harbour porpoise disturbance, no reaction from caged trout, fish mortality evidence.
Drilling	Linear SPL	145	191	Several deep water measurements. Large range of levels. No shallow water measurements.	Reported response to playback tests. Cetacea avoid when received level is high.
Gravity Foundation Installation	n/a	n/a	n/a	No available measurements.	No available observations.
Dredging	Peak spectral energy (80-200Hz)	177		Some shallow water measurements of suction and hopper dedgers.	Mixed reactions. Cetacea avoid when received level is high.
Rock Laying	Linear SPL	Within background.		One inconclusive measurement.	No available observations.
Trenching	dBht(*Orcinus orca*) dBht(*Phocoena phocoena*) dBht(*Phoca vitulina*) dBht(*Gadus morhua*) dBht(*Limanda limanda*) dBht(*Salmo salar*)	150 120 100 75 50 50		One measurement of pipe trenching. No available measurements of windfarm cable laying, which will be significantly different.	No available observations.
Turbine Structure Installation	n/a	n/a	n/a	No available measurements.	No available observations.
Wind Turbines	Peak spectral energy (16 Hz)	142	153	Two measurements available for low power (<1MW) individual turbines.	Very little knowledge. Porpoise behavioural reponse to playback experiments.
Blast	Linear SPL dBht(*Gadus morhua*) dBht(*Limanda limanda*) dBht(*Phoca vitulina*) dBht(*Phocoena phocoena*) dBht(*Orcinus orca*)	 191 169 190 207 213	272	Verified empirical models for peak pressure and impulse available.	Well used near source blast injury model available. Some cetacean avoidance observations.
Jet Cutting	n/a	n/a	n/a	No available measurements.	No available observations.
Diver Tools	Peak SPL Average SPL	200 161		One set of measurements available covering: drills, wrenches, bolt guns, grinder and jackhammer.	No available observations.

Table I. Summary of available information on windfarm related underwater noise sources

Contents

1 Introduction

Offshore windfarms are an important factor in the government's objective to produce 15 % of the nation's electricity from renewable sources by 2015. A concerted effort is currently being made by industry and regulators to minimise any undesirable effects relating to the development and operation of these windfarms. One potential effect of offshore windfarm development is the creation of underwater noise. While the impacts caused by underwater noise are not yet fully understood, it has been cited as having the potential to impede communication amongst groups of animals, drive them away from feeding or breeding grounds, or to deflect them from migration routes.

Noise can be generated by a wide range of activities, both offshore and underwater. Sources of noise in the marine environment not only include windfarm development but also leisure activities, such as diving or the use of jet skis, and other commercial activities, such as rock blasting, construction work and oil exploration.

The Crown Estate owns most of the seabed to 12 nautical miles off the UK coast and have leased, or are planning to lease, areas of this land for windfarm development. To help assess the environmental impact of windfarm development and provide guidance to developers they have set up COWRIE (Collaborative Offshore Wind Research Into the Environment). The Group is made up of experts from the offshore wind industry, English Nature, Countryside Council for Wales, Joint Nature Conservation Committee, CEFAS (Centre for Environment Fisheries and Aquaculture Science), the Royal Society for the Protection of Birds, the DTI (Department of Trade and Industry) and the BWEA (British Wind Energy Association) and have identified the effect of windfarm related underwater noise as one of several priority areas for research [1].

The research includes both a desk based study into the potential effects of underwater noise, and the collection and analysis of underwater noise measurements from windfarms in operation and under construction. This report addresses the first of the above deliverables and is subsequent to the report commissioned by the DTI entitled, 'Assessment of the effects of noise and vibration from offshore windfarms on marine wildlife'[2].

This review primarily addresses the available information on windfarm related noise sources, with an emphasis on reported measured sound levels. Behavioural and physical responses to noise are briefly covered where appropriate but are not treated in any great depth. Two sections are included, for readers unfamiliar with either offshore windfarms or underwater acoustics, which provide a sufficient background to understand the terms and concepts used in the review. These are followed by the body of the report which contains a summary of the available information on windfarm related noise sources.

2 Introduction to offshore windfarms

2.1 Background

A broad understanding of offshore windfarms is required for any assessment of their environmental effect. The location, technology and duration of all events relating to windfarm development will all have a bearing on their effect on local marine wildlife. As an example, a wind turbine's operating power may effect underwater noise as well as the depth of water at its location.

These issues are addressed below, with an emphasis on their relevance to the generation and propagation of underwater sound. Other considerations include the abundance of marine species at the proposed windfarm location, but these matters are best dealt with in environmental impact assessments and are not covered here.

2.2 Offshore windfarm technology

2.2.1 Foundations

One of the major differences of siting a turbine offshore, compared to its onshore equivalent, is the foundation design. Currently there are four options for foundation design: monopile, multipile, gravity and caisson.

Monopile and multipile foundations consist of one or more open ended steel cylinders that are forced into the sediment through a combination of pile driving and drilling. Gravity and caisson foundations are concrete structures that are floated out to the turbine locations and secured in place. Of these gravity foundations are more developed and have been used for wind turbine foundations in Europe. They weigh between 500 and 1000 tonnes and are filled with ballast at the turbine location. It is unlikely that one foundation design will be the best in all situations. Currently the most popular design is the monopile foundation, which has been used at both the North Hoyle and Scroby Sands windfarms, but in the long-term this may not be the most economic foundation option [3].

2.2.2 Turbine structure

Offshore turbine structures are broadly similar to their onshore equivalent, consisting of a support tower that tapers towards its highest point. The support tower may be fixed to the foundation via a transition piece that provides a physical coupling between the two components, and may include maintenance access amongst other provisions.

2.2.3 Nacelle

The nacelle houses several components of a wind turbine and rests upon the turbine tower. Key components include the gearbox and generator, with ancillary components such as pitch control gear and brakes dependent on the specific turbine design. The design of the nacelle may have a bearing on the radiated underwater noise from a wind turbine. The degree of mechanical refinement, the control mechanisms and the turbine's power rating may all influence wind turbine noise.

2.2.4 Turbine blades

Connected to the hub of the nacelle are the turbine blades, which convert the passing wind energy into rotational energy. Their design will affect the aerodynamic noise from the wind turbine, which may contribute to underwater noise.

2.2.5 Ancillary structures

In addition to an array of wind turbines, offshore windfarms may also include ancillary structures such as monitoring masts and offshore transformers. These will require below water foundations and above water installation, and may contain vibrating machinery. For similar foundation types, it can be assumed that foundation installation noise for these structures will be similar. However, operational noise from these structures is unlikely to be similar to wind turbine noise.

2.3 The location of offshore windfarms

A windfarm's location has three major influences on the environmental effect of underwater noise. It determines how much sound enters the water, the efficiency with which that sound travels and the predominant marine species in the vicinity. The economics of offshore technology currently dictates that offshore windfarms are located in waters less than approximately 30 metres deep [4]. This is partly due to the preference for steel monopile foundations. Research into deep water foundations is currently being conducted with a view to siting larger turbines further offshore. As the technology and economics of deeper water foundations become more favourable, and shallow coastal water sites less abundant, the construction of offshore windfarms may move into deeper waters.

The language used to describe regions of water is varied and subjective, for example a definition of 'shallow water' may depend on a vessel's draught. For clarity, Figure 1 defines some of the terms that are used to describe the location of windfarms in this report. The term littoral is used to describe the area between high and low water mark on a shore. Coastal describes the region between the shore and the oceanic edge of the continental shelf, which may differ dramatically in depth and distance from the shore. For the purposes of this report 'shallow coastal' is used to describe coastal waters less than 30 metres in depth, which is where the development of current windfarms is proposed. Within this area, windfarms may be built upon shoals, which are elevations in a body of water and include features such as sandbars. The edge of the continental shelf marks the division between deep oceanic water and coastal waters.

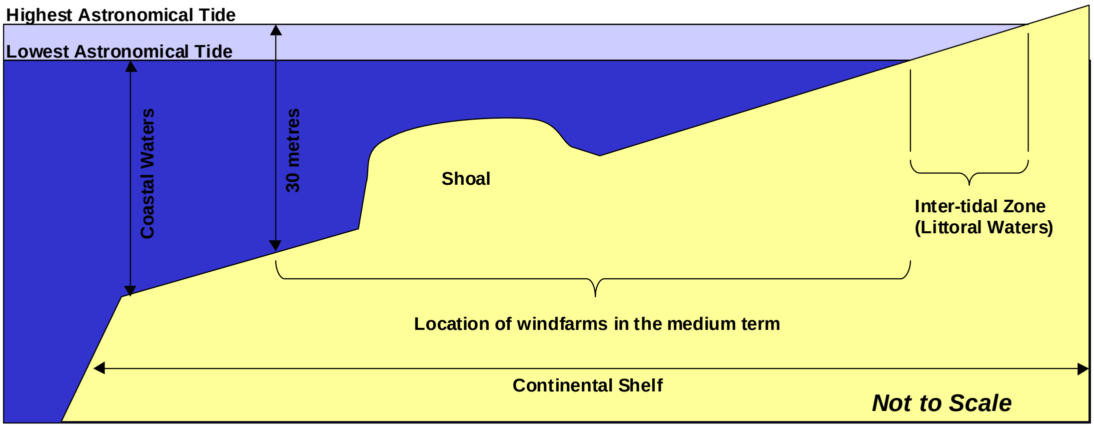

Figure 1. Definition of coastal regions.

The majority of round one and two offshore windfarm sites are located within the following three areas: the Thames Estuary, the Greater Wash and the Eastern Irish Sea (from Liverpool Bay to the Solway Firth). Other locations include Blyth and Teesside on the North East coast and Scarweather Sands on the South Wales coast. At the time of writing a two turbine array is operational at the Blyth site founded on a sandy shoal approximately 500 metres from the shore. At North Hoyle a 30 turbine array is operational 7 km off Rhyl, North Wales, in coastal water with mixed substrate. At Scroby Sands, a sandy shoal 2 km from the Norfolk coast, 30 turbines have been installed and will be operational in October 2004 and an offshore windfarm is under construction on the Kentish Flats.

The generation and propagation of underwater noise is affected by the geography and geology of the windfarm location. On a scale of several metres, the sea floor geology at a wind turbine location will affect the generation and propagation of both turbine and turbine foundation installation noise. At a 100 metre scale, the sea floor geology and bathymetry will affect the transmission characteristics of all windfarm related noise and the level of background noise from wave motion. Within kilometres of the windfarm location, land shadowing may effect the propagation of sound further afield. Land shadowing is likely to restrict the propagation of sound from currently earmarked sites to the Irish Sea and North Sea, except for Scarweather Sands on the South Wales coast which offers the potential for propagation into the Atlantic. Where sound does propagate beyond the continental shelf, it may be focused into the SOFAR (**SO**und **F**ixing **A**nd **R**anging) or deep water channel. This is a phenomena particular to deep waters where sound speed variation with depth acts like an acoustic lens, focusing sound into a narrow channel. This results in efficient transmission of sound to distances of several 100 km. Examples of this effect include the reception of seismic survey noise across the Atlantic.

2.4 The offshore windfarm lifecycle

A windfarm's lifecycle can be split into four phases: the pre-construction phase, the construction phase, the operational phase and the decommissioning phase. Figure 2 gives an overview of the marine activities that take place during these phases. The amount of exposure the marine environment has to a noise source may be significant in assessing the long term cumulative effects of underwater sound. However not enough is known for the influence of level and exposure to be assessed. In the diagram, an estimate has been made of the length of time a particular activity will be undertaken at sea.

2.4.1 Pre-construction

At the start of a windfarm's lifecycle a suitable location must be found which, amongst other considerations, must be windy and suitable for wind turbine foundations. The first of these requirements can initially be assessed from pre-existing historical meteorological information, but at some stage more detailed information will be required. At this point a meteorological mast will be installed. This will provide information on local weather conditions, such as wind speed and wave height, which are an essential part of the design of a windfarm. They are typically of a steel lattice construction, and are built on similar foundations to wind turbines. This can be either a monopile, multipile or gravity foundation structure and in good conditions should take less than a week to install. Once completed the mast will require maintenance, increasing vessel traffic in the area.

Geophysical surveys are used, in the first instance, to assess the suitability of the location for wind turbine foundations, and as a development progresses they provide information for foundation design. Surveys are often conducted from small (less than 30 m) vessels and are conducted intermittently before and during a windfarm's development. It should be noted that not all the surveys conducted will lead to the development of a windfarm.

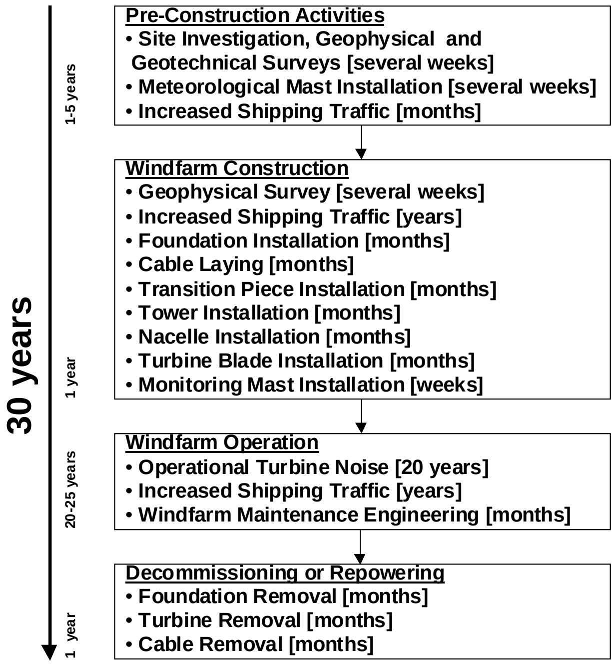

Figure 2. The lifecycle of an offshore windfarm.

2.4.2 Construction

The construction programme for an offshore windfarm will depend on consent conditions. It typically begins with the installation of the wind turbine foundations. At present, the preferred foundation type is a driven monopile, however other options are available including gravity foundations and multipile foundations. Installing mono and multipile foundations is achieved using similar equipment, namely pile drivers and drilling equipment. Gravity foundations are floated out to the location, filled with a heavy fluid and grouted into place. For each turbine, foundation installation may take up to one week, and for a 30 turbine windfarm, foundation installation typically lasts between 3 and 4 months. While individual events such as pile driving or drilling will not be continuous throughout this period, they will occur regularly and this repeated exposure offers the potential to displace marine species.

Cable laying can take place before, during and after foundation installation. Cables are required both between turbines and to shore. The cables are buried in soft substrate using a cable plough or remotely operated vehicle (ROV), or may be covered in a protective rock blanket if this is not possible. Cable installation may take several months.

Cables and foundations are the only subsurface installations, except for those required for ancillary structures, such as monitoring mast foundations and offshore transformer stations. All other construction is performed above water. A transition piece is installed on the foundation to provide a suitable connection between the foundation and the turbine tower, and to allow for access to the structure. The turbine tower raises the structure to the required height for the nacelle, which houses the majority of the mechanical and electrical systems used in the wind energy conversion process. Finally, turbine blades are fixed to the hub of the nacelle. These tasks, and other minor installations, are performed from a jack-up barge. The wind turbine components are lifted into place using a crane or derrick on the barge. For a 30 turbine array, turbine installation may take up to 9 months. Over this period, turbines may be commissioned individually until the entire array is operational.

2.4.3 Operation

Currently windfarms are designed to have a 20 to 25 year life-span, and therefore the marine environment will suffer a longer period of exposure to wind turbine noise than any other related noise source. A windfarm will be operational continuously during this period, except for occasional shut down for maintenance or because of severe weather conditions, but the proportion of operational turbines will vary. Maintenance and pleasure craft may visit the site while it is operational.

2.4.4 Decommissioning

The last phase of a windfarm's lifecycle comes when it has finished its energy producing life and must be decommissioned. The majority of the activities involved in windfarm decommissioning are a reversal of the installation process, except for foundation removal, which is currently a grey area. Pearson [5] concludes that piled foundation removal will be achieved using mechanical cutting techniques, leaving an open verdict on gravity foundations. However, experience in the oil and gas industry suggests that explosives are most commonly used for cutting piles [6]. The time scale for windfarm decommissioning may be similar to that of windfarm construction. Offshore windfarms may instead be re-powered after coming to the end of their designed life span.

3 Underwater acoustic principles

3.1 Non-technical overview

A broad understanding of the terms and units used to describe underwater sound is required for an appreciation of the issues involved in assessing its environmental impact. The most important consideration is the sound level that is received by an animal in the water, which can be described in a number of ways. The most common measure is the Sound Pressure Level (SPL), measured in deciBels referenced to 1 microPascal (dB re 1 µPa). In underwater acoustics, 0 dB re 1 µPa is a very low sound level, whereas 300 dB re 1 µPa is very high. The Sound Pressure Level is based on an average of the pressure over a short period of time. This can give errors when the sound pressure varies quickly with time, such as impulsive sounds. For this class of signals, the peak Sound Pressure Level (SPL_{peak}) is a better measure. This gives the maximum sound pressure over an event or a short period of time.

A Sound Pressure Level is not always a good indicator of environmental effect and other measures may provide a better estimate. Very high levels of underwater sound may cause physical injury, and impulse has been shown to be a good measure of this effect. It is related to the length of time a given time pressure is acting, with the implication that a pressure of given amplitude acting for a set time will give rise to the same effect as a pressure of half the amplitude acting for twice the time.

Behavioural effects may be better modelled by using the dB_{ht}(*Species*) measure. This relates the magnitude and frequency content of the sound pressure to an animal's hearing ability. Using this measure, a level of 0 to 10 dB_{ht}(*Species*) is only just audible to the animal, whereas levels over 90 dB_{ht}(*Species*) are thought likely to cause behavioural effects.

It is often useful to predict the sound level at locations other than where measurements have been made. To achieve this the propagation of sound must be modelled, which may be achieved in a number of ways. One way to model sound propagation is using the Source Level – Transmission Loss model. This may be applied to any of the measures described above. Using this technique, the apparent sound level at one metre from the sound source is first defined. This is usually achieved by applying a correction to sound level measurements taken much further away. The sound level at any distance from the source may then be calculated by subtracting a Transmission Loss.

Transmission Loss is the rate at which sound attenuates with distance. It can vary significantly both with time and location. It is related to both the geometric spreading of sound and the absorption of sound with distance. Often a logarithmic definition of Transmission Loss is sufficient, and a common figure is '$20\log_{10}(r)$', or spherical spreading of sound. This means that for each tenfold increase in distance from the source the sound level will reduce by 20 dB. For example, a 150 dB re 1 µPa at 1 m Source Level will reduce to 130 dB re 1 µPa at 10 metres, 110 dB re 1 µPa at 100 metres and so on.

3.2 Sound in air and water

Sound is the common term for an acoustic pressure disturbance, and is characterised by molecules moving back and forth in the direction of propagation of the wave, resulting in alternate regions of rarefaction and compression. This motion is typically perceived by both animals and instrumentation as a deviation from the local ambient pressure.

