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Enabling Actions Report

Review of current knowledge of underwater noise emissions from wave and tidal stream energy devices

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Scoping study: Review of current knowledge of underwater noise emissions from wave and tidal stream energy devices

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EXECUTIVE SUMMARY

This report describes a scoping study commissioned by The Crown Estate with the aim of reviewing the current knowledge of underwater noise emissions from wave and tidal stream energy devices. This consisted of a review of existing data assembled from the public domain, as well as from commercial measurements (often commissioned by developers); a review of measurement methodologies; and a discussion of knowledge gaps and recommendations for a consistent approach. Designs of wave and tidal stream devices currently under development have a range of associated noise spectra, and this study was aimed at reviewing the existing noise data, drawing conclusions about its use in assessing the impact on marine receptors, and making recommendations for future work. As such, whilst drawing broad conclusions about the likely potential impact, the study focused on acoustics rather than biological questions related to impacts on specific species.

A total of 29 relevant studies were identified worldwide, 17 of which made statements of absolute levels of radiated noise in either the operational or construction phase of development (or both). Because of the commercial nature of some of these data, it has not been possible to cite all of these results explicitly in this review. However, even where the data has some commercial sensitivity, it has been possible in most cases to describe the findings and acknowledge the existence of the work. This means that the contents of such commercial reports may be used to inform the generic conclusions of this review even though the specific noise data are not revealed here.

With regard to the available data from the UK, the Pentland Firth and Orkney Waters (PFOW) developers were approached for information for this review. In addition, both Marine Scotland and Scottish Natural Heritage have supplied information. As part of the study, the authors also consulted extensively with staff of the European Marine Energy Centre (EMEC), where a number of the noise data sets described here originate. The authors are also grateful for invaluable discussions with Dr Ben Wilson of Scottish Association for Marine Science (SAMS). A number of reports describing absolute measurements were available from non-UK sources, and these were also incorporated into the review.

From the review of the existing data, it is possible to make the following observations:

- There was a lack of a common approach to measurement by different researchers, with a range of methodologies applied;

- The data were rarely reported in a common manner using similar metrics, making it difficult to compare the noise data for different devices, and accurate data for Source Levels were rarely provided;

- The harsh environments (fast tidal flow, strong wave action, etc) pose severe problems for accurate measurements, motivating the need to explore novel measurement techniques.

There are relatively few high quality data sets describing the noise radiated by wave and tidal stream energy devices. Without accurate data for the Source Levels of wave and tidal stream devices, it is very difficult to make *definitive* statements about the likely impact of the radiated noise, for example in terms of zones within which specific exposure criteria are likely to be exceeded. However, it is possible to examine how the radiated noise levels reported compare to other noise sources, and thereby give a general indication of the potential for impact on receptors. In a number of studies reviewed, the operational noise (and sometimes the noise of drilling during construction) is likened to that of a modest sized vessel. This is probably a good analogy to choose, though the operational noise levels quoted in some of the studies are actually lower than the values quoted for other activities such as the transiting of a modest sized vessel, or marine aggregate extraction. It should be noted that marine percussive piling (a high energy, low frequency impulsive source of underwater sound) was not used during construction for any of the studies reviewed here.

In general, background noise levels at sites of wave and tidal stream energy described in the reports are typically at higher levels than classic ‘deep water’ noise curves. The development sites appear to be *naturally* noisier than deeper water sites. This is due to a variety of reasons including additional local sources of noise in the vicinity, severe wave action, local (rather than distant) shipping, sediment transport, etc. The high levels of background noise present will mean that devices with relatively low operational noise output may not be audible to marine receptors even at surprisingly short ranges. This is borne out by some of the reported findings from operational noise surveys where, on some occasions, the received level from the device was below the background noise level once the measuring hydrophone was more than few hundred metres from the device.

The noise radiated during operation is likely to be strongly correlated with the background noise level, since both (at least to a degree) depend on environmental conditions. An example would be wave energy converter systems as they become more energetic in higher sea states, and where the increased surface agitation (creating surf, wind and wave related noise) would also lead to a commensurate increase in background noise levels. Similarly, for tidal stream devices, the acoustic output levels are likely to depend on revolution speed and operational mode, this being related to the tidal flow. Conditions of high tidal flow will cause increased background noise levels due to increased turbulence and sediment agitation. Currently, there is not a good understanding of the potential influence of the changes in radiated noise relative to background noise on the risk of impact. In particular, the relative signal-to-noise ratio (the amplitude of the radiated noise level compared to the background noise) will influence perception capability, and therefore the collision risk.