The speed of propagation of an acoustic wave can be expressed in terms of the bulk modulus of the medium, which in simple terms is a measure of its compressibility, as follows:

$$c = \sqrt{\frac{\gamma\beta}{\rho_0}} \qquad (1)$$

Here, c is the speed of propagation of an acoustic wave, γ is the ratio of specific heats, β is the (isothermal) bulk modulus and ρ_0 is the ambient medium density. One of the major differences between the air and water is the sound speed, which in water is approximately 1500 m/s compared to 343 m/s in air. The higher sound speed in water is due to the relative incompressibility (large bulk modulus) of water compared to air, in other terms, water is stiffer than air. This has another interesting implication on sound in water, sound pressure levels are generally higher in water than in air.

3.3 Measuring noise

3.3.1 Pressure and the deciBel scale

There is a very wide range of sound pressures measured underwater, from around 0.0000001 Pa (Pascal or Newton per square metre is the fundamental unit of sound pressure) in quiet sea to say 10,000,000 Pascal for an explosive blast. For convenience, sound pressure is expressed through the used of a logarithmic scale. The use of a logarithmic scale compresses the range so that it can be easily described (in this example, from 0 dB to 260 dB re 1 µPa). Sound expressed in this manner is termed the Sound Pressure Level or SPL.

The SPL is defined as:

$$SPL = 10\log_{10}\left(\frac{\overline{P^2}}{P_{ref}^2}\right) \qquad (2)$$

where P is the sound pressure to be expressed on the scale and P_{ref} is the reference pressure, which for underwater applications is 1 µPa. For instance, a pressure of 1 Pa would be expressed as an SPL of 120 dB re 1 µPa. An additional advantage of working with the SPL is that many of the mechanisms affecting sound underwater cause loss of sound at a constant rate when it is expressed on the dB scale.

Acoustic pressure readings vary above and below a mean value (the ambient pressure) with time. To allow for this variation, the sound pressure P is first squared (to make all values positive) and than averaged (to smooth out the rapid fluctuations with time) before the deciBel level is calculated. In Equation 2, the averaging process is represented by a bar above the squared pressure, $\overline{P^2}$. In practice, the Sound Pressure Level is calculated by taking the deciBel value of the ratio of root mean square (RMS) pressure, over a specified time period, to the reference pressure as follows:

$$SPL = 20\log_{10}\left(\frac{P_{RMS}}{P_{ref}}\right) \tag{3}$$

Certain classes of signals do not lend themselves well to being averaged, for example impulsive signals vary significantly over time, having an average that is unrepresentative of their instantaneous level. One way to report the pressure level of this class of signals is by using their peak pressure. The maximum pressure obtained during one event is found, with the deciBel level calculated as follows:

$$SPL_{peak} = 20\log_{10}\left(\frac{P_{peak}}{P_{ref}}\right) \tag{4}$$

A brief note about the difference between deciBel levels in air and water is worthwhile for clarity. The convention for in air acoustics is to use a pressure reference of 20 μPa when calculating SPLs, as this is, for humans, approximately the minimum audible pressure for a 1 kHz tone. It is possible to convert between reference pressures by adding a constant value, and in this instance 20 μPa is 26 dB greater than 1 μPa. However, care must be taken when applying this correction as the efficiencies of sound generation and reception in air and water differ markedly, and simply adding a constant to the underwater SPL will not allow a reasonable assessment of the perceived loudness of a sound.

3.3.2 Impulse

For some effects of underwater sound, such as physical injury, average or peak pressure are inadequate measures. This arises because a sound, having a given pressure level and duration, may have the same effect as one of half the duration and twice the level. This behaviour is better modelled by the use of impulse. In an extensive study into the effects of underwater blast [7,8], the likelihood of injury for submerged mammals was shown to be related to the impulse received by the animal.

The impulse, *I*, is defined as the integral of pressure over time and is given by:

$$I = \int P(t)dt \tag{5}$$

where I is the impulse in Pascal-seconds (Pas), *P(t)* is the acoustic pressure in Pa of the blast wave at a time, *t*. Impulse may be thought of as the average pressure of the wave multiplied by its duration. The importance of impulse is that in many cases a wave acting for a given time will have the same effect as one of twice the pressure acting for half the time. The impulse of both these waves would be the same. Impulse is the parameter of high pressure short duration events normally used as the measure of its strength in respect of lethality.

3.3.3 Units of perception - the dB_{ht}(Species)

The authors have developed a generic dB scale which enables better estimates of the behavioural effects of sound on marine species to be made. The measure of a species' ability to perceive sound is the audiogram, which presents the lowest level of sound, or threshold, at which a species can hear as a function of frequency. Examples of audiograms for species common to UK waters are shown in Figure 3. Levels of sound lower than the hearing threshold defined in the audiogram of a species cannot be perceived by that species; the degree of perception of the sound relates to the amount it is above the threshold.

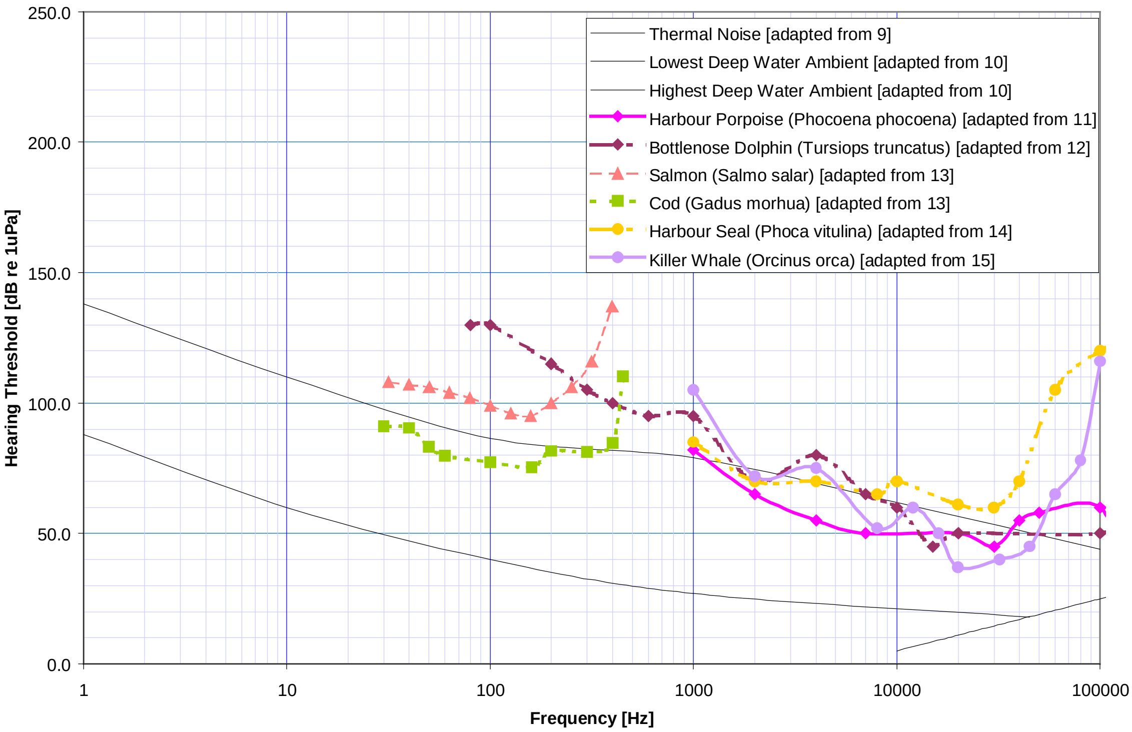

Figure 3. Examples of species' audiograms with the extent of ambient noise for reference.

In the dB_{ht}(*Species*), a frequency dependent filter is used to weight the sound. The suffix 'ht' relates to the fact that the sound is weighted by the hearing threshold of the species. The dB_{ht}(*Species*) level is estimated by passing the sound through a filter that mimics the hearing ability of the species, and measuring the level of sound after the filter; the level expressed in this scale is species specific and corresponds to the perception of the sound by the species. In effect, the scale may be thought of as a dB scale where the species' hearing threshold is used as the reference unit. The dB_{ht} measure reflects the level of sound above a species' threshold. The benefit of this approach is that it enables a single number to describe the effects of the sound on that species.

The process used to calculate the dB_{ht}(S*pecies*) is similar to that used to calculate dB(A) levels, which is the standard measure of noise in air. Indeed it is possible to calculate dB_{ht}(*Homo sapiens*) using the human hearing thresholds (in air) and this will give similar results to a dB(A) weighted level. The advantage of this technique becomes apparent after considering that bats are one of the loudest land animals, but as the majority of the sound energy they produce is at frequencies above that which can be heard by humans, or in other terms is ultrasonic, they are not a noise nuisance.

Usually, effective noise levels of sources measured in dB_{ht}(*Species*) are much lower than the unweighted levels, both because the sound will contain frequency components that the species cannot detect, and also because most marine species have high thresholds of perception of (are insensitive to) sound.

Human hearing has a dynamic range, from the threshold of hearing, to the threshold of pain, of about 130 dB. The range is determined by physical constraints; at the lower end, hearing is limited by natural background noise, and at the upper end, by displacements of the sensory structures associated with hearing to a degree that causes traumatic damage. When the sound exceeds about 90 dB above the threshold level, it is likely to cause significant behavioural effects and in particular avoidance. It may be proposed that since these limits are set by physical constraints, the dynamic ranges available to other species may be similar, and a similar criterion will apply.

Modelled dB_{ht}(*Species*) level for Doel system	**Doel system efficiency**	**Hartlepool system efficiency**
76 dB_{ht}(*Limanda limanda*)	21% (flatfish results)	16% (flatfish results)
90 dB_{ht}(*Gadus morhua*)	50% (roundfish results)	54% (whiting results)
98 dB_{ht}(*Clupea harengus)*	80%	80%

Table 1. Efficiency of acoustic fish deflection system [16].

Amongst the evidence for strong avoidance reactions when received sound levels exceed a 90 dB_{ht} threshold is the successful use of acoustic fish deflection systems designed using this criteria. Table 1 details the measured efficiencies against dB_{ht} level for fish deflection systems at two power station inlets [16], and shows an increasing efficiency with increasing level above threshold. Although similar data is lacking for other species, it is indicated that at 90 dB_{ht} significant behavioural reactions will occur, and at 70 dB_{ht} mild behavioural reactions will occur. These thresholds are currently undergoing validation as part of a DTI funded research program [17].

3.4 Noise propagation modelling

In order to provide an objective and quantitative assessment of degree of any environmental effect it is necessary to estimate the sound level as a function of range. To estimate the sound level as a function of the distance from the source, and hence the range within which there may be an effect of the sound, it is necessary to know the level of sound generated by the source and the rate at which the sound decays as it propagates away from the source. These two parameters are the Source Level (i.e. level of sound) generated by the source, and the Transmission Loss, that is, the rate at which sound from the source is attenuated as it propagates.

3.4.1 Source Level

The Source Level is defined as the effective level of sound at a nominal distance of one metre, expressed in dB re 1 μPa @ 1 m. However, the assumptions behind this simple definition warrant careful explanation.

Source Level is a somewhat confusing term as it is rarely measured, as would be expected, at one metre from the source. Complex interactions between contributions from different parts of the source occur at short ranges causing irregularities in the sound field that are difficult to predict. This region extends to a range, $r_{0,}$ which is given by:

$$r_0 = \frac{A}{\lambda} \tag{6}$$

where A is a characteristic dimension of the source and λ is the wavelength of the frequency of interest [18]. The region from the source to r_0 is termed the near field. The region beyond this range is termed the far field.

There is in general no reliable way of predicting the noise level from sources of man-made noise, and hence it is normal to measure the Source Level indirectly where a requirement exists to estimate far-field levels. The sound level is measured in the far field, and this pressure is used to estimate the apparent (or effective) level at a nominal one metre from the source. The apparent level may bear no relation to the actual level.

A measurement of the apparent level can be accomplished by assuming inverse dependence of sound level on the range, r, from the noise source, or by extrapolating the far field sound level. For instance, if measurements were made in the range 100 metres to 10000 metres in the example in Figure 4 the apparent level would, as illustrated by the extrapolation, be much higher than the actual level at one metre. The Source Level - Transmission Loss model is thus a linear fit to measured far field levels, where the intersection and gradient of the line are termed Source Level and Transmission Loss respectively. This model should only be used to estimate sound levels in the far field.

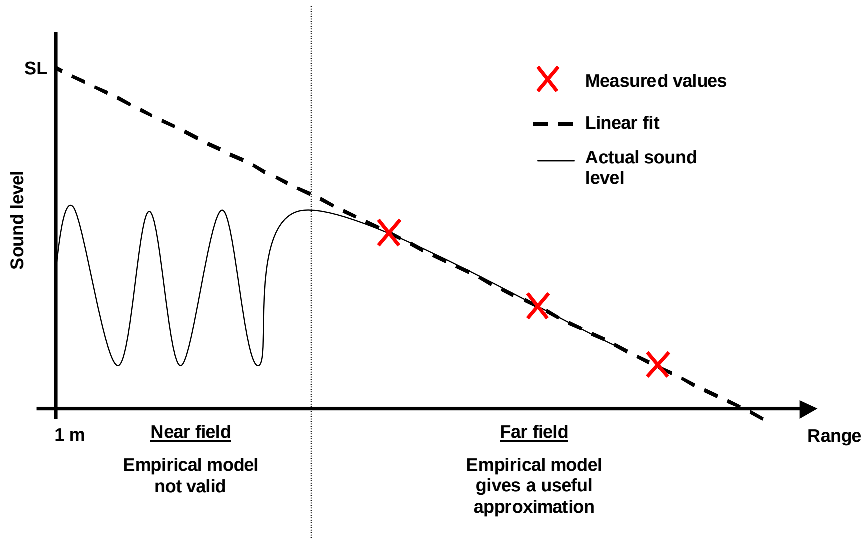

Figure 4. Source Level - Transmission Loss model.

3.4.2 Transmission Loss

Transmission Loss, or TL, is a measure of the rate at which sound energy is lost, and is defined as:

$$TL = 20\log_{10}\left(\frac{P_0}{P_r}\right) \tag{7}$$

where P_o is nominally the pressure at a point at one metre from the source, and P_r is the pressure at range *r* away from it.

The usual method of modelling the Transmission Loss is from the expression:

$$TL = N\log_{10}(r) - \alpha r \tag{8}$$

where *r* is the range from the source in metres and N and α are coefficients relating to geometric spreading of the sound and absorption of the sound respectively. High values of N and α relate to rapid attenuation of the sound and limited area of environmental effect, and low values to the converse.

Transmission in the ocean has probably been the subject of more interest than any other topic in underwater communication, since it is the parameter that is the least predictable and the least capable of being influenced. The sound from a source can travel through the water both directly and by means of multiple bounces between the surface and seabed. Sound may also travel sideways through the rocks of the seabed, re-emerging back into the water at a distance. Refraction and absorption further distort the sound, leading to a complex wave arriving at a distant point which may bear little resemblance to the wave in the vicinity of the source. Finally, sound may be carried with little loss to great distance by being trapped in sound channels. Here, variations in sound speed restrict sound propagation to a narrow channel thereby limiting geometric attenuation. Examples of channels include the SOFAR channel, the surface or mixed layer channel and the shallow water channel.

Several mathematical models exist which estimate Transmission Loss for given water column properties. A value of N=20 corresponds to spherical spreading of the sound and is often assumed near to a source in deep water. Further afield, N=10 represents cylindrical spreading that can occur in deep water channels and shallow water columns. Often a value of N=15 is used, and a mathematical model exists which justifies this for a particular shallow water scenario.

Despite these models, predicting the level of sound from a source is a difficult task, and where possible use is made of simple models or empirical data based on measurements for its estimation. Referring again to Figure 4, measurements of sound levels must be taken in the far field to give a reasonable estimate of sound attenuation within this region. Transmission loss is the gradient of a linear fit to this data. In the authors' experience, shallow water Transmission losses of between N=20 and N=25 are most commonly measured [e.g. 19, 20].

Whether it is measured or predicted, the Transmission Loss used will affect the predicted sound level significantly. For example, over a 10 metre range a noise subject to N=15 Transmission Loss will be 10 dB louder than the same noise subject to N=25 Transmission Loss. Over a 10 km range, using the same example, the difference will be 40 dB. Where there is insufficient data for an accurate estimation of Transmission Loss using a linear fit, for example when measurements are only reported for one range, a Transmission Loss of N=20 will be assumed for Source

Level calculations. This equates to spherical spreading. However care must be taken to remember the influence of Transmission Loss on these calculations.

3.4.3 Summary

Knowledge of Source Level and Transmission Loss allow the sound level at all points in the far field to be estimated, and in the current state of knowledge are best measured at sea, although it is in principle possible to estimate the Transmission Loss using numerical models. Usually these data have to be extrapolated to situations other than those in which the noise was measured and the usual method of modelling the level is from the expression:

$$SPL = SL - TL \tag{9}$$

where SPL is the Sound Pressure Level in dB, SL is the Source Level in dB, and TL is the Transmission Loss in dB.

If the level of sound at which a given effect of the sound is known, an estimate may be made of the range within which there will be an effect.

Although the SL-TL model is defined in terms of SPLs in Equation 9, it may be applied to any logarithmic measure of sound including the dB_{ht}. Using this approach it is possible to estimate the range at which the dB_{ht} value will exceed a certain threshold, which is useful in assessing the behavioural response of animals at different distances. In general, the SL-TL model is frequency dependent with some frequencies attenuated more with distance than others. As the dB_{ht} is a frequency dependent filter, this implies that SLs and TLs will vary with each species.

4 Available information on windfarm related underwater noise

4.1 Pre-existing noise

4.1.1 Deep water ambient noise

Ambient noise in the ocean is sound that is always present and cannot be attributed to an identifiable localised source [21]. Examples of ambient noise sources include noise from rain falling on the ocean, from bubbles entrained into the ocean by breaking waves, wave interaction, seismic disturbances of the sea floor, and noise emitted by marine wildlife. The noise comes from all directions, but varies in both magnitude and frequency content with direction, depth, location and time. It is therefore difficult to predict the properties of ambient noise for any given measurement, giving rise to statistical and empirical models for the received level.

A significant body of ambient noise measurements were taken in deep water during the first half of the 20th century. These measurements came as a result of the fact that a limiting factor in the performance of military SONAR (**SO**und **N**avigation **A**nd **R**anging - a system used by boats and submarines to locate objects in water) is the amount of ambient noise present at the receiver location, which created a significant incentive to gain further understanding of the ambient noise process.

An important contribution to the field of knowledge was made by Knudsen [22], who identified that between 200 Hz and 50 kHz the level of ambient noise is dependent on the sea-state. The underlying physical processes which cause this variation are still unclear, but flow noise from surface wind, breaking waves and bubble formation are all thought to contribute. Wenz [10] built on the region defined by Knudsen, extending to the low and high frequency ranges. Below 10 Hz measured noise is thought to be due to oceanic turbulence and seismic disturbances. In the region around 100 Hz distant shipping makes a significant contribution in almost all of the world's ocean. Mellen [9] showed that at very high frequencies, from 50 kHz upwards, molecular motion of water (thermal noise) contributes to the noise level at an increasing rate.

Figure 5 gives a summary of the range of ambient noise in the ocean as given in a paper compiled by Wenz [10]. Low frequency ambient noise from 1 to 10 Hz is mainly comprised of turbulent pressure fluctuations from surface waves and the motion of water at the boundaries. It exhibits a dependence on both wind strength and water currents. This is especially the case in shallow water. Turbulent pressure changes are not generally acoustic in nature: they do not propagate as alternate regions of high and low pressure. Hydrophones are equally as sensitive to turbulent pressure changes as propagating sound waves, and measurements will be a combination of both. However low frequency propagating sound does exist, and can be measured where turbulent noise does not dominate. Low frequency acoustic noise in this region includes distant earthquakes and explosions.

Between 10 and 100 Hz distant anthropogenic noise begins to dominate, with its greatest contribution between 20 Hz and 80 Hz. The noise in this region is not attributable to one specific source, but a collection of sources at distance from the receiver. Distant shipping traffic is the greatest contributor to man-made ambient noise, with received levels up to 55 dB re 1 μPa for usual and 65 dB re 1 μPa for heavy shipping traffic.

In the region above 100 Hz, the ambient noise level depends on weather conditions, with wind and wave related effects creating sound. The peak level of this band has been shown to be related to the wind speed, measured using the Beaufort scale, with levels ranging from 20 dB re 1 μPa to 55 dB re 1 μPa. The level of wind related noise decreases with increasing frequency above approximately 500 Hz, falling with a slope of between 5 and 6 dB per octave (doubling of frequency).

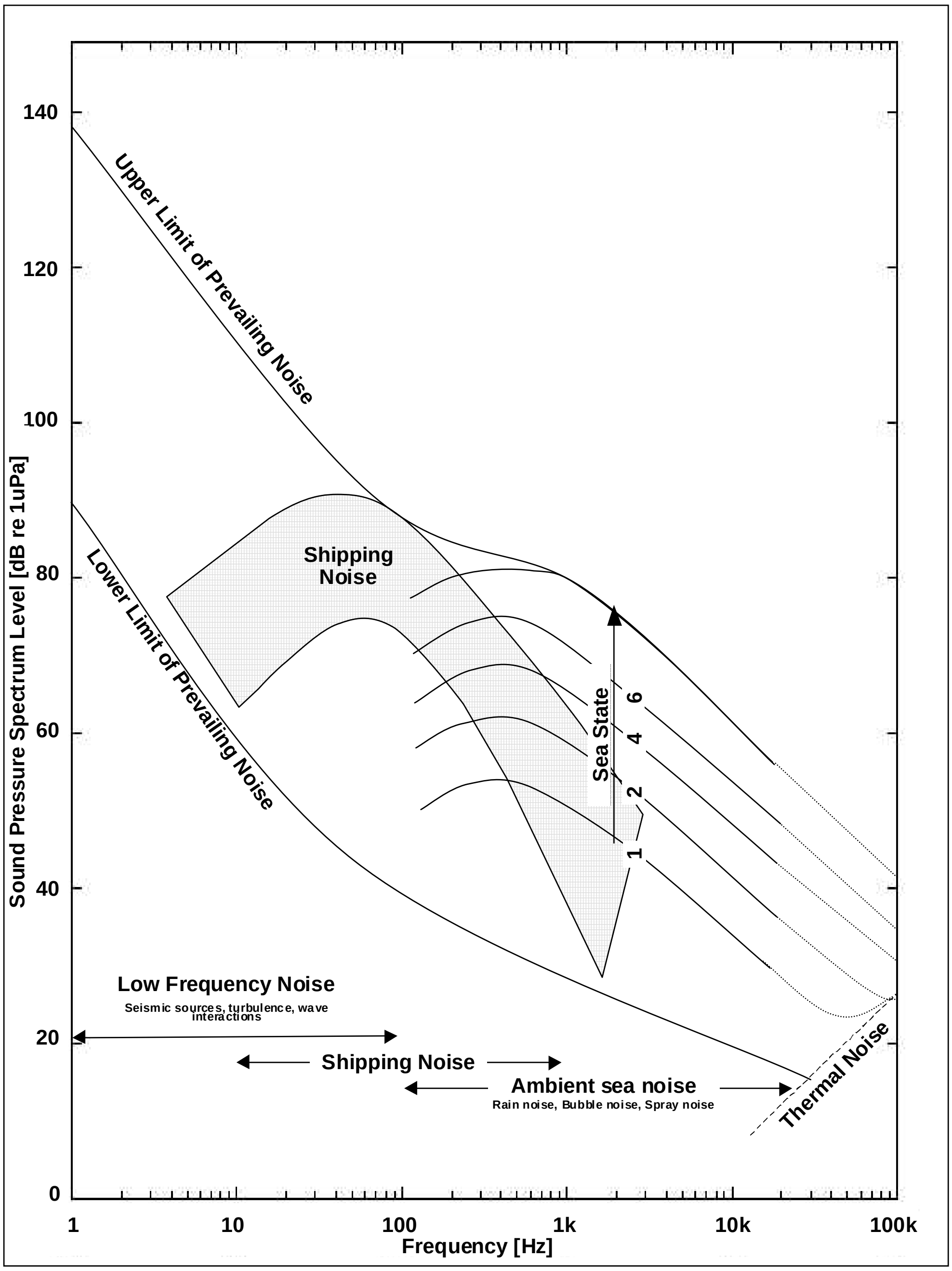

Figure 5. Background noise [adapted from 10].

At frequencies above 20 kHz, measured sound levels may be influenced by thermal noise at the lowest of ambient noise levels. This increases from a level of -10 dB re 1 μPa at 35 kHz by a rate of 6 dB per octave. During high winds, thermal noise may not dominate below frequencies of several 100 kHz. Other contributions to ambient noise include sea-ice, biological sources and near shore industrial activity.

4.1.2 Shallow water ambient noise

Due to the focus of military activity being in deep waters, oceanic ambient noise characteristics are relatively well understood. Windfarms however, will be situated in shallow coastal waters for well into the medium term future. Ambient noise in these regions is less well understood and extremely variable; it can be both significantly quieter and louder than deep water ambient noise. Sources of noise include those listed above and is typically dominated by shipping, wind and wave and biological sources. Wenz [10] states that ambient noise is 5 dB higher in shallow waters than in deep, but this is an over simplification.

Measurements by Piggot [23] off the Scotian Shelf (5 miles off the coast of Fort Lauderdale, Florida) in 700 ft deep open water showed a 7.2 dB increase per doubling of wind speed in the region 10 Hz to 3 kHz. These measurements, which are defined as shallow water, are in water significantly deeper than that of current offshore windfarms. This again raises the question of the definition of 'shallow water'. A common definition in the underwater acoustics field is water that is less than 200 m deep, however this definition covers the significantly different conditions of continental shelf and inshore harbours and bays. A more useful definition includes frequency dependence, with shallow water being of a depth of the same order of magnitude as the acoustic wavelength. For offshore windfarms, water can be considered shallow for frequencies ranging from below 50 Hz to below 750 Hz, which corresponds to water depths of 30 m and 2 m respectively. This definition is based on sound propagation considerations and, though not related to the generation of ambient noise, it will have a bearing on its distribution.

4.1.3 Background noise

In addition to ambient noise (which includes distant shipping traffic), in shallow coastal areas, local shipping traffic, pleasure craft, oil and gas platforms, other mechanical installations and local wildlife all add to the level of noise received at a hydrophone. The combination of ambient noise, which cannot be attributed to a particular source, and these easily identifiable local sources is termed background noise. This is all the noise received at a particular time and location that is in addition to the source of interest.

An assessment of the background noise is essential for a valid assessment of the potential for effect from the introduction of a windfarm, as background noise may mask the sound produced by the source. However, given the variability of background noise it may mask the source at some locations and times, but be well below at other locations and times. One way to manage this variance is to characterise background noise in terms of its average and range of values, taking a statistical approach. A suitable number of measurements have been taken in deep waters to allow statistical models of deep water background noise to be made, however only a handful of shallow coastal water background noise measurements have been taken. As this will be the focus of windfarm development in the medium term, further measurements in shallow coastal water are needed to allow a reliable assessment of their impact on the average underwater noise level in these regions.

4.1.4 Summary

In order to accurately assess the effect of introducing a new sound source into the marine environment a knowledge of the pre-existing (background) noise is required. In this context, background noise is all the noise which exists that is not windfarm related. It can vary in magnitude and frequency content in both space and time. The importance of this is that it may mask windfarm related noise at some locations and times, but be well below the source given different conditions.

There are a number of models that allow the mean level and variation of deep water noise to be predicted. However, knowledge of shallow coastal water background noise is scarce, and although it is known that may be both significantly lower and higher than deep water background noise, shallow coastal water background noise models are not well developed.

4.2 Vessel and machinery

4.2.1 Background

Throughout the lifecycle of a windfarm there will be an increase in vessel traffic. Before construction, survey vessels will be used to plan for the development. During construction, significant small and large vessel support will be required and, at a reduced frequency, this will continue throughout the operational phase on order to conduct regular maintenance. The operational phase may also bring tourism to the site, with vessels ranging from private motorboats and yachts to commercial pleasure boats, while other shipping traffic may be re-routed for safety or navigational purposes. Decommissioning will in essence be a reversal of the installation process and, except for some survey work, will require an equal amount of vessel support.

Examples of vessels include a small RIB to transfer crew from one vessel to another, boats for survey work, windfarm tourist pleasure boats, large construction support vessels and jack-up barges. All these will create underwater noise in the vicinity of the windfarm adding to the general level of vessel and machinery noise from nearby ports and distant shipping.

Boat noise is dominated by propeller noise, except when operating at very low speeds where hull radiated noise dominates [24]. During windfarm construction, both propeller noise from small boats or ships underway and hull radiated noise from stationary vessels conducting works may be significant sources. In addition to this, navigational aids such as depth sounders and side scan sonars purposefully radiate high level sound energy into the surrounding water.

4.2.2 Available information

Measurements of noise from small boats are limited, as the main focus of research has been into noise from large vessels at sea. Richardson et al. [25] lists a range of Source Levels for small boats ranging from a 5 m, 25 hp (outboard) Zodiac with a 152 dB re 1 μPa @ 1 m Source Level, to a 25 m tug pulling an empty barge with a 170 dB re 1 μPa @ 1 m Source Level. Estimated $^1/_3$ octave band levels are also given that show spectra peaking between 100 and 1000 Hz. In comparison, measurements by Arveson et al. [26] of the *M/V Overseas Harriette*, a bulk cargo ship (length 173 m, displacement 25,515 tons) powered by a direct drive low-speed diesel engine, gave Source Levels of 192 dB re 1 μPa @ 1 m when she was at 16 kt, 140 rpm. The cargo ship has a design representative of many modern merchant ships, but is significantly larger than ships likely to be used for windfarm construction.

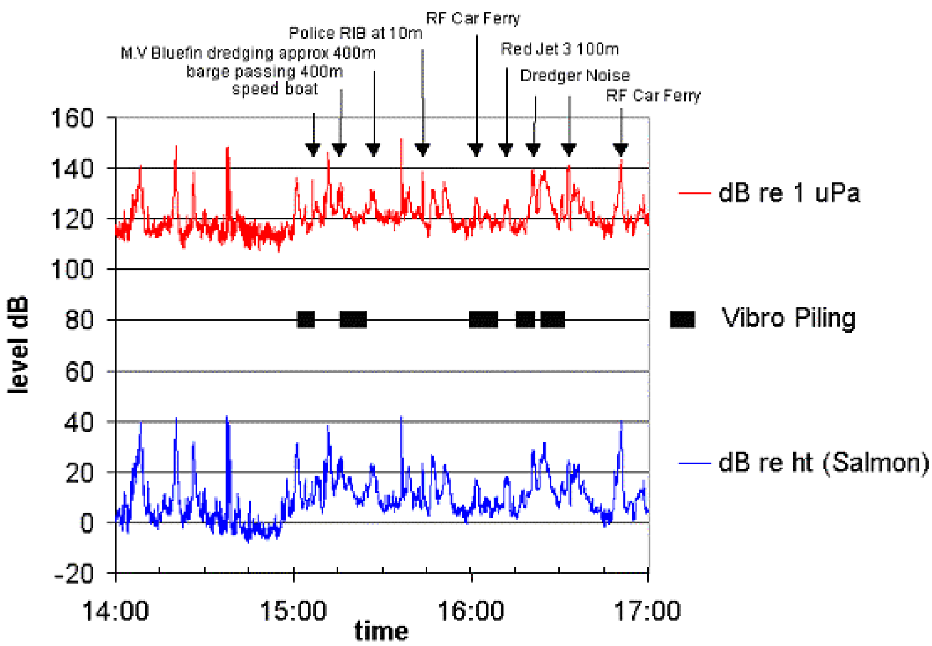

Figure 6. Sound pressure level vs. time obtained at the end of Town Quay, Southampton during construction works at the Red Funnel terminal [27].

A recent set of measurements were taken of construction work at the Red Funnel ferry terminal that took place during the Southampton Boat Show [27]. The objective of the measurements was to monitor pile driving, but during construction down time they gave an insight into sound levels in a busy port. Figure 6 shows a graph of both linear and dB_{ht}(*Salmo salar*) (or salmon hearing threshold weighted) sound pressure levels against time during a September afternoon at the end of Town Quay, Southampton. Marked on the graph are the presence of known local sources, such as the passing of boats, ranging from large container vessels to small boat show traffic, and including the vibrodriving of piles for a new link span at the terminal. A feature of these measurements was the existence of monitored caged fish during the works that were used to correlate dB_{ht} levels to fish reaction.

The result of double blind analysis of the caged fish video recordings showed no significant behavioural reactions during the course of the survey. This agrees with the dB_{ht} results, which show levels well below the proposed 70 dB_{ht} reaction threshold. Thus, for salmon at least, these measurements show that an increase in vessel traffic is unlikely to create significant behavioural changes.

Richardson et al. [25] reviews evidence of marine mammal disturbance by ships and boats, noting that it is often difficult to differentiate visual and auditory behavioural reaction in this case. Several reports [28, 29, 30] detail harbour seal (*Phoca vitulina*) moving into water as boats approach haul out sites, however reactions to canoes and kayaks can be equally as strong [31, 32] suggesting visual cues are in this case the dominant force. Reactions to boat noise by toothed whales (odontocetes) is a complicated matter, with both attraction, for example dolphins riding bow waves, and avoidance, for example in response to hunting vessels, having been recorded. The dependence of the type of reaction on noise level is uncertain, and may vary within species. The understanding of the reaction of baleen whales is similar, with reports of both attraction and avoidance reactions. There is no clear evidence that cetacea will avoid a certain region due to increased boat noise. However, without a benchmark survey of noise and species abundance before boat traffic is increased, it may be difficult to prove whether or not there has been an effect. Other considerations include the long term cumulative effects of increased underwater noise, such as increased stress, but little is known about these and it is difficult to make an assessment.

4.2.3 Summary

It is clear that throughout a windfarm's lifecycle there will be an increase in vessel traffic and a consequent increase in the general level of underwater noise, however the environmental effect of this is not obvious. Documented Source Levels range from 152 dB re 1 μPa @ 1 m for a small vessel with an outboard engine to 192 dB re 1 μPa @ 1 m for a large container ship. Behavioural reactions to boat noise include avoidance and attraction.

4.3 Geophysical survey

4.3.1 Background

Geophysical surveys are made at an early stage in the planning process for an offshore windfarm to provide an insight into the suitability of a location for windfarm construction. They provide information on sediment, rock strata and underlying geological structures underneath the seabed. The results of these surveys are initially used to assess the potential for windfarm development, and when a suitable site is chosen, surveys reveal information needed for shallow water engineering (e.g. location and design of turbine foundations and cabling). Geophysical surveys will most likely occur intermittently during the years leading up to windfarm construction, with increasing frequency as the program develops. During construction, further surveys may be performed, especially to plan for cable routing.

During surveys, high-energy acoustic sources are used in water to transmit sound into the sea floor. When the acoustic waves encounter a change in acoustic impedance, for example when rock or sediment composition changes, a portion of its energy is reflected back to the receiver, which is typically an array of hydrophones, to form an image. The sources are impulsive, and are generated using a variety of mechanisms.

Airguns are used extensively in the oil and gas industry for deep and occasionally shallow water surveys where penetration depth is more important than resolution. These inject air at very high pressure into the water, which forms a rapidly expanding and then collapsing air bubble. The oscillations of the air bubble generates high-level, low frequency sound waves.

Where resolution is of greater importance then penetration depth, for example in shallow water construction, mid-frequency sources are commonly used. These include boomers and sparkers which have both found wide use for windfarm related surveys. Boomers consist of two plates separated by a coil across which a high voltage impulse is created. The resultant magnetic field causes one plate to vibrate and radiate acoustic energy into the surrounding water. Sparkers also generate sound from a high voltage impulse, but in this instance sound is generated by the oscillations of the gas bubble produced from the rapid temperature rise caused by a spark forming across a pair of electrodes.

High frequency sub bottom profilers use piezo-electric transducers and provide greater resolution but sacrifice penetration depth. These may be used for planning windfarm cabling routes.

4.3.2 Available information

Independent measurements of the noise produced by geophysical surveys in the far field is scarce for all sources except airguns, which have been extensively studied in deep and, more recently, in shallow waters because of environmental concerns.

Manufacturers state Source Levels for boomers and sparkers in their literature, and these range from 215 to 230 dB re 1 μPa @ 1 m [25, 33, 34], but the reliability of these figures is uncertain. Independent measurements of geophysical surveys using airguns state Source Levels for individual airguns from 216 to 232 dB re 1 μPa @ 1 m [25] and airgun arrays from 235 to 259 dB re 1 μPa @ 1 m [25]. High perceived Source Levels, from 142 to 216 dB_{ht}(*Species*), have also been shown for several species of fish and cetacea [35].

There are no published observations of marine animal reaction to geophysical survey using boomers and sparkers. Recorded reactions to airgun noise are limited to observations of cetacea, and are limited for this order. Richardson et al. [25] provides a review of documented reactions to airguns, which includes several surveys of baleen whales, especially grey (*Eschrichtius robustus*) and bowhead (*Balaena mysticetus*) whales, showing reaction to received levels of approximately 160 dB re 1 μPa. Published observations of odontocete reaction to airguns include one report of a dolphin sighting in the vicinity of a survey [36] and two reports of behavioural reaction from sperm whales (*Physeter catodon*) that detailed avoidance reactions [37] and reduced vocalisations [38].