From the data that were reported in the studies reviewed here, it is possible to draw some conclusions with regard to the likely impact of the radiated noise from wave and tidal stream developments:

- The radiated noise during operation of wave and tidal stream devices is not at a level likely to cause injury to the hearing of marine receptors, even at relatively close range;

- Similarly, the radiated noise during the construction phase of wave and tidal stream devices, though sometimes of greater amplitude than during operation, is also unlikely to cause injury to the hearing of marine receptors;

- Radiated noise during operation and construction is unlikely to cause significant behavioural effects at long ranges from the site development site;

- Accurate data for radiated noise from wave and tidal stream energy devices is important for assessing behavioural response in the vicinity of individual devices and for scaling up to large scale commercial arrays;

- There is currently not a good understanding of the potential influence of the changes in radiated noise relative to background noise on the risk of impact on a range of receptors. In particular, the relative signal-to-noise ratio will influence perception capability, and therefore the collision risk.

From the review, it has been possible to indicate current knowledge gaps and key areas of uncertainty. These include:

- Operational noise source characteristics (acoustic and vibrational) of new and emerging technologies under different operating conditions and modes;

- Relative importance of device noise relative to background noise, particularly in terms of behavioural response;

- Unknown behavioural response of marine receptors to 'novel' acoustic signatures provided by these emerging technologies both in terms of individual devices and large scale array development.

Recommendations

Finally, as part of the review, a prioritised list of recommendations has been identified. These provide a program of noise measurements that could reasonably be undertaken to inform future applications for regulatory approval for the deployment of wave and tidal stream energy devices. Where relevant, a description has been given of the likely routes to future standardisation of methodologies for noise measurement.

The main theme of the recommendations is that the approaches adopted should be proportional to the perceived risk, should aim to fill in key knowledge gaps, and should aim at the most cost effective solution. The prioritised recommendations are:

1. Strategic coordinated approach
   A strategic coordinated approach should be adopted in devising a measurement programme for the radiated noise during installation and operation (including different operational modes, start up, full capacity, etc) of wave and tidal stream energy devices. This will lead to cost savings in the long-run, will avoid duplication, and allow comparison of data across projects. This would best be achieved if the noise measurement programme were coordinated by a central facilitating organisation, where best measurement practice could be adopted and testing could take place at well-characterised sites (where the acoustic environment is well understood).

2. Type-testing in combination with modelling
   For operational noise assessment, consideration should be given to "type-testing" in combination with the use of theoretical modelling where appropriate. Type-testing would be an activity that takes place once at the design testing stage in order to accurately determine the acoustic Source Level and characterise the operational acoustic signature of the machine in differing environmental conditions. The measured data could then be used to validate theoretical models of the noise generation mechanisms, where these are available. Further acoustic measurement

would then be required only if significant changes are made to the design, or in order to validate extensions to theoretical models (for example for scaling up to an array). On-going monitoring at each development site would not then be required. However, it is recognised that there are many different designs, particularly of wave energy devices, and each separate design may require initial assessment. With regard to construction, if specific construction activities are likely to cause concern (for example, if marine percussive impact piling is used), then a noise monitoring program may be required during the construction phase.

3. Standard measurement methodologies
   Standardised measurement methodologies are needed to accurately derive an acoustic Source Level independent of the acoustic environment for use in predictive models, and to facilitate comparison between different sources measured in different locations. In the first instance, it would be beneficial if generic guidance were provided for making acoustic measurements in the marine environment. It should be possible to reach consensus among expert acousticians on the appropriate metrics to use to describe the acoustic fields, and on the basics of good measurement practice, including uncertainty estimates. There have already been some initiatives in this area, for example those begun by The Crown Estate and Marine Scotland. Secondly, agreed measurement methodologies must be developed for each wave or tidal stream device type. With the technical difficulties posed by the different design of device and the harsh environments, compromises may have to be made, but it should be possible to harmonise the approaches and converge on a common methodology. In the medium to long-term, standards will be provided by international standards committees such as ISO TC43 SC3 and IEC TC114, and the any work begun in the UK must be cognisant of these developments, and ideally the UK work should feed into the development of new standards.