4.3.3 Summary

There are no independent measurements or animal reaction studies available of geophysical survey sources, such as boomers and sparkers, used in windfarm development. Airguns have been studied and the literature shows that they produce linear Source Levels ranging from 215 to 260 dB re 1 μPa @ 1 m; dB_{ht} Source Levels from 142 to 216 dB_{ht}(*Species*) and behavioural reactions in cetacea. While this data may not be used to assess the environmental effect of windfarm geophysical surveys, it suggests that windfarm related geophysical surveys are an area for concern and research should be conducted.

4.4 Pile driving

4.4.1 Background

A pile driven turbine foundation involves forcing a hollow cylindrical steel tube into soft ground to such a distance that it provides a suitable foundation upon which to build a wind turbine. Depending on the foundation design, either a large single pile or several smaller piles are used to form the foundation. These are termed monopile and multipile foundations respectively. Pile driving techniques include impact pile driving, where a pile is hammered into the ground by a hydraulic ram, and vibrodriving, where rotating eccentric weights create an alternating force on the pile, vibrating it into the ground. Impact driven monopiles have become the favoured foundations for offshore wind turbines in recent years, with only this foundation type currently in existence in the UK. The dimensions of the steel monopiles vary, but for current installations are approximately 4 metres in diameter and 20 to 30 metres long. Where piles are installed in mixed substrate conditions, hard rock may be encountered, and in this case a socket must be drilled for the pile. Once this is completed the pile may be hammered to its required depth. Underwater noise from drilling is covered in Section 4.5. It should be noted that there are many variations in pile hammer design, and that a pile may be hammered from both above and below the water surface. These factors may have a considerable effect on the radiated noise level, however the scarcity of available measurements means that it is difficult for an assessment to be made.

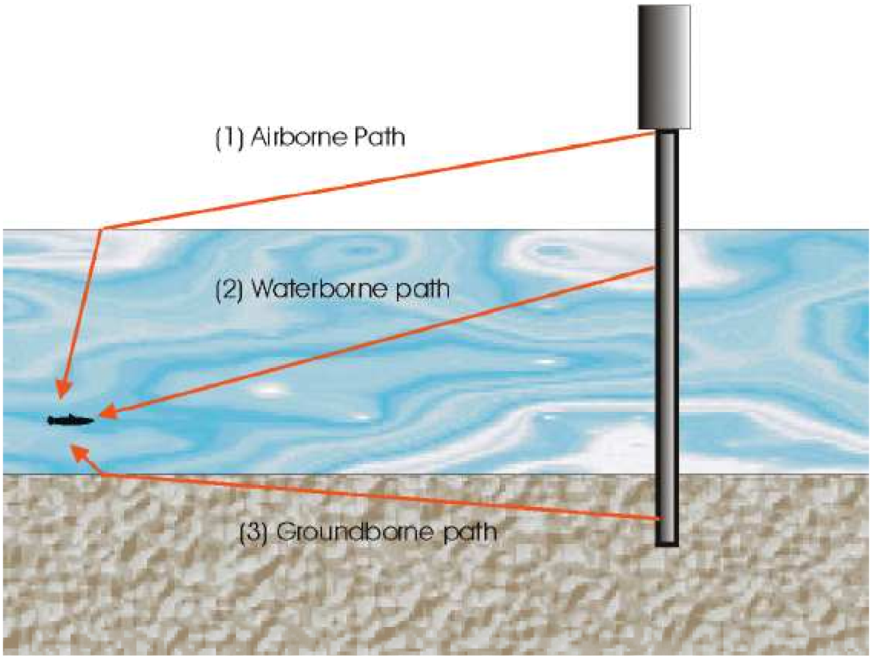

Figure 7. Sketch to illustrate noise paths during impact pile driving.

The mechanics of underwater noise generation and propagation during impact piling are not well understood and there is little literature available on the subject. However, an appreciation of this is useful for the identification of suitable noise control measures. Figure 7 illustrates the paths by which the noise propagating from a pile may travel to a distant underwater point when it is struck by a pile driving hammer. Sound may enter the water and propagate to a distant receiver via at least one of three paths. When the hammer strikes the pile sound is generated in the air surrounding the hammer and the pile. This sound may enter the water via an airborne path, where airborne noise is incident upon the air-water interface and a portion of the sound energy enters the water. Gerjuoy [39] showed that for sound incident at an angle greater than 13° to the normal all of the energy is reflected back from the water surface, within this range increasing proportions of the sound's energy will be transmitted. According to this model the majority of airborne sound will be transmitted in the region adjacent to the pile, although some sound may enter the water outside this region because of surface roughness. As well as the angle of incidence, the difference in acoustic impedance effects the amount of acoustic energy transferred from one substance to another. For air and water this difference is large and, for this reason, it is thought unlikely that airborne transmission of pile hammering noise will contribute significantly to the level of underwater sound from pile driving.

Between the sea surface and sea floor the pile will be surrounded by water. The contribution from the sound generated at this interface is thought to give the greatest contribution to the sound at the receiver location. The complex structural vibrations of the pile, which may consist of both propagating compressional and shear waves and non-propagating whole body motions, will generate sound waves in the surrounding water.

At the lower end of the pile, an impulsive force is exerted on the seafloor by the pile. Energy is transmitted from the hammer by the pile not only by the mean force exerted on the sea floor but also by the structural waves radiating down the pile inducing lateral waves in the seabed. These may travel as compressional waves, in a similar manner to the sound in the water, as shear waves, where wave motion is perpendicular to the direction of propagation, or as more complex wave types such as Rayleigh waves. The waves can travel outwards through the seabed, and as they propagate sound will tend to “leak” upwards into the water, where it contributes to the sound at the receiver. Since the speed of sound is generally greater in consolidated sediments than in water, these waves usually arrive before the waterborne wave.

The transmission paths for vibropiling are likely to be similar to that of impact piling. However, in this instance, the pile is struck several times a second (between 5 and 50 strikes per second) with a hammer causing the pile to vibrate into the ground. The impact energy of each strike is typically less than for a similar impact pile hammer which suggests that vibropiling is the quieter of the two methods. Indeed, where airborne noise is a concern during land based construction, vibropiling is typically the preferred installation method for this reason. There is no reason to suggest that this would not be the case for underwater noise. However, vibropiling may not be suitable in a number of cases, and where it is used the installation is often finished with an impact pile hammer [40].

4.4.2 Available information

Published measurements of underwater noise from piling are relatively sparse, and even more rare are studies linking both noise and marine wildlife observations, making an assessment of the potential effects from windfarm related piling difficult. In addition to this, piling may encompass a wide range of operations, piling equipment, substrate types, water depths, etc giving a wide range of possible noise Source Levels and Transmission Losses.

Measurements of underwater noise in the river Arun, Littlehampton, were made during piling the construction of a quay wall [41]. The piles were 700 mm in diameter, significantly smaller than those likely to be used for offshore windfarms. In respect of the unweighted noise from impact piling, the losses were mainly due to absorption; with a reasonable fit given by:

$$SPL = SL - N_a(r) \tag{10}$$

where the Source Level is about 192 dB re 1 μPa @ 1 m, and the Transmission Loss rate (N_a) is about 0.07 dB per metre.

The measurements for selected cases were processed into dB_{ht} levels. Of most interest are the results for the salmon, which indicate a maximum (at a range of 7.5 metres from the piling) of 26.9 dB_{ht}(*Salmo salar*). This figure is not greatly above the threshold of hearing of the species, and it is concluded that, in this case, the risk of the sound inducing behavioural responses was small. However, the report noted that this could have arisen from the particular conditions prevailing at Littlehampton and hence it could not be concluded that piling is, in all cases, unlikely to cause environmental effects.

Nedwell [27] reports on monitoring measurements of the waterborne noise resulting from impact piling and vibropiling at Town Quay, Southampton, during construction operations at Red Funnel's Southampton Terminal in September 2003. The piling involved impact piling and vibropiling of piles of 508 mm diameter and 914 mm diameter. The average Source Level of the impact piling was found to be about 189 dB re 1 μPa @ 1 m for the 508 mm diameter piles, and 201 dB re 1 μPa @ 1 m for the 914 mm diameter piles. These Source Levels were associated with a Transmission Loss rate of about 0.15 dB per metre.

Würsig [42] reports on piling in shallow water in Hong Kong, and the use of a bubble curtain to attenuate the noise. The piling was by a 6 tonne diesel hammer, with a blow energy of 90 kJ. The noise was measured on two days at distances of 250, 500 and 1000 metres; it was found that the broadband noise levels were reduced by 3 to 5 dB by the curtain. The best performance of the curtain was found to be from 400 Hz to 6400 Hz.

Unfortunately, the results were not being presented as peak pressures but as averaged levels, which limits their use. In addition, no information is given as to the size of the piles. The authors quote a typical impulse duration of 40 ms and an average strike rate of 1.15 blows per second, or a duration between impulses of 830 ms. This implies that the peak level would be about 13 dB higher than the averaged level.

By using this correction it is found that the results agree well with a Source Level for the piling of 198 dB re 1 μPa @ 1 m, and a linear Transmission Loss of 0.04 dB/metre. The Source Level is thus slightly higher than that at Littlehampton (192 dB re 1 μPa @ 1 m) and the rate of attenuation slightly lower (0.04 dB/metre as compared to 0.07 dB/metre).

Nedwell [43] reports on the noise created during piling in water of approximately 180 metres depth during construction in the Magnus Field. The piling was characterised by short impulsive events as the pile driver struck the pile; the impulses occurred at intervals of about 1½ seconds with the peak pressures of sound recorded varying somewhat from impact to impact. The peak-to-peak pressures of the impulses were, within the variability of the results, independent of the depth of the measurement. The peak pressure was found to be associated with a Transmission Loss of about $24\log_{10}(r)$, where r is the range in metres. This is rather more rapid attenuation than is given by spherical spreading of the noise, which leads to a Transmission Loss of $20\log_{10}(r)$. The corresponding effective Source Level of the pile driving was about 246 dB re 1 µPa @ 1 m.

Biologists in northern California held caged Pacific salmon (*Onchorhynchus spp.*) at various distances from pile driving being undertaken for a major road crossing [44]. The piles were 2.4 metres diameter. The measured noise levels for a pile being driven with a 1,000 kJ hammer and without any attenuation measures being taken are given in Figure 8. A logarithmic trend line has been added to the measured data to estimate the Source Level and Transmission Loss. This indicates a Source Level of 261 dB re 1 µPa @ 1 m and a Transmission Loss of N=30. The Transmission Loss given by a logarithmic fit to the data may not be a true representation of the actual Transmission Loss due to the low number of measured levels. If this is the case the Source Level given above is an overestimate. Using a more reasonable Transmission Loss of N=20, the data gives an average Source Level of 240 dB re 1 µPa @ 1 m. Based on the measurements, caged fish trials and observations of predation, the report concluded that fish within 10 to 12 m of the pile driving died immediately as a result of the received sound levels, and that fish up to 1000 m from the pile were likely to suffer such injuries that they would die shortly after pile driving.

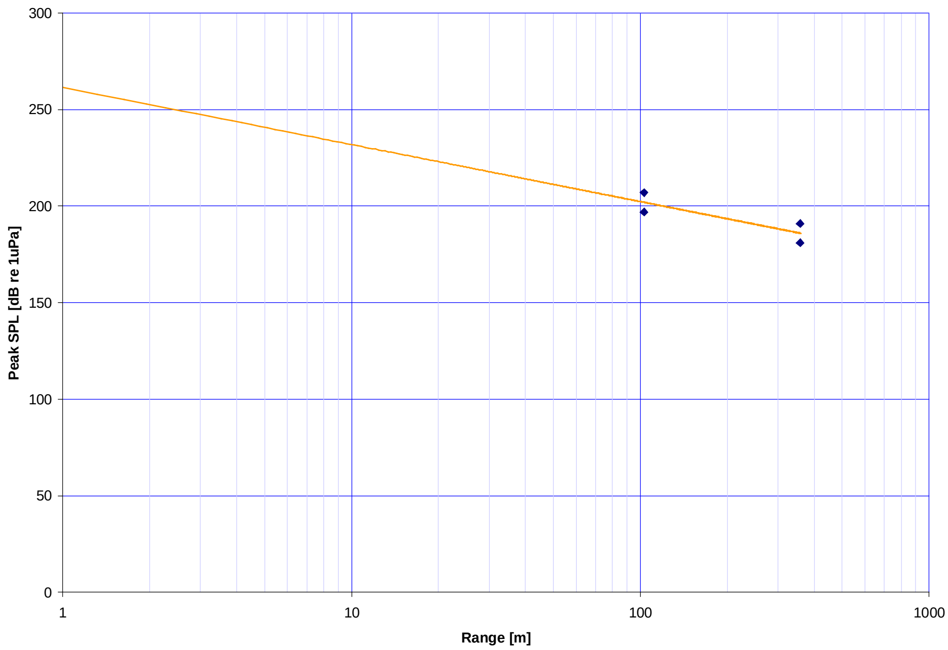

Figure 8. San Francisco pile installation underwater noise measurements (blue) and trend line (orange) [44].

Vagle [45] provides a recent review of several underwater pile installation investigations conducted in coastal waters in Canada. Results range from a 20 kPa, 206 dB re 1 μPa @ 1 m, peak over pressure Source Level for a 8" (203 mm) cedar pile, to a 150 kPa, 223 dB re 1 μPa, peak overpressure at an unspecified range for a 36" (914 mm) closed end steel pile. For the steel pile fish mortality was observed in the vicinity. The use of bubble curtains is investigated in the report and it is concluded that this mitigation measure had only a small effect on the overall pressure levels. It is also concluded that large and especially closed end piles should be carefully monitored and mitigation measures implemented.

Recent measurements of underwater noise during wind turbine monopile hammering in Sweden are of the greatest relevance [46]. The measurements were made at half water column depth at 30, 320, 490 and 720 metres from the pile during the installation of one pile. Across the measurement locations the water depth varied from 4 to 6 metres, and the wind speed varied from 1 to 4 m/s, wave heights ranged from 0.5 to 1.5 metres. Unfortunately, neither details of the pile (diameter) or hammer (impact energy) are presented in the report, but it may be reasonable to assume these are similar to other windfarm developments. Measurements are presented as $^{1}/_{3}$ octave band spectra, equivalent one second averaged sound levels (Sound Exposure Levels or SELs), and as approximately $^{1}/_{100}{}^{th}$ of a second time averaged levels. No high resolution time histories or instantaneous peak pressures have been presented.

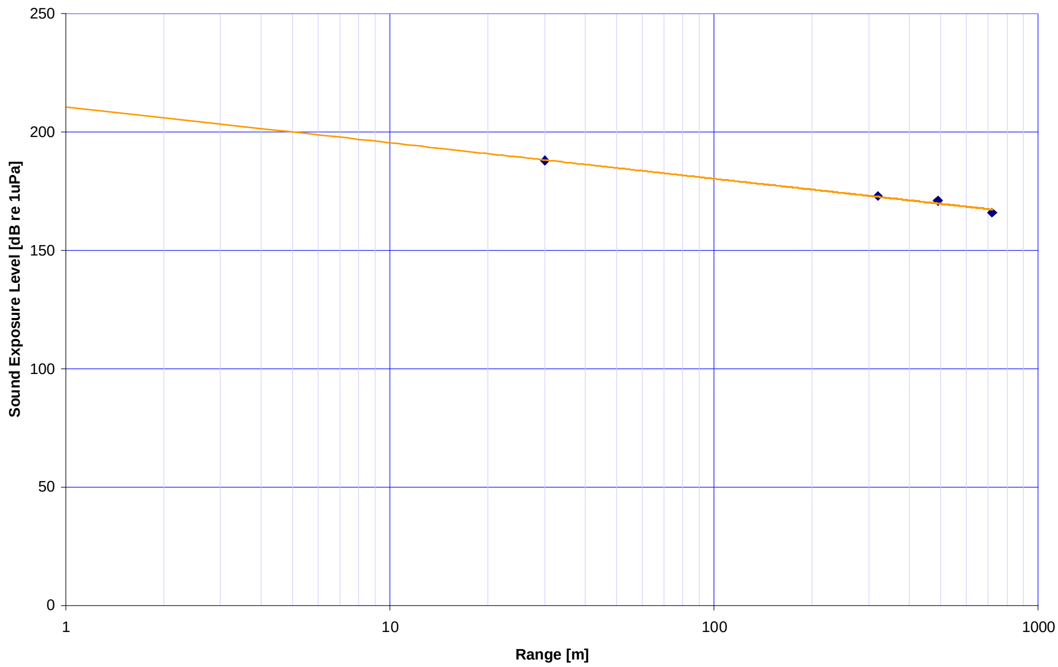

Figure 9. Underwater noise from pile hammering (blue) against distance redrawn from measurements taken of windfarm construction in Sweden [46]. A logarithmic trend line is also shown (orange).

Figure 9 shows the calculated Sound Exposure Levels for the four measurement positions from 30 to 720 metres. The levels range from 166 dB to 188 dB re 1 μPa. A logarithmic trend line has been added to the data to allow an estimate of Source Level to be made. This gives a SEL Source Level of 210 dB re 1 μPa @ 1 m with a 15 dB per decade Transmission Loss. The 15 dB per decade Transmission Loss corresponds to intermediate spreading, which is a common model used for shallow water transmission.

Sound Exposure Levels are calculated by summing an impulsive event's acoustic energy and then calculating the level for a one second tone that has the same energy. They are a measure commonly used for in air acoustic analysis, but are have not been shown to relate to either behavioural or physical responses in marine wildlife. It is therefore difficult to make an assessment of the likely reaction of marine wildlife using this metric. High resolution time histories will give peak pressures significantly above SELs, but as these are not available, the $^{1}/_{100}{}^{th}$ of a second time averaged levels can be used for an indication, and are between 10 and 15 dB above the SELs. Thus, piling peak Source Levels are at least 215 dB re 1 μPa @ 1 m for the Swedish wind turbine installation piling.

A $^{1}/_{3}$ octave band spectra is shown in the report for the region from 1 Hz to 20 kHz for a pile hammering event, and is redrawn in Figure 10. Although absolute levels from spectra of impulsive events are not reliable because of time domain averaging, they do provide an insight into the relative frequency content of a signal. For these measurements piling noise spectra peaks at approximately 250 Hz, which is where fish species such as cod and salmon have their greatest hearing (Figure 3). The frequency content shown in the paper peaks at 250 Hz, piling noise is shown to have significant frequency content at both higher and lower frequencies, being fairly broadband.

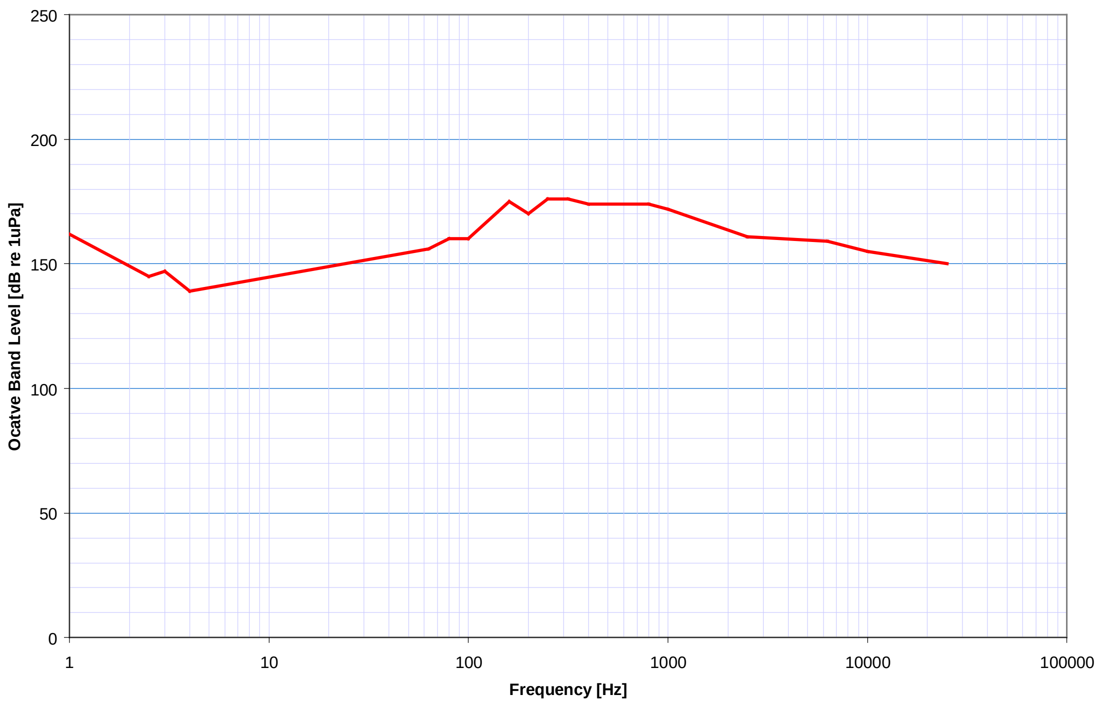

Figure 10. Measured 1/3 octave band Sound Pressure Level 320 metres from turbine foundation piling [adapted from 46].

Harbour porpoise (*Phocoena phocoena*) have their greatest hearing sensitivity at approximately 30 kHz (Figure 3), well above the peak frequency of piling noise

(Figure 10). In a study conducted during the construction of 80 wind turbines at the Horns Reef windfarm in Denmark [47], it was concluded that pile driving affects harbour porpoise acoustic activity on time scales of a few hours. The abundance and general activity of harbour porpoises were affected over larger time scales to a distance of up to 15 km from the source. The study used both boat based observers and passive acoustic monitoring devices to study the animal's activity in the vicinity of the construction activity and a nearby haul out area. It is the only study of its kind known to the authors. It should be noted that the displacement of harbour porpoise during pile hammering was intended, with acoustic deterrents placed in the water before hammering as an injury mitigation measure. However, the report states that it is unlikely that all the effects observed can be attributed to the deterrents alone, which were of a low intensity compared to the piling noise.

Engell-Sørensen [48] makes an assessment of the effect of the pile driving noise reported by McKenzie-Maxon [46] on fish species predominant near Rødsand, Denmark. The report assesses the potential behavioural and physical effects of the noise levels and concludes that: avoidance reactions are likely to occur up to 30 m from the source, especially for species with swim bladders; the measured noise levels could harm the hearing ability of clupeids such as herring (*Clupea herengus*) and sprat (*Sprattus sprattus*), but this may regenerate over time; and, other than those already mentioned, the noise from pile driving is unlikely to cause any other physical effect. Feist [49] showed that juvenile pink (*Oncorhynchus gorbuscha*) and chum (*O. keta*) salmon distribution and general behaviour was affected by pile driving operations in Northwest America.

4.4.3 Summary

From the research reviewed above, piling noise has been reported to have such diverse consequences as little or no effect [27], avoidance [46, 47, 49] and mortality [44, 45] for marine animals. It is most likely that the significant factors which affect the noise level include pile diameter, local geology and bathymetry. The first two of these factors affect the impact energy needed to drive the pile [50], while the last two determine the efficiency of noise generation and propagation. Given the results in [46], it is likely that the Source Level for a 4 metre diameter impact driven monopile hammer strike will be above 200 dB re 1 μPa @ 1 m, and will contain a broad range of frequencies peaking between 100 and 1000 Hz.

The effect of the noise generated by piling will not only depend on the level sound but will also be dependant on the species and the animal's size. For windfarm pile installation, one report states that harbour porpoise behavioural responses have been observed during impact piling [47], while a second [48] predicts behavioural and physical effects on fish. As there is only one reported observation of the effect of windfarm related piling noise on marine wildlife, further research is required to allow a reasonable assessment of environmental impact.

Mitigation techniques used to date include bubble curtains [42], which reduce the Source Level of the piling noise, and acoustic deterrents [47], which 'scare' marine species from the immediate vicinity of construction activity. Other possibilities include monitoring, including acoustic and human observation techniques, to ensure species are not within the area during pile driving. Monitoring has been conducted to measure behavioural effect [47], but to date it has not been used to prevent possible harm to marine species.

4.5 Drilling

4.5.1 Background

Drilling may take place during the installation of wind turbine pile foundations in conjunction with pile driving. Its use will depend on the substrate at the turbine location, with sedimentary substrates allowing an entirely impact driven pile and hard rocky substrates requiring a drilled socket for the pile. The design of drills varies depending on the substrate type, required diameter and mechanical constraints but will typically consist of a single rotating shaft attached to several cutting heads. The cutting heads are geared off the shaft and may rotate at different speeds, and have a number of cutting teeth on their face.

Although little research has been performed into drilling noise, it is likely that sound will be transmitted into the water during transmission via either a ground borne or structure borne path. Ground borne vibration will be created at the drill-rock interface by the movement of the drill head. This will radiate out as both compressional and shear waves to the ground water interface where it will propagate into the water. The mechanical vibrations that are generated in the drill may also be transmitted to the water via the drill shaft and the surrounding pile. In addition to these sources, rock debris and water will be discharged from the top of the pile, which may create noise on entering the water below.

4.5.2 Available information

The authors are not aware of any measurements of underwater noise from shallow water construction drilling operations, however some measurements have been reported for oil and gas exploration and production drilling. The platform used to conduct offshore drilling may have an effect on the underwater noise produced. Types of platform include natural or man-made islands, platforms on legs and floating or semi-submersible drilling vessels. Although not entirely applicable to current windfarm development, future deep water windfarms may employ some of the drilling techniques detailed below. It should be noted, however, that the drilling vessels detailed below may be much larger than those used for windfarm development.

Shallow water measurements (6-7m deep) taken in the vicinity of a drill rig on an ice pad gave results at 130 m of approximately 125 dB re 1 μPa [51], and at 480 m of 86 dB re 1 μPa. Hall et al. [52] took measurements of drilling from a concrete caisson showing little difference in levels of frequencies above 30 Hz between drilling and background noise. However, low frequency (1 to 2 Hz) tones were noted corresponding to the rotation velocity of the drilling turntable. These were at level of 121-124 dB re 1 μPa at ranges between 222-259 metres. The noise from the Canmar steel sided drilling caisson was measured in 15 metre deep water with 100 % ice cover by Gallagher [53]. Tonals were reported at frequencies of 5, 20, 60,150 and 450 Hz with the dominant 5 Hz tone having a level of 119 dB re 1 μPa at a 115 metre range. Drill ships and semi-submersible drill rigs have been reported to have a Source

Level from 145 [54] to 191 dB re 1 μPa @ 1 m [55], but are unlikely to be used during windfarm development.

Richardson et al. [25] reviews reported disturbance reactions to drilling noise. Limited observations have been made of several species of cetacea near both industrial installations and drilling noise playback experiments. The review concludes that cetacea avoid drilling activities when the received levels of underwater noise are strong (well above background levels), but not when the sounds are barely detectable. This agrees with the dB_{ht} hypothesis that behavioural reaction is dependent on the sound level above a species' hearing threshold.

4.5.3 Summary

Based on the available measurements, drilling noise is often of a low level, low frequency nature with several tonal components. However, there is not enough research available to allow these results to be applied to situations that are not similar to those in which the measurements were taken. There is some evidence that behavioural reactions by cetacea are proportional to the received level above background noise. In relation to drilling for wind turbine foundations, the above results may only be used for comparison, as the drilling conditions will be markedly different.

4.6 Gravity support structure installation

4.6.1 Background

Among the possibilities for wind turbine foundations are gravity support structures. They consist of a pre-fabricated concrete foundation that is floated out to the wind turbine location. Once there, the structure is filled with either sand or a fluid so that it sinks to the seafloor where it is secured. Scour protection is typically placed about the foundation. The turbine tower is fixed to the structure. This foundation method is not currently in favour with windfarm developers with the majority of windfarms known to the authors having a steel monopile foundation.

4.6.2 Available information

To date, no gravity support structures have been installed for wind turbine foundations in the UK. In the authors' knowledge no underwater noise measurements have been made of gravity support structure installation and no behavioural observations have been made.

4.6.3 Summary

Gravity support structures have not been used for wind turbine foundations to date in the UK, although they have been used in Europe. As the technology and economies of offshore windfarms develop, they may become a more favoured option. No measurements of, or behavioural observation to, underwater noise from the installation of this foundation type are available.

4.7 Dredging

4.7.1 Background

Although significant dredging, in the authors' knowledge, has not yet been undertaken as part of the construction of windfarms, it is possible that as developers become more experienced and suitable windfarm sites more scarce, dredging will be undertaken. The motivation for this may be to modify the windfarm site bathymetry, for example to allow jack-up barge access, to clear cable laying routes, for wind turbine foundation scour protection or to clear post-construction sedimentary build up at the windfarm site.

Dredging techniques include transfer dredging, where moored ships use suction pipes to collect sand and gravel from the sea floor and discharge pipes to deposit to the discharge site; hopper dredging involves a ship that will fill its hoppers with material and offload at the discharge site via gates in the bottom of the ship; a clamshell dredger scoops sand and gravel between two buckets and deposits this either at the discharge site or on a barge. The mechanics of noise transmission during dredging will vary with dredging technique but is likely to consist of machinery noise, transmitted via the dredger's hull and submersed machinery, and sediment transportation noise, for example the motion of slurry along a pipe or the scraping of sediment with buckets.

4.7.2 Available information

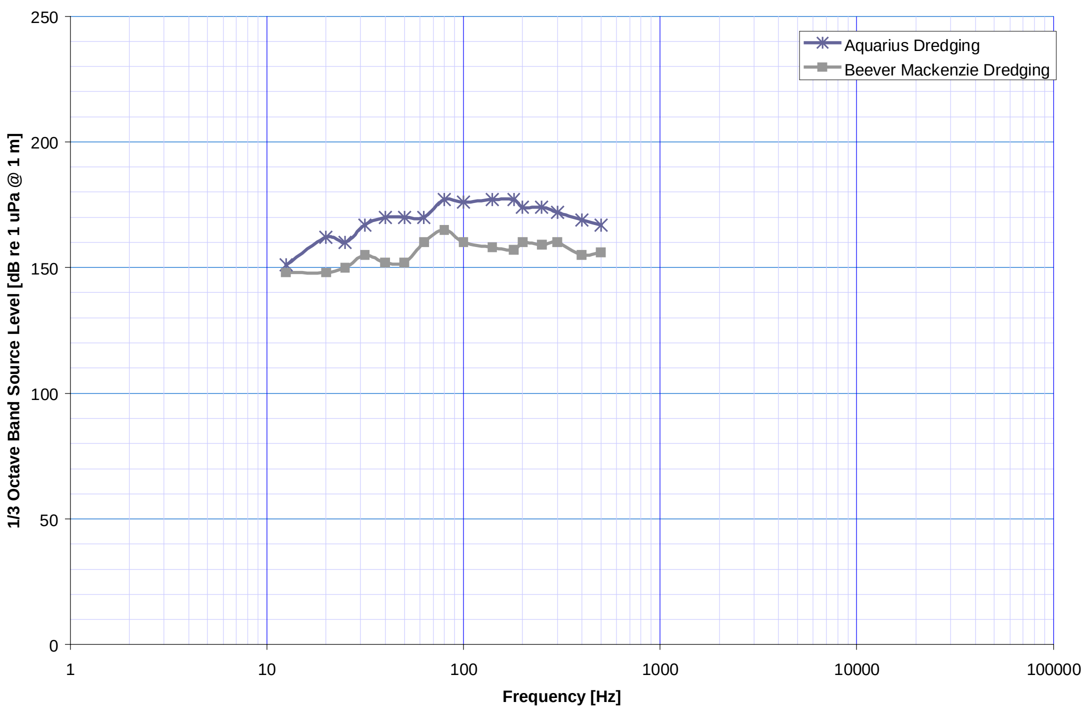

Figure 11. Estimated 1/3 octave band Source Levels for two dredgers [adapted from 25].

Measurements of two suction dredgers, the *Aquarius* and *Beaver Mackenzie*, are shown in Figure 11 as Source Level octave band spectra [55]. Their octave band spectra peak between 80 and 200 Hz, with the *Aquarius* having the higher of the two spectra peaking at approximately 177 dB re 1 μPa. In the 20-1000 Hz band the

Beaver Mackenzie and the *Aquarius* were measured to have a 133 dB re 1 μPa level at 0.19 km and a 140 dB re 1 μPa level at 0.2 km respectively. Measurements of a hopper dredger, the *Cornelis Zanen*, loading at a range of 0.93 km and pumping out at a range of 13.3 km gave 20-1000 Hz band levels of 142 and 117 dB re 1 μPa respectively in 20 m deep water [55]. In the same paper measurements were detailed of the *Geopotes X* whilst loading as 138 dB re 1 μPa at 0.43 km in band level between 20-1000 Hz in 21 m deep water, and the *Gateway* whilst dumping in 12 m deep water of 131 dB re 1 μPa at 1.5 km in the same band.

Documented reactions to dredging noise is scarce. One study of bowhead whale (*Balaena mysticetus*) reactions to the playback of dredging noise [25] showed that, as with drilling noise, where received levels were comparable to background noise little or no reaction was observed, but more conspicuous avoidance was observed for levels 20-30 dB above ambient.

4.7.3 Summary

There is little knowledge of dredging, but what does exist suggests that the noise is audible to cetacea several kilometres from the source. Behavioural reactions should be expected at close range to the source where the sound level is well above background. For other marine wildlife, no behavioural observations are available. The measurements detailed above were conducted in shallow coastal waters and cover suction and hopper dredgers. Where similar dredging techniques and propagation conditions prevail, this limited set of results can be used as a guideline for expected noise levels.

4.8 Rock laying

4.8.1 Background

Rocks may be placed on the sea floor during windfarm construction for one of two reasons, as scour protection about turbine foundations and to protect cables between the turbines and to shore. The process of laying rocks on the sea floor will produce noise as they crash into each other and in addition to this sound will radiate from machinery onboard the placement vessel.

4.8.2 Available information

Measurements of rock placement noise are very scarce, with only one known to the authors. The *Rollingstone* [43] is a dedicated rock placement vessel that can accurately place gravel / rock in a controlled manner up to a water depth of 600 metres via a fall pipe deployed through a moon pool. The bottom of the fall pipe is monitored using a ROV. Measurements were taken while the *Rollingstone* was laying rock in the Yell Sound near the Shetland Islands, in waters between 60 and 70 metres deep. The report concluded that there was no evidence that rock placement was contributing to the noise level, and that some low frequency tonals were present from machinery noise both while rock placement was not taking place and during rock placement. The authors know of no marine wildlife observations in the vicinity of rock placement.

4.8.3 Summary

The lack of measurements and behavioural observations make it difficult to assess the potential for environmental effect from rock placement. The one available measurement shows rock placement noise is within background levels. No measurements of shallow water rock placement measurements have been published in the authors' knowledge.

4.9 Trenching

4.9.1 Background

A significant amount of cable must be installed with a windfarm both as interconnections between the turbines and cables to the shore based station. To protect the cables from damage they are trenched into the seafloor using special machines, such as a towed cable plough or a cable laying ROV. In addition to the noise produced by the motion of the plough through the sea floor, noise will be transmitted through the hull of the cable laying barge from onboard machinery and high powered sub-bottom profilers may be used to give real time information of the local substrate. It should be noted that trenching will only take place where the seafloor consists of a suitable soft sediment, with other means of cable protection such as rock placement being used where this is not the case.

4.9.2 Available information

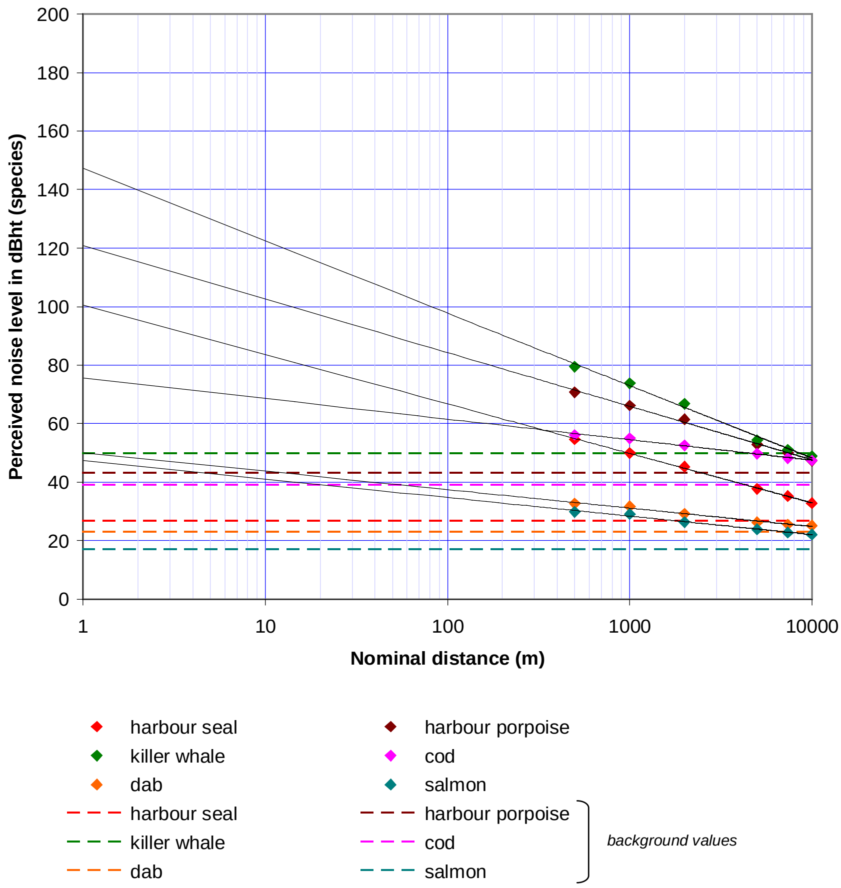

Figure 12. dB_{ht}(*Species*) against range for trenching noise from the Trenchsetter in the Yell sound [adapted from 56]. Long dashed lines indicate background noise levels and short dashed lines are extrapolations.