4. Validated modelling capability
   Modelling of energy devices, for example using finite element techniques, holds considerable promise and should be encouraged in order to gain a better physical understanding of the radiation mechanisms and contributions of different components of the devices. This approach also allows consideration of future variants or design options before construction and installation. Ultimately these models need to be validated by comparison with empirical data. Close collaboration, (data sharing, analysis feedback, etc) between device developer engineers, modellers and acoustic measurement teams should be encouraged to quantify acoustic characteristics of new systems under development.

5. Improved measurement technology
   Recent developments in acoustic technology have greatly increased the capability for measurement of ocean noise, and encouragement should be provided for new technology developments that address the specific difficulties encountered when making measurements of wave and tidal stream energy devices. Examples of further developments of measurement tools are long-term acoustic data loggers, drifting systems, and static systems designed to mitigate flow noise. The noise measurement technology should ideally be cost effective, robust, simple to install, and scalable to array sizes. The protocols developed under item (3) should not be so constraining that they stifle creativity and innovation – for example the use of new technologies and instruments.

6. Background noise assessment
   Background noise at specific sites/locations should be measured by longer-term deployments using new autonomous recorders of sufficient acoustic performance. This could be limited to representative sites that could be used as a proxy for other

sites (rather than every development site needing to measure background noise over the long-term). There is also need to consider array-scale spatial variations in ambient sound particularly in tidal areas. Where measurements are undertaken, they should cover the range of environmental conditions likely to be experienced (to match the different operational modes investigated during the radiated noise measurements).

7. Acoustic data exchange

   Although commercial sensitivities may occasionally militate against it, regulators should encourage developers to share data and collaborate where possible allowing greater coordination across the industry as new devices and sites are developed. Where possible within commercial restraints, data collected to meet licence conditions should be made available in the public domain to allow developers and researchers to learn from existing work establishing an industry wide pool of data. Any publically-funded research programme should as a matter of course mandate that any data acquired be made public.

8. Acoustic near-field measurements

   Where feasible, measurements should be encouraged to include the acoustic near-field of the energy device as well as the far-field. Ideally, these should include measurements of the particle velocity and seabed vibration, since some species show sensitivity to motion rather than sound pressure. However, it is recognised that the technology to undertake such measurements, and the knowledge of appropriate exposure criteria, is immature. In the future, developments in the technology may make such measurements viable, and progress with biological research may enable suitable exposure criteria to be developed.

Glossary and List of Abbreviations

acoustic	a synonym for “sound”, as in acoustic pressure or sound pressure
ambient noise	acoustic signals originating from sources other than the source of interest; the acoustic noise in the absence of the source under investigation; sometimes called “background noise”
background noise	acoustic signals originating from sources other than the source of interest; the acoustic noise in the absence of the source under investigation; sometimes called “ambient noise”
dB	decibel; a logarithmic unit expressing the level of a quantity; equal to $10.\log_{10}(a_1^2/a_0^2)$, which is mathematically equivalent to $20.\log_{10}(a_1/a_0)$, where a_1 is the absolute value of the quantity and a_0 is the reference value of that quantity
drilling	a method of installing a structure on the seabed where a drill is used to create a hole or socket for the structure (eg a pile); an installation technique commonly used for hard seabed or sediment (rock or compacted chalk); a common technique used for installation of WEC and TEC devices
ERNL Effective Radiated Noise Level	a term used *in this report* to indicate a sound output metric describing a source which is calculated from the received level corrected for propagation between source and receiver at range R by use of a simple spreading model of the type $N.\log_{10}(R)$, where the spreading constant (N) has a value other than 20; a measure of the acoustic output of the source which is not independent of the environment; an output metric reported by a number of the authors of the studies reviewed here;
ESL Effective Source Level	a term used by some researchers for the ERNL metric; in spite of the name, this is not a true acoustic Source Level.
EIA	Environmental Impact Assessment
EMEC	European Marine Energy Centre, Orkney, UK
ES	Environmental Statement
frequency	the “pitch”, or number of oscillations per second of a sound wave
JNCC	Joint Nature Conservation Committee, UK
LU	Loughborough University
MSFD	EU Marine Strategy Framework Directive
monopile	type of wind turbine foundation that consists of a cylindrical pile that is driven into seabed, often by percussive piling
monopole	a point acoustic source which has an omni-directional acoustic output (the acoustic energy is radiated in all directions equally)
noise	unwanted signal (sound) received by a receptor
NPL	National Physical Laboratory
piling	the installation of a pile into the seabed; may be achieved by percussive piling using a hammer (marine impact piling), or by drilling, or by vibro-piling;
percussive piling	marine pile driving where the pile is driven into the seabed using a succession of blows with a hammer; often called marine impact piling; a high amplitude low-frequency source of sound;
TTS	Temporary Threshold Shift (recoverable auditory fatigue)
PFOW	Pentland Firth and Orkney Waters
PPL	Peak Pressure Level; the level of the maximum sound pressure in a transient or pulsed signal; may be expressed in decibels as $20.\log10(p_1/p_0)$; Unit: dB re 1µPa