In the authors' knowledge, there are no published measurements of cable trenching noise. However, during a survey of deep water pipe laying noise in the Yell Sound near Shetland [56], measurements of pipe trenching noise from the *Trenchsetter* were taken, and are shown in Figure 12 as dB_{ht} levels against range. Here the measurements of the level above several species' thresholds are plotted with range. Measurements are highest for the killer whale, with a level of approximately 80 dB_{ht}(*Orcinus orca*) at 500 metres, which is 10 dB above the proposed 70 dB_{ht} reaction threshold. The harbour porpoise has a level of approximately 70 dB_{ht}(*Phocoena phocoena*) at 500 metres, which indicates that a reaction is likely to occur within this range. The other species have levels below this threshold at 500 metres, but the sound level exceeds this value for all species except dab (*Limanda limanda*) and salmon (*Salmo salar*) at some point within this range.

It should be noted that the *Trenchsetter* was digging trenches for the laying of oil and gas pipelines, significantly larger in diameter then those required for windfarm cabling. In addition, cable laying is often performed with a machine that trenches, lays cable and backfills simultaneously, whereas in the cited survey these were separate operations.

4.9.3 Summary

The only measurement of trenching noise known to the authors gives high dB_{ht} levels, which according to the reaction thresholds outlined in Section 3.2.3 suggest that behavioural reactions are likely at close range. However, the measured trenching noise is for pipe laying, which is likely to be significantly different to windfarm cable laying. No measurements of shallow water cable laying noise have been published and therefore no conclusions may be taken to its environmental effect.

4.10 Turbine and support structure installation

4.10.1 Background

Several major installation operations will occur above water after successful installation of the wind turbine foundation, these include transition piece, turbine mast, nacelle and rotor installation. These operations will, in most instances, be performed by a barge secured close to the turbine foundation, and will involve the lifting of the components onto the foundation where they will then be fixed. Apart from engine and machinery noise radiated through the barge and support vessel's hulls, there is also the possibility of underwater noise being transmitted from the installations processes themselves, either through the air water interface or through the foundation structure.

4.10.2 Available information

In the authors' knowledge there are no published measurements of the underwater noise from turbine and turbine support structure installation.

4.10.3 Summary

Turbine and support structure installation will take place above the water surface but has the potential to radiate underwater noise via turbine foundations and installation vessels. In the authors' knowledge no measurements have been published of the underwater noise emitted during this operation.

4.11 Wind turbine operational noise

4.11.1 Background

Of all windfarm related noise sources the marine environment will undergo the greatest exposure from operational wind turbine noise. Whereas, pre-construction, construction and decommission will all take place over a period of months, operational noise will occur over a number of years and thus may effect a generation of marine wildlife. Therefore a rigorous assessment of the environmental effect from a windfarm must be made.

An appreciation of the underlying processes involved in the generation and transmission of sound from wind turbines is beneficial in the assessment of its environmental effect. The turbine rotor blades will generate aerodynamic noise as they pass through the air, which may enter the water via an airborne path. Aerodynamic noise will increase with increasing rotational velocity of the turbine. The movement of air over the whole structure including the turbine blades and the hydrodynamic forces from passing waves will induce structural vibrations. In addition to this, structure borne vibrations will originate from mechanical vibrations generated in the nacelle. Vibrations of the nacelle will depend on the degree of mechanical refinement of the wind energy conversion process. As there is an efficiency advantage in reducing these vibrations, the system will be highly refined. However it is likely that the magnitude of the vibrations will increase with the machine's age due to component wear. The level of vibrations will also increase with increasing wind speed, as the forces on the mechanical parts increase. All of these generation mechanisms are likely to be dependent on each turbine's design and build quality.

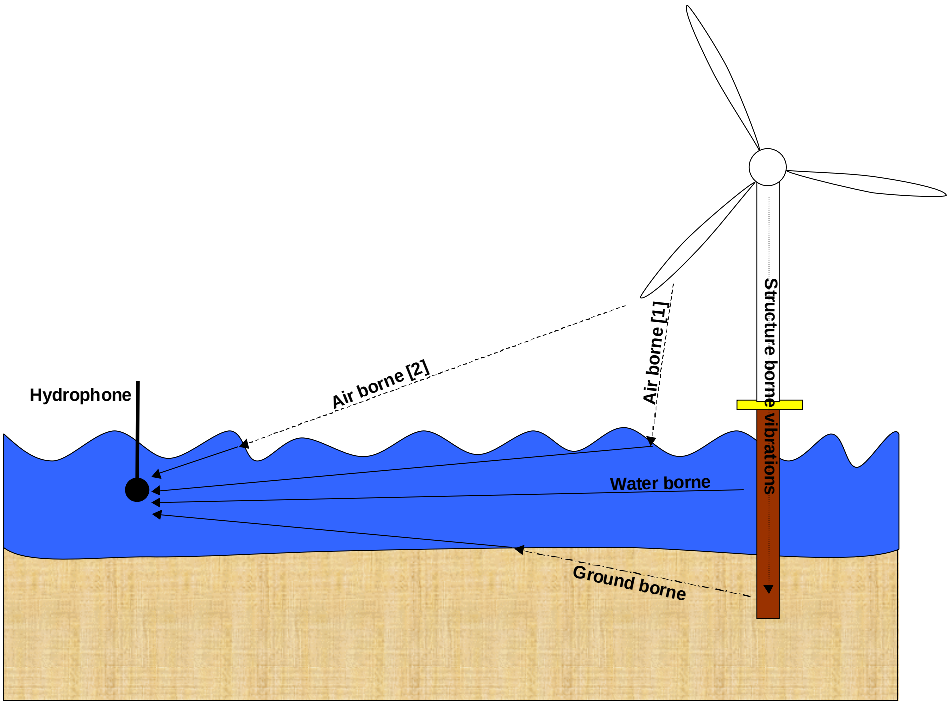

Figure 13. Wind turbine underwater noise transmission paths.

The structural vibrations may enter the water via one of three paths: airborne, waterborne or ground borne, whereas aerodynamic noise will only reach the water via an airborne path. In addition to this, vibrations in the turbine support structure, nacelle and rotor blades will also create airborne noise. Airborne noise will radiate from the turbine and some will encounter the air-water interface. As previously discussed for airborne piling noise, the majority of airborne transmission occurs directly beneath the turbine with a small contribution due to sea surface roughness outside this area, as shown in Figure 13, but it is unlikely to be the dominant transmission path.

Structural vibrations that are transmitted to the turbine's foundation will encounter the turbine water interface. Here, the structural vibrations will directly induce waterborne sound waves that will propagate to a distant receiver. It is thought that this will contribute the most to underwater wind turbine noise. The design of the turbine foundation will have an impact on the efficiency of both the transmission of vibration from the turbine tower to the foundation and from the foundation to the surrounding water. Current designs include steel pile and concrete gravity foundations.

Both foundation types will be in contact with the sea floor, with piled foundations protruding several metres into it. Where they are in contact with sediment and rock in the seabed, structural vibrations will induce both compressional waves, in a similar manner to the sound in water, and seismic waves. The waves can travel outwards through the seabed, and as they propagate sound will tend to leak upwards into the water, where it contributes to the received sound level (Figure 13). Since sound absorption in the seabed is generally greater than in water, and not all the energy in the ground borne wave will enter the water, the contribution of the ground borne is likely be less than the water borne wave.

The identified sound generation and transmission mechanisms suggest that the received level of sound due to a wind turbine will be affected by the local wind speed, sound speed profile, water column depth, sea surface roughness and seabed geology. Of these factors, wind speed, sound speed profile and sea surface roughness will depend on weather conditions, and water column depth and sound speed profile will depend on tidal conditions. Seabed geology is unlikely to change significantly in the short to medium term.

4.11.2 Available information

Measurements of underwater noise from windfarms are scarce, with only two published measurements known to the authors. An extensive study of the Lelystad (Denmark) windfarm is noted to have been in preparation by Vella et. al. [2], however the report is currently unavailable.

The first measurements of underwater noise from an operating wind turbine were conducted by Westerburg in the mid 1990s [57]. The measurements were of the first offshore wind turbine in the world, a 220 kW Windworld AS turbine on a 35 metre tower, located close to the shore on the South-East coast of Sweden. The results show that, at wind speeds between 6 and 12 ms^{-1}, wind turbine noise consists of harmonics of the turbine's frequency of rotation (between 2.08 to 2.13 Hz). Figure 14 shows measured levels above ambient noise at 100 metres from the turbine. The Figure shows peaks at 8 and 16 Hz for a wind speed of 12 ms^{-1}, and a single peak at 16 Hz for a 6 ms^{-1} wind speed. The 16 Hz peak for both wind speeds remains a constant level above background noise. Also detailed in the report are the absolute (as opposed to relative to the background noise) sound pressure levels for the 16 Hz peak as 102 and 113 dB re 1 μPa for lower and higher wind speed respectively. This shows that although the absolute level of the turbine noise increases with wind speed, its level above background noise, which is also wind dependent, remains relatively constant.

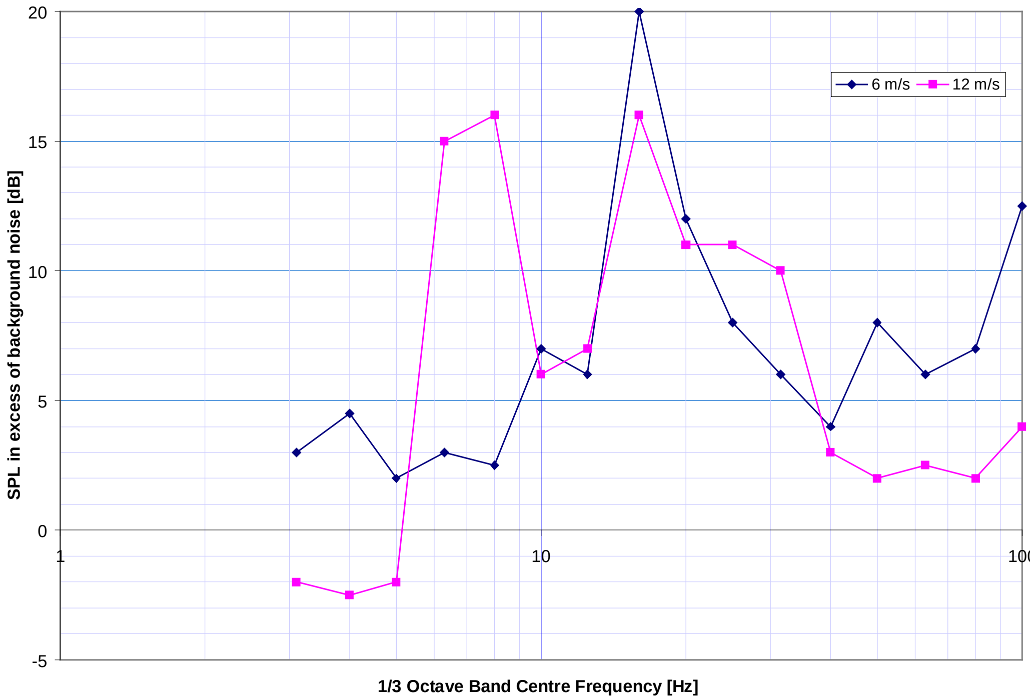

Figure 14. Wind turbine (35 m tower, 220 kW Windworld AS turbine) noise above background for two wind speeds [redrawn from 57].

In a report by Degn [58], two 500 kW turbines of differing foundations were investigated with the aim of predicting the level for a proposed development of an array of 2MW turbines. The measurements are unique in that they include tower vibration measurements of both a 500 kW offshore turbine and a 2MW onshore turbine. These were conducted to allow a prediction of the rate of underwater noise increase with turbine power. The Vindeby (Denmark) 450 kW Bonus Wind turbine is founded on a concrete gravity foundation, and the Gotland (Sweden) 550 kW Windworld turbine is founded on a steel monopile foundation.

Figure 15 shows $^1/_3$ octave band spectra of the two wind turbine measurements, both taken 20 m from the foundations. The measurements were taken during wind speeds of approximately 13 ms^{-1} and include background noise taken while the turbine was not operating. At Vindeby, the measurements show that wind turbine noise contributes to the spectra up to 400 Hz, peaking at 119 dB re 1 μPa (33 dB above background) at 25 Hz. It is unclear if the peak at 20 Hz is a harmonic of the turbine's rotational frequency as this is not specified, but assuming a frequency of approximately 2 Hz, as in Westerburg's measurement, would suggest this is the 11^{th} harmonic. The Gotland spectra do not suggest harmonic content, with a broad peak of 95 dB re 1 μPa at 160 Hz (25 dB above background noise) falling to background noise level at 63 and 630 Hz.

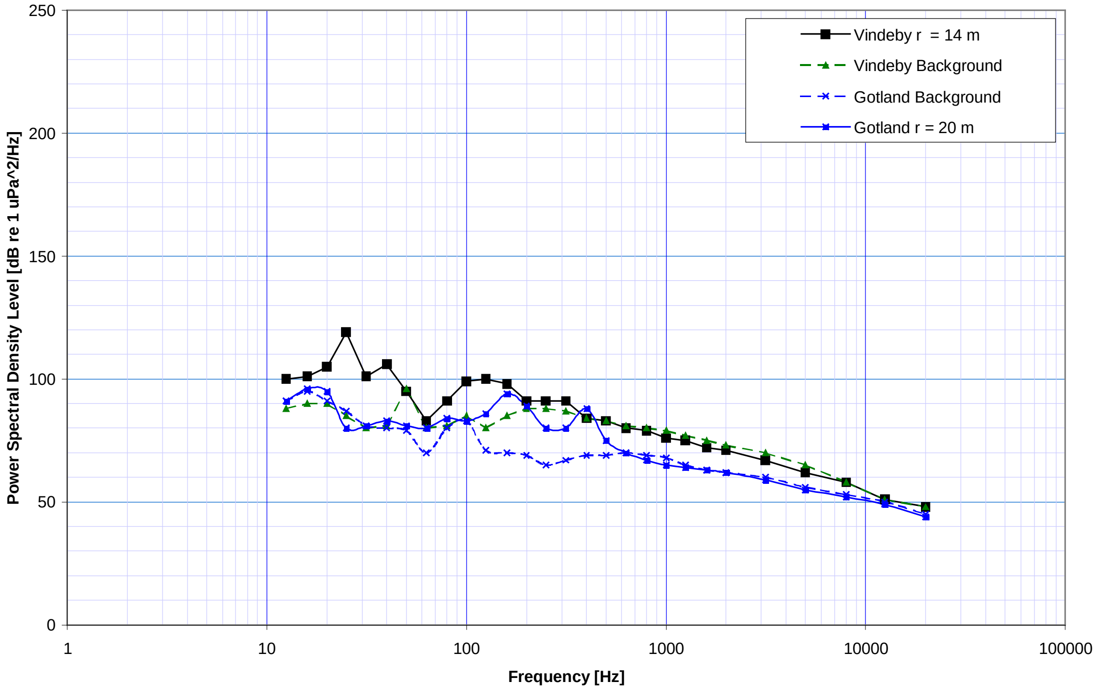

Figure 15. Measured wind turbine noise and background noise for two windfarms [adapted from 58].

Tower vibration measurements were also taken from the two turbines at the same time as underwater noise measurements. Both the Gotland and Vindeby tower velocity spectra show spectral peaks that correlate with those measured underwater at 160 Hz and 25 Hz respectively, although in this case these are not the dominant components. This would suggest that the underwater noise from wind turbines originates via structure borne paths, although further research is needed to confirm this. In addition to the two offshore wind turbines, vibration measurements were also conducted on a 2 MW onshore turbine. In conjunction with structure borne vibration to underwater noise transfer function estimates derived from the above measurements, these have been used to predict the underwater noise level from a 2 MW offshore turbine. The result must be treated with caution as the reliability of this technique has not been proven and the predicted increase in power is within the measurement uncertainty given in the report.

A study by Koschinski [59] investigated the response of seals and porpoises to simulated wind turbine noise based on the above calculation of noise from a 2 MW turbine. The study used a CD player and an underwater loudspeaker to reproduce sounds in the Fortune Channel, Canada, which is a (acoustically) quiet fjord-like area with a population of harbour seal (*Phoca vitulina*) and harbour porpoise (*Phocoena phocoena*). The report concludes that for the playback experiment harbour porpoise: are able to hear the wind turbine noise; seemed to be cautious when confronted with the stimulus and explored the sound source with their biosonar. It is noted that the porpoise do not show avoidance behaviour similar to that previously observed close to acoustic deterrent devices such as gillnet pingers. The investigation into harbour seal (*Phoca vitulina*) reactions was less detailed, and concluded that harbour seals could hear the sound and increased their median distance to the sound source when surfacing.

Anecdotal evidence from a fisherman local to the Vindeby windfarm suggests avoidance of the windfarm area by turbot (*Psetta maxima*) during high wind speeds [60]. The Vindeby windfarm has eleven 450 kW turbines. The report investigates both the effect of underwater noise and magnetic fields on local flatfish and concludes that underwater noise is unlikely to be the cause of the reported reaction and leaves an open conclusion with respect to magnetic fields.

In addition to the measurements and observation reported above, there are several reports that make judgements as to the likely effect of underwater noise from operating wind turbines [2, 61]. In general the potential for effect is judged from marine wildlife hearing abilities in conjunction with assumptions as to the likely level and frequency content of the underwater noise. These studies show that within the community it is common to assume a relationship between the level of a sound above a species' hearing threshold and behavioural response, which is a hypothesis behind the dB_{ht} approach. However, without a set of measurements to reinforce the assumed sound levels in conjunction with behavioural studies they cannot be used as proof in the assessment of environmental effect.

4.11.3 Summary

Published results of wind turbine noise measurements and behavioural observations are limited. However, based on current evidence radiated underwater noise from wind turbines is of a low level and a low frequency, possibly harmonic in nature. The Sound Pressure Level increases with increasing wind speed along with the background noise level, maintaining a constant level above background. Published results show some behavioural reaction to actual or simulated underwater noise by harbour seal (*Phoca vitulina*) and harbour porpoise (*Phocoena phocoena*). Reactions include avoidance, but no 'fright reactions' were observed during a harbour seal and porpoise playback experiment [59]. Anecdotal evidence of turbot (*Psetta maxima*) displacement from the Vindeby windfarm during high winds could not be attributed to underwater noise.

4.12 Underwater blast

4.12.1 Background

At the end of a windfarm's lifecycle there will be a requirement to decommission the site. While the majority of site decommissioning will be a reversal of the installation process, such as removal of the nacelle and rotor blades, turbine foundation removal may be a difficult process. Current opinions on how this will take place vary. Jet cutting below the sea floor [5] is an option. Experience in the offshore oil and gas industry however, suggests that blasting may be required [6]. Explosives may be required for pile severance, to clear scour protection material and to break up concrete gravity foundations for subsequent dredging.

When an explosion is initiated, solid explosive material is converted into incandescent gas at extremely high pressure. The way in which the energy of an explosive is converted into blast, and the form of the accompanying pressure wave, depend on the category of explosive and the way in which it is used. High explosives like TNT and other nitroglycerine based explosives explode by a detonation process. A violent chemical reaction, following in the wake of the shock front propagating through the explosive, turns the solid of the explosive into a gas at extremely high pressure. The velocity of detonation of high explosives is about 5,000 to 10,000 ms^{-1}. The detonation produces a very fast build up in pressure, the resultant energy wave having a very rapid rise and decay time [62]. This in turn causes a blast wave (pressure wave) to propagate into the surrounding medium. As the shock wave radiates outward over an expanding area, the amplitude of the peak pressure rapidly decreases, but gradually slows as distance increases from the point of detonation. Eventually the shock wave degenerates into a low-amplitude acoustic wave. The shock wave from a charge detonated in the sea bed travels in a well-defined cone, expanding towards the surface.

4.12.2 Available information

Although unconfined and borehole blasting have been studied extensively and are relatively well understood, pile severance and gravity foundation removal will probably use charges situated near to or slightly below the sea floor. This application falls somewhat in between the two areas. However, recent measurements of the severance of well heads, which are similar in structure to piled foundations, in the North Sea [63] have shown that in this case the explosive shock wave behaves as if it were an unconfined charge. That is the pipe work and sediment surrounding the charge do not act as an effective confinement mechanism. Wellheads typically have a diameter of less than 1 metre, which is about a quarter of the size of a wind turbine monopile foundation.

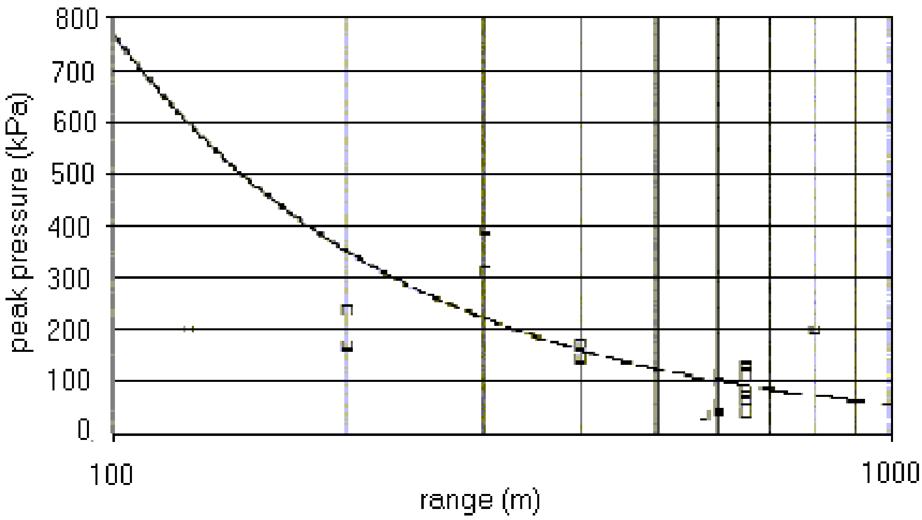

Figure 16. Peak pressure against range for North Sea wellhead blast measurements including predicted level with range for a 45 kg charge [63].

Figure 16 is a plot of the peak pressure versus range for measurements of the severance of several well heads and, for comparison, the estimated peak pressure for a unconfined 45 kg charge (Equation 11). Pipe diameters were typically 30" (762 mm) requiring between 36 and 81 kg of liquid high explosive placed at between 2 and 3 metres below the mud line. The water depth ranged between 32 to 116 metres. The measurements agree reasonably well with the model for an unconfined charge given that the measured charge mass varies for each wellhead. Figure 17 is drawn from the same data as Figure 16 but in this case impulse is plotted against range. An extensive study by Yelverton [7,8] showed that blast related injury was strongly correlated with the received level of impulse for submerged mammals, and similar models exist for fish mortality [64]. In this study an impulse of 69 Pas is given as leading to a low incidence of trivial blast injuries with no eardrum ruptures. The results given in Figure 17 show that for a typical 45 kg charge the blast impulse will fall to this level at a range of about 2.2 km. In addition to these figures, dB_{ht} levels were calculated from the stand off distances measurements at 600 metres, these are given as 136 dB_{ht}(*Gadus morhua*) cod, 114 dB_{ht}(*Limanda limanda*) dab, 135 dB_{ht}(*Phocoena phocoena*) harbour seal, 152 dB_{ht}(*Phocoena vitulina*) harbour porpoise and 158 dB_{ht}(*Orcinus orca*) killer whale. The linear SPL at this range was 217 dB re 1 μPa. These figures are in excess of the 90 dB_{ht} reaction threshold. Observations of dead fish in the blast area were also reported by MMOs (Marine Mammal Observers).

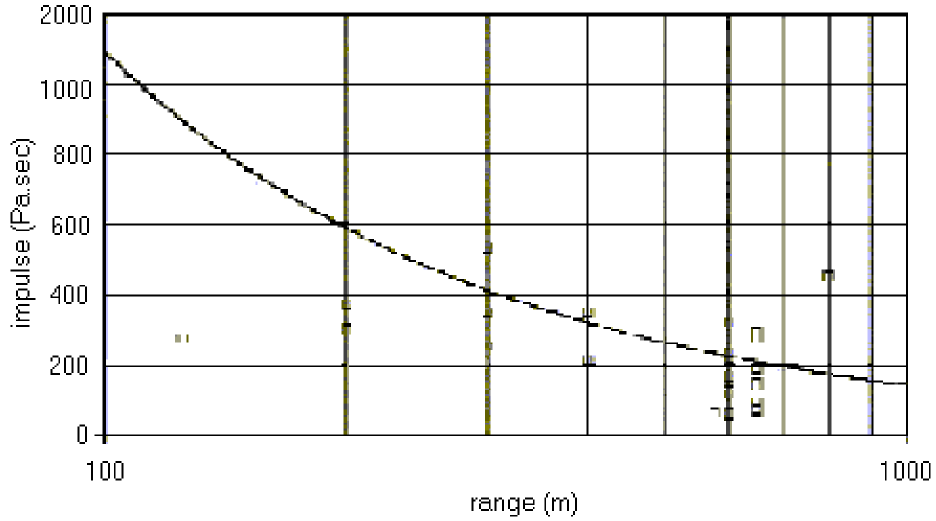

Figure 17. Impulse against range for North Sea wellhead blast measurements including predicted level with range for a 45 kg charge [63].

Most of the information that is available concerning estimating levels of unconfined blast results from the military use of explosives, and hence concerns large charges that are fired in deep water and are freely suspended in the water without any confinement [for example 65, 66, 67, 68, 69, 70, 71, 72]. Most of the work concerns TNT charges, but the author (Nedwell) has found that other high explosives of similar explosive strength give very similar results.

For unconfined TNT charges in deep water expressions for estimating the values of peak pressure and impulse are:

$$P_{\max} = 5\times10^{7}\times\frac{W^{0.27}}{r^{1.13}}[Pa] \qquad (11)$$

$$I = 6\times10^{3}\times\frac{W^{0.63}}{r^{0.89}}[Pas] \qquad (12)$$

where W is the charge weight in kilograms and *r* is the range from the explosive in metres.

Along with the Yelverton model [7, 8], these equations provide the basis for estimating the likelihood of injury for submerged mammals in the vicinity of a blast. The Yelverton model was based on experiments using submerged land mammals, which do not have any of the adaptations to their lungs or other gas filled cavities that diving mammals have. This may result in an over estimation of the injury that may occur to marine wildlife in the vicinity of underwater blast. However, underwater blast may injure or kill marine wildlife and this has been observed on several occasions [25].

4.12.3 Summary

It is possible that explosives will be required for wind turbine foundation removal. Related measurements of wellhead severance demonstrate both high sound levels and injury to marine wildlife from the use of explosives. The extent and range at which these responses will occur is a function of the charge weight. Marine wildlife mitigation measures have previously been used when blasting takes place, including monitoring and acoustic deterrents.

4.13 Jet Cutting

4.13.1 Background

Current non-explosive pile cutting techniques include mechanical and abrasive cutting. Mechanical cutters use hydraulically actuated carbide tipped tungsten blades to mill through the inside of tubular structures (piles) [5]. Abrasive cutters have mechanisms to direct a water jet containing cutting materials to abrasively wear away steel. In both these techniques sound will be generated by the action of the cutter on the pile and by the machinery which drives the cutter. This sound may radiate into the water directly through the pile via a waterborne path or via the substrate by a groundborne path.

4.13.2 Available information

No measurements of, or behavioural reactions to, the underwater noise produced by these sources are known to the authors.

4.13.3 Summary

The lack of published results make it difficult to assess the environmental impact of jet cutting.

4.14 Diver tools

4.14.1 Background

Divers are often used to clear obstacles in the path of cable routes, and may also be used to cut steel monopile foundations. A variety of underwater hand-held tools are available for the various tasks required from a diver, which include gas cutting equipment, jet cutters, jackhammers, grinders, bolt guns and hydraulic wrenches. The mechanism of sound generation in each of these techniques varies.

4.14.2 Available information

Information on the noise levels from these sources is scarce, with the only measurements known to the authors conducted by Nedwell [73, 74] of drills, wrenches, grinders, bolt guns and jackhammers. These measurements gave peak Source Levels of up to 200 dB re 1 μPa, and averaged levels of up to 161 dB re 1 μPa. Using average levels weighted by a diver's hearing sensitivity the report indicates that, based on in-air noise dose models, the sound levels from the bolt gun and impact wrench would exceed recommended levels.

4.14.3 Summary

Divers are able to use the tools a few feet from their ears but their effect on divers has not been reviewed in detail. In air acoustic models suggest an unacceptable level of noise for some tools. The only available set of diver tool measurements show peak Source Levels of up to 200 dB re 1 μPa, and averaged levels of up to 161 dB re 1 μPa. No published observations are available of behavioural reactions to these sources by marine wildlife.

5 Conclusions

The purpose of COWRIE funding is to 'provide generic research to benefit the early stages of the offshore windfarm industry' [1], and windfarm related noise sources have been reviewed as part of this goal. The review has been conducted with an emphasis on reported measured sound levels, but also including the effect of sound on marine wildlife. This is the only significant summary available of underwater noise and its effects through a windfarm's lifecycle. Forthcoming research that is being conducted as part of the COWRIE funded study and underwater noise monitoring that is required of windfarm developers will significantly add to the knowledge summarised within this review.

The reviewed noise sources are summarised in Table 2 for comparison. There are significant gaps in knowledge, and where research has been conducted it is not often in an easily comparable form. Where possible, the minimum and maximum Source Levels for specified measurement quantities are given for each source. All the data is taken from Section 4 although, where appropriate, measured levels are adjusted using a $20\log_{10}(r)$ Transmission Loss to give Source Level. A brief note summarising the knowledge which has led to these levels is given along with a summary of reviewed behavioural observations.

5.1 Assessment of available information

5.1.1 Source Level and Transmission Loss

Working through the sources that may be present during a windfarm's lifecycle, the following conclusions may be drawn for each source.

- **Vessel and machinery.** Reported Source Levels range from 152 to 192 dB re 1 μPa @ 1 m. This range is based on several measurements of large vessels in deep water and a few measurements of small vessels in shallow water.
- **Geophysical survey.** Windfarm developments will typically use boomers and sparkers during geophysical survey, but no reliable information is available on these sources. Airguns, which are often used for geophysical survey in the offshore oil and gas industry, have Source Levels ranging from 215 to 260 dB re 1 μPa @ 1 m.
- **Pile driving.** A number of measurements of pile driving noise have been taken of piles ranging from 208 mm to approximately 4 m in diameter. Source Levels vary, range from 192 to 261 dB re 1 μPa @ 1 m, and on average increase with increasing pile diameter. Only one measurement of wind turbine pile installation is available, giving an SEL Source Level of up to 215 dB re 1 μPa @ 1 m for impact pile driving. No measurements of wind turbine pile installation using a vibro-driver are available, but other measurements suggest this technique is quieter than impact piling.
- **Drilling.** Measurements of drilling are restricted to deep water measurements of oil and gas facilities. Based on available measurements, the range of Source Levels is from 145 to 192 dB re 1 μPa @ 1 m. No measurements are available of shallow water drilling such that would be used for installing wind turbine piled foundations.
- **Gravity foundation installation.** No measurements are available.

- **Dredging.** Some measurements of dredging in shallow coastal waters are available, which show peak spectral energy of 177 dB re 1 μPa between 80 and 200 Hz. Where similar techniques are used in offshore windfarm development these results may be used for comparison.
- **Rock laying.** There is one inconclusive measurement of relatively deep water rock placement.
- **Trenching.** There is one measurement available of pipe trenching in the North Sea, which shows high dB_{ht} levels. There are no available measurements of cable trenching noise, which may be significantly different.
- **Turbine structure installation.** No measurements are available.
- **Wind turbines.** There are two available measurements of low power (<1MW) wind turbines, which show sound levels of a low frequency of a level up to 153 dB re 1 μPa.
- **Blast.** Explosives may be required for windfarm decommissioning. Verified empirical models exist to predict blast Source Levels given a charge weight. Given knowledge of this parameter, a reasonable assessment of physical injury to marine wildlife may be made according to the well used models, although behavioural responses are still unclear.
- **Jet cutting.** No measurements have been made of this alternative to blasting for the decommissioning of piled foundations.
- **Diver tools.** One set of measurements are available covering drills, wrenches, bolt guns, grinders and jackhammers. Peak SPLs of up to 200 dB re 1 μPa @ 1 m and average SPLs of up to 161 dB re 1 μPa @ 1 m are reported.

5.1.2 The effect of noise on marine wildlife

The effect of noise on marine wildlife has been covered in this report, but not in any great depth. Based on the evidence herein reviewed, the noise sources may be split into four classifications of effect. Those where no observations have been made include gravity foundation installation, rock laying, trenching, turbine structure installation, jet cutting and diver tools. Varying reactions, including avoidance and attraction, have been reported for shipping, dredging, drilling, and wind turbines. Avoidance, but no attraction reactions have been noted for geophysical survey, pile driving and blast. Physical injury has been observed in the vicinity of blast and pile hammering.

Windfarm related noise source	Measurement quantity	Source Level		State of knowledge	
		Min	Max	SL & TL	Behavioural response
Background Noise	SPL	Highly variable. Frequency dependent.		Good knowledge of deep water ambient noise. Poor knowledge of shallow water ambient noise.	Concern about the effects of increasing background noise on marine wildlife.
Shipping and Machinery	Linear SPL dBht(*Salmo salar*)	152 30	192 60	Poor for small craft, otherwise realtively good.	Mixed observations including attraction and avoidance.
Geophysical Survey	Linear Peak SPL Peak dBht(*Gadus morhua*) Peak dBht(*Orcinus orca*) Peak dBht(*Phocoena phocoena*)	215 142 159 144	260 195 216 203	Good for airguns, very poor for typical windfarm survey sources such as boomers and sparkers.	Some cetacean airgun avoidance observations.
Pile Driving	Linear Peak SPL SEL Peak dBht(*Salmo salar*)	192 210 40	261 215	Limited set of measurements with a large variation in results. SL possibly related to pile diameter.	Observation of harbour porpoise disturbance, no reaction from caged trout, fish mortality evidence.
Drilling	Linear SPL	145	191	Several deep water measurements. Large range of levels. No shallow water measurements.	Reported response to playback tests. Cetacea avoid when received level is high.
Gravity Foundation Installation	n/a	n/a	n/a	No available measurements.	No available observations.
Dredging	Peak spectral energy (80-200Hz)	177		Some shallow water measurements of suction and hopper dedgers.	Mixed reactions. Cetacea avoid when received level is high.
Rock Laying	Linear SPL	Within background.		One inconclusive measurement.	No available observations.
Trenching	dBht(*Orcinus orca*) dBht(*Phocoena phocoena*) dBht(*Phoca vitulina*) dBht(*Gadus morhua*) dBht(*Limanda limanda*) dBht(*Salmo salar*)	150 120 100 75 50 50		One measurement of pipe trenching. No available measurements of windfarm cable laying, which will be significantly different.	No available observations.
Turbine Structure Installation	n/a	n/a	n/a	No available measurements.	No available observations.
Wind Turbines	Peak spectral energy (16 Hz)	142	153	Two measurements available for low power (<1MW) individual turbines.	Very little knowledge. Porpoise behavioural reponse to playback experiments.
Blast	Linear SPL dBht(*Gadus morhua*) dBht(*Limanda limanda*) dBht(*Phoca vitulina*) dBht(*Phocoena phocoena*) dBht(*Orcinus orca*)	 191 169 190 207 213	272	Verified empirical models for peak pressure and impulse available.	Well used near source blast injury model available. Some cetacean avoidance observations.
Jet Cutting	n/a	n/a	n/a	No available measurements.	No available observations.
Diver Tools	Peak SPL Average SPL	200 161		One set of measurements available covering: drills, wrenches, bolt guns, grinder and jackhammer.	No available observations.

Table 2. Summary of available information.

6 Recommendations

6.1 Noise source ranking

To aid in the assessment of potential for environmental effect from windfarm related noise and provide research priorities the authors have included their personal assessment of these factors below. It should be emphasised that the judgements are comparative and not relative, are based on the authors' significant experience in the field and are not solely a reflection of the measurements herein reviewed or otherwise. Hence, it is in the authors' opinion that, for windfarm related noise sources, the relative potential for environmental effect is as follows (greatest risk first):

- Foundation decommissioning using explosives.
- Piled foundation installation and windfarm related geophysical survey.
- Drilling, rock laying, cable trenching, diver tools.
- Vessel and machinery, wind turbine operation.

This assessment does not include the cumulative effects of noise, which would emphasise wind turbine and vessel noise because of the exposure the marine environment has to these sources. An assessment cannot be made of jet cutting, turbine structure installation and gravity support structure installation, as no measurements are available of these sources.

Amongst the sources of underwater noise, the authors believe the following areas are priority areas for investigation (greatest priority first):

- Piled foundation installation, wind turbine operation, and windfarm related geophysical survey.
- Cable trenching, drilling, rock laying, diver tools, jet cutting, gravity foundation installation, vessel and machinery, turbine structure installation.

In all areas, research should be conducted into both the sound levels from these sources and its possible effect on marine wildlife. Without an understanding of both of these factors a reasonable assessment of environmental effect cannot be made. Where an unacceptable environmental effect may occur, mitigation measures should be identified, considered and if necessary implemented.

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8 References

[1] COWRIE website, [online document], Jan 2004, Available WWW: http://www.crownestate.co.uk/estates/marine/windfarms/cowrie.shtml

[2] Vella, G., Rushforth, I., Mason, E., Hough, A., England, R., Styles, P., Holt, T., Thorne, P., "Assessment of the Effects of Noise and Vibration from Offshore Windfarms on Marine Wildlife.", ETSU W/13/00566/REP, DTI/Pub URN 01/1341, 2001, Available WWW: http://www.dti.gov.uk/energy/renewables/publications/pdfs/w1300566.pdf

[3] Watson, G., "Structure and Foundations Design of Offshore Wind Installations", [online document], Rep. On the Offshore Wind Energy Network Workshop, Mar. 2001, Available WWW: http://www.owen.org.uk/workshop_3/ws3_final.pdf

[4] Delft University Wind Energy Research Institute, "Ready to Power a Sustainable Europe", Concerted Action on Offshore Wind Energy in Europe: Final report, Dec. 2001, Report Ref: Duwind 2001.006, Available from: Delft University Wind Energy Research Institute (Duwind).

[5] Peason, D., "Decommissioning Wind Turbines In The UK Offshore Zone", Enron Wind, Prince Consort House, 27-29 Albert Embankment, London, SE1 7TJ.

[6] Committee on Techniques for Removing Fixed Offshore Structures, "An assessment of techniques for removing offshore structures", Marine Board, National Research Council, 1996, [online document], Available WWW: http://books.nap.edu/catalog/9072.html

[7] Yelverton, J., et. al., "Underwater explosion damage risk criteria for fish, birds, and mammals.", presented at 102nd Meet. Acoust. Soc. Am., Miami Beach, FL, Dec., 1981.

[8] Yelverton, J., et. al., "Safe distances from underwater explosions for mammals and birds..", DNA 3114T, Rep. From Lovelace Foundation for Medical Educ. And Res., Alburquerque, NM, for Defence Nuclear Agency, Washington, DC, 67 p, NTIS AD-766952.

[9] Mellen, R., "Thermal noise limit in the detection of underwater acoustic signals.", *J. Acoust. Soc. Am.*, vol. 24, p. 478, 1952.

[10] Wenz, G., "Acoustic ambient noise in the Ocean: Spectra and Sources", *J. Acoust. Soc. Am.*, vol. 34, p. 1936, 1962.

[11] Andersen, S., "Auditory sensitivity of the harbour porpoise *Phocoena phocoena*.", *Invest. Cetacea*, vol. 2, pp. 255-259, 1970.

[12] Johnson, C., "Sound detection thresholds in marine mammals.", 1967, in: W.N. Tavolga (ed), Marine bio-acoustics, vol. 2. Pergamon, Oxford, UK.

[13] Hawkins, A., et al., "Hearing and sound communication under water.", 1983, In: Bioacoustics: a comparative approach. B. Lewis (ed.), pp. 347-405. Academic Press, New York.

[14] Møhl, B., "Auditory sensitivity of the common seal in air and water.", *J. Aud. Res.*, vol. 8, no. 1, pp. 27-38, 1968.

[15] Szymanski, M.et al., "Killer whale (Orcinus orca) hearing: Auditory brainstorm response and behavioral audiograms.", *J. Acous. Soc. Am.*, vol. 106, no. 2, pp. 1134-1141, 1999.

[16] Nedwell, J R, et al., "Objective design of acoustic fish deterrent systems." Proceedings of the Symposium on Cooling Water Intake Technologies to Protect Aquatic Organisms, Environmental Protection Agency, May 6- 7, 2003. Hilton Crystal City at National Airport, Arlington, VA.

[17] Research in progress. Contact Subacoustech Ltd., Hampshire, UK, for further information, quoting reference 534.

[18] Urick, R., *Principles of underwater sound*, New York: McGraw Hill, 1983.

[19] Nedwell, J., et. al., "Measurement of sound during a 3D seismic survey in blocks 14.14a of the North Sea", Subacoustech Ltd., Hampshire, UK, Tech. Rep. 356R0108, 1999.

[20] Turnpenny, A., et al., "The effects on marine fish, diving mammals and birds of underwater sound generated by seismic surveys.", Fawley Aquatic Research Laboratories Ltd, Fawley, Hampshire, Tech. Rep. No FRR 089/94, 1994.

[21] Urban, G., "Directional measurement of ambient noise spectra.", in *Proceedings of the European Conference on Underwater Acoustics*, pp.222-226, 1992.

[22] Knudsen, V., et al., "Underwater ambient noise", *J. of Mar. Res.*, vol. 7, p 410, 1948.

[23] Piggot, C., "Ambient sea noise at low frequencies in shallow water of the Scotian Shelf.", *J. Acous. Soc. Am.*, vol. 36, p. 2152, 1965. Original source not seen, reference is cited in [11].

[24] Ross, D., *Mechanics of Underwater Noise*, New York: Pergamon Press, 1976.

[25] Richardson et al., *Marine mammals and noise*, San Diego: Academic Press, 1995.

[26] Arveson, P., et al., "Radiated noise characteristics of a modern cargo ship.", *J. Acous. Soc. Am.*, vol. 107, no. 1,pp. 118-129, 2000.

[27] Nedwell, J., et al., "Measurements of underwater noise during piling at the Red Funnel Terminal, Southampton, and observations of its effect on caged fish.",

[online] Subacoustech Ltd., Hampshire, UK, Tech. Rep. 558R0207, October 2003, Available WWW: www.subacoustech.com/downloads.

[28] Reijnders, P., "Management and conservation of the harbour seal, *Phoca vitulina*, population in the international Wadden Sea area.", *Biol. Conserv.*, vol. 19, no. 3, pp. 213-221, 1981.

[29] Brasseur, S., "Tolerance of harbour seals to human related disturbance sources during haulout.", in *Abstr. 10th Bienn. Conf. Biol. Mar. Mamm.* (Galveston, TX, p. 130, Nov. 1992).

[30] Bowles,et. al., "Disturbances to the pinnipeds and birds of San Miguel Isalnd, 1979-1980.", in *Jehl, J., et al., Potential effects of space shuttle sonic booms on the biota and geology of the California channel Islands: Research reports.* (Tech. Rep. 80-1 Rep. from Cent. Mar. Stud., San Diego State Univ., and Hubbs/Sea World Res. Inst., San Diego, CA, for US Air Force, Space Div. 246p.)

[31] Allen, S., et al., "The effect of disturbance on harbor seal haul out patterns at Bolinas Lagoon, California.", *Fish Bulletin*, vol. 82, no. 3, pp 493-500, 1984.

[32] Osborn, L., "Population dynamics, behaviour, and the effect if disturbance on haulout patterns of harbor seal *Phoca vitulina richardsi*, Elkhorn Slough, Monterey Bay, California.", B.A. Thesis, Dep. Environ. Stud. & Dep. Biol., Calif., Santa Cruz., p. 75, 1985.

[33] "AAE 200 Boomer Plate with Catamaran", [online document], Available WWW: http://www.seatronics-group.com/geophys/aaeboom.htm, Feb. 2004.

[34] "GeoPulse Boomer/Sparker Profiling System", [online document], Available WWW: http://www.geoacoustics.com/specs/PDF_Files/GeoPulse_Boomer.pdf, Feb. 2004.

[35] Nedwell, J., et al., "Measurement of sound during a 3D seismic survey in blocks 14/14a of the North Sea.", Subacoustech Ltd., Hampshire, UK, Tech. Rep. 356R0108, 1999.

[36] Duncan, P., "Seismic sources in a marine environment.", in *Proc. Workshop on Effects of Explosive Use in the Marine Environment*, (Halifax, N.S., Jan, 1985, pp 56-88).

[37] Mate, B., et al., "A change in sperm whale (*Physeter macrocephalus*) distribution correlated to seismic surveys in the Gulf of Mexico.", *J. Acous. Soc. Am.*, vol. 96, no. 5, pt. 2, pp. 3268-3269, 1994.

[38] Bowles, et al., "Relative abundance and behaviour of marine mammals exposed to transmission from the Heard Island Feasibility Test.", *J. Acoust. Soc. Am.*, vol. 96, no. 4, pp. 2469-2484, 1994.

[39] Gerjuoy, E., "The sound pressure in water resulting from a point source in air.", *Physical Review*, vol. 72, p. 745, 1947.

[40] Andersen, M., et al., "Flange connections between offshore wind turbine towers and mono pile foundations.", LICengineering A/S, Ehlersvej 24, DK-2900 Hellerup, Denmark.

[41] Nedwell, J., et al., "Measurements of underwater noise in the Arun River during piling at County Wharf, Littlehampton", Subacoustech Ltd., Hampshire, UK, Tech Rep. 513R0108, 2002.

[42] Wursig, B., et al, "Development of an air bubble curtain to reduce underwater noise of percussive piling.", *Marine Environmental Research*, vol. 49, pp. 79-93, 2000.

[43] Nedwell, J., et al., "Noise measurements during pipeline laying operations around the Shetland Islands for the Magnus EOR project.", Subacoustech Ltd., Hampshire, UK, Tech. Rep. 473R0112, 2001.

[44] San Francisco – Oakland Bay Bridge, Pile Installation Demonstration Project, Fisheries Impact Assessment, PIDP EA 01208, Caltrans Contract 04A0148, Task Order 205.10.90, PIDP 04-ALA-80-0.0/0.5, 2001.

[45] Vagle, S., "On the Impact of Underwater Pile-Driving Noise on Marine Life", Ocean Science Productivity Division, Institute of Ocean Sciences, DFO/Pacific, 2003.

[46] McKenzie-Maxon, C., "Offshore Wind Turbine Construction, Offshore Pile-Driving Underwater and Above Water Noise Measurement and Analysis.", Rep. to: SEAS Distribution A.m.b.A, Slagterivej 25, 4690 Haslev, Danmark, Tec. Rep. 00.877, 2000.

[47] Tougaard, J., et al., "Short-term effects of the construction of wind turbines on harbour porpoises at Horns Reef.", Tech. Rep. HME/362-02662, to: TechWise A/S., Hedeselskabet, Roskilde, 2003.

[48] Engell-Sørensen, K., et al., "Evaluation of the Effect of Noise from Offshore Pile-Driving on Marine Fish", Bio/consult as, Johs. Ewaldsvej 42-44, DK-8230 Åbyhøj, Tech Rep. 1980-1-03-1- rev. 2. to: SEAS, Slagterivej 25, DK-4690 Haslev.

[49] Feist, B., et al., "Potential Impacts of Pile Driving on Juvenile Pink (oncorhynchus gorbuscha) and Chum (O. keta) Salmon Behaviour and Distribtuion", University of Washington, School of Fisheries, 1992.

[50] "Engineering Instructions for Pile Driving Equipment", US Army Corp Engineering Instruction, U.S. Army Corps of Engineers, Engineering Division Directorate of Military Programs, Washington, DC 20314-1000 EI 02G00, 1997.

[51] Richardson et, al., "Acoustic effects of oil production activities on bowhead and white whales visible during spring migration near Pt. Barrow, Alaska - 1989 phase.", OCS Study MMS 90-0017, 1990.

[52] Hall, J., et al., "Measurements of underwater sounds from a concrete island drilling structure located in the Alaskan sector of the Beaufort Sea.", *J. Acous. Soc. Am.*, vol. 51, no. 2, pp. 515-517, 1991.

[53] Gallagher, M., et al., "ARCO Alaska, Inc. Cabot prospect/Site specific monitoring plan/Final report.", Coastal & Offshore Pacific Corp., Walnut Creek, CA, for ARCO Alaska Inc., 1992. [50] Greene, C., "Characteristics of oil industry dredge and drilling sounds in the Beaufort Sea.", *J. Acoust. Soc. Am.*, vol. 82, no. 4, 1315-1324, 1987.

[54] Gales, R., "Effects of noise of offshore oil and gas operations on marine mammals - An introductory assessment.", NOSC TR 844, 2 vol., U.S. Naval Ocean Systems Cent., San Diego, CA., NTIS AD-A123699 + AD-A123700.

[55] Greene, C., "Characteristics of oil industry dredge and drilling sounds in the Beaufort Sea.", J. Acoust. Soc. Am., vol. 82, no. 4, 1315-1324, 1987.

[56] Nedwell, J., et al., "Report on measurements of underwater noise from the Jack Bates drill rig.", Tech. Rep. 462 R 0202, Subacoustech Ltd., Hampshire, UK, 2001.

[57] Westerburg, H., "Impact Studies of Sea-Based Windpower in Sweden.", Pres. At: Technische Eingriffe in marine Lebensraume, Bundesamt für Naturschutz, Internationale Naturschutzakademie, Insel Vilm, 1999.

[58] Degn, U., "Offshore Wind Turbines VVM (EIA), Underwater Noise Measurements Analysis and Predictions", Tech. Rep. 00.792 rev. 1, Rep. to: SEAS Distribution A.m.b.A., Slagterivej 25, 4690 Haslev, Danmark, 2000.

[59] Koschinski, S., et al., "Behavioural reactions of free-ranging porpoises and seal to the noise of a simluated 2MW windpower generator", *Mar. Ecol. Prog. Ser.*, vol. 265,pp. 263-273, 2003.

[60] Engell-Sorensen, K., "Possible effects of the offshore windfarm at Vindeby on the outcome of fishing.", Tech. Rep. 1920-03-001 rev. 2., Bioconsult report to SEAS, 2002.

[61] Hoffman, E., et al., "Effects of marine windfarms on the distribution of fish, shellfish and marine mammals in the Horns Rev area.", Tech. Rep. Baggrundsrapport nr.24, Prep. by: ELSAMPROJEKT A/S to: Danish Institute for Fisheries Research, Department of Marine Fisheries, Charlottenlund Castle, DK 2920 Charlottenlund, 2000.

[62] Tyler, R., "Use of dynamite to recover tagged salmon.", *Ser. Sp. Sci. Rep. Fish.*, vol. 353, pp. 9, 1960.

[63] Nedwell, J., et al., "The effects of underwater blast during wellhead severance in the North Sea.", Tech. Rep. 469R0202, Subacoustech Ltd., Hampshire, UK, 2001.

[64] Department of Fisheries and Oceans, Canada, "Policy and guidelines for the use of explosives in the waters of the Northwest Territories.", DFO Western Region, Winnipeg, Manitoba, 1982.

[65] Cole, R., *Underwater explosions*., Princetown, NJ, 1948.

[66] Arons, A.,et al., "Secondary pressure pulses due to gas globe oscillations in underwater explosions.", *J. Acous. Soc. Am.*, vol. 20, pp. 271-276, 1948.

[67] Coles, J., et al., "Shockwave parameters from spherical TNT charges detonated underwater.", Underwater Explosives Laboratory, Woods Hole, MA, 1946.

[68] Gaspin J., et al., "Source levels of shallow underwater explosions.", Naval Ordinance Laboratory, NOLTR, pp. 71-160, 1971.

[69] Hillier, H., "Experiments on the pressure wave thrown out by submarine explosion.", Tech. Rep. 142/19, British Department of Scientific Research and Experiments, 1919.

[70] Kirkwood, J., et al., "The pressure wave produced by an underwater explosion.", Tech. Rep. 588, Office of Scientific Research and Development, 1942.

[71] Lauer, R., et al., "A computer model of the explosive acoustic source.", *J. Acous. Soc. Am*, vol. 1, p. 71, 1976.

[72] Slifco, J., "Pressure-pulse charecteristics of deep explosives as functions of depth and range.", Naval Ordinance Laboratory, NOLTR, pp. 67-87, 1967.

[73] Nedwell, et al., "Underwater tool noise: implications for hearing loss", *Advances in underwater technology, ocean science and offshore engineering*, vol. 31, pp. 267-275, 1993.

[74] Parvin, S., et al., “A survey of noise exposure of divers operating underwater tools.” Tech. Rep. QinetiQ/CHS/PPD/CR010322/1.0, QinetiQ Ltd, Alverstoke, Fort Road, Gosport, Hants., PO12 2QU, 2001.

[75] Danish Wind Turbine Manufacturers Association (2001) Web Site, [online], Available WWW: http://www.windpower.dk, Feb 2002.

[76] "Horns Rev Offshore Wind Farm Environmental Impact Assessment - Summary of EIA Report", Tech. Rep. EP00/025/JKG/HG by: ELSAMPROJEKT A/S, Kraftværksvej 53, DK-7000 Fredericia, Prep. for: I/S Elsam, Overgade 45, DK-7000 Fredericia, 2000.

[77] Henriksen, O., "Does underwater noise from offshore wind farms potentially affect seals and harbour porpoises?", [online document], Available WWW: http://www.middelgrunden.dk/MG_UK/article/sealsnoise.htm, Feb 2004.

[78] "Northsea offshore wind - a powerhouse for Europe.",Tech. Rep. Prep. For: Greenpeace Germany (GPD).

[79] Dolman, S., et al., "Marine wind farms and cetaceans.", Tech. Rep. IWC/SC/55/E4.

[80] Simmonds, M., et al., "Oceans of Noise", Whale and Dolphin Conservation Society (WDCS), Brookfield House, 38 St Paul St, Chippenham, Wiltshire, SN15 1LJ, Available WWW: http://www.wdcs.org.

[81] de Boer., M., et al., "Small cetaceans along the coasts of Wales and Southwest England", Whale and Dolphin Conservation Society (WDCS), Brookfield House, 38 St Paul St., Chippenham, Wiltshire, SN15 1LJ., Available WWW: http://www.wdcs.org.

[82] San Francisco – Oakland Bay Bridge, Pile Installation Demonstration Project, Marine Mammal Impact Assessment, Tech. Rep. PIDP EA 01208, Caltrans Contract 04A0148, Task Order 205.10.90, PIDP 04-ALA-80-0.0/0.5.

[83] Burdic, *Underwater acoustic systems analysis*, Englewood Cliffs: Prentice-Hall, 1984.

[84] Anderson, A., et al., "Ambient noise measurements at 30, 60 and 150 kHz in five ports", *J. Acous. Soc. Am.*, vol. 49, p. 928, 1971.

[85] Goold, J., et al., "Broadband spectra of seismic survey air-gun emissions, with reference to dolphin auditory thresholds.", *J. Acoust. Soc. Am.*, vol. 103, no. 4, pp. 2177-2184, 1998.

[86] Bargar, J., et al., "The airgun as an implosive underwater transducer.", *J. Acous. Soc. Am.*, vol. 68, no. 4, pp. 1038-1045, 1980.

[87] Greene, C., "Characteristics of marine seismic survey sounds in the Beaufort Sea.", *J. Acous. Soc. Am.*, vol. 83, no. 6, pp. 2246-2254, 1988.

[88] "San Francisco – Oakland Bay Bridge, Pile Installation Demonstration Project, Marine Mammal Monitoring Plan", EA 012000, Caltrans Contract 04A0148, 2000.

[89] Koschinski, S.,"Offshore windfarms.", [onine document], Article from the German society for dolphin conservation., Available WWW: http://www.delphinschutz.org, Feb. 2004.

[90] Nedwell, J., at al., "Measurements of drill rig noise.", Tech. Rep. 452R0102, Subacoustech Ltd., Hampshire, UK, 2001.

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