PL	Propagation Loss; reduction of sound level with range from the source, expressed in decibels; Unit: dB
PTS	Permanent Threshold Shift; auditory damage in the form of permanent hearing sensitivity reduction
radiated noise	the acoustic noise radiated by a specific source of interest
RL	Received Level – acoustic sound level measured at the receiver position (the receiver could be a hydrophone, or a marine receptor)
RMS	Root mean squared quantity; a time-averaged quantity where the amplitude is first squared, then averaged over a specified time interval, then square-rooted to derive the final RMS value
RNL Radiated Noise Level	a sound output metric describing a source; calculated from the received level corrected for propagation between source and receiver by use of a simple spherical spreading model of the type $20.\log_{10}(R)$; a measure of the acoustic output of the source which is not independent of the environment; commonly used to express the acoustic output of ships in deep water;
SEL	Sound Exposure Level; the integral of the pressure squared over a stated time interval; related to the received acoustic energy at the receptor over the stated time (typically over an event such as an acoustic pulse, or over a specified time duration); may be summed to produce the cumulative SEL over many events (or a long duration)
signal-to-noise ratio	the relative amplitude of the acoustic signal from the source compared with background noise; often expressed in decibels (dB)
SL	Source Level; a measure of the acoustic output of a source which is independent of the environment; may be related to sound energy or power output; Source Level is sometimes stated as a spectral level as a function of frequency (eg in third-octave bands) or as a broadband level (summed over all the frequencies of radiation); Unit: dB re 1µPa referred to 1 m
spectrum	a quantity expressed as a function of frequency, either as a narrowband spectrum (eg 1 Hz bands) or as aggregated bands (eg third-octave bands)
SPL	Sound Pressure Level; the level of the RMS sound pressure; may be expressed in decibels as $20.\log_{10}(p_1/p_0)$, where p_1 is the absolute sound pressure and p_0 is the reference value (1 µPa); by convention, SPL is a root mean square (RMS) quantity, and the averaging time must be defined; note: mathematically equivalent to $10.\log_{10}(p_1^2/p_0^2)$, and so may also be regarded as the level of the mean squared sound pressure; Unit: dB re 1µPa
TEC	Tidal Energy Converter
TL	Transmission Loss; synonym for acoustic Propagation Loss; reduction of sound level with range; expressed in decibels (dB)
TOB	Third Octave Band, frequency band consisting of one-third of an octave, an octave representing a doubling of frequency
SNH	Scottish Natural Heritage
UK	United Kingdom
WEC	Wave Energy Converter

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1. INTRODUCTION

This report has been published by The Crown Estate as part of our enabling work to support development of the Pentland Firth and Orkney Waters wave and tidal projects. This work aims to accelerate and de-risk the development process, looking at a range of key issues. Work is selected, commissioned and steered by The Crown Estate in close discussion with the project developers.

For more information on The Crown Estate's work in wave and tidal energy, see:
http://www.thecrownestate.co.uk/energy/wave-and-tidal/ or contact
waveandtidal@thecrownestate.co.uk

The National Physical Laboratory (NPL) has been commissioned by The Crown Estate to undertake a scoping study to review current knowledge of underwater noise emissions from wave and tidal stream energy devices. In delivering the work, NPL has worked in close collaboration with Dr Paul Lepper of Loughborough University.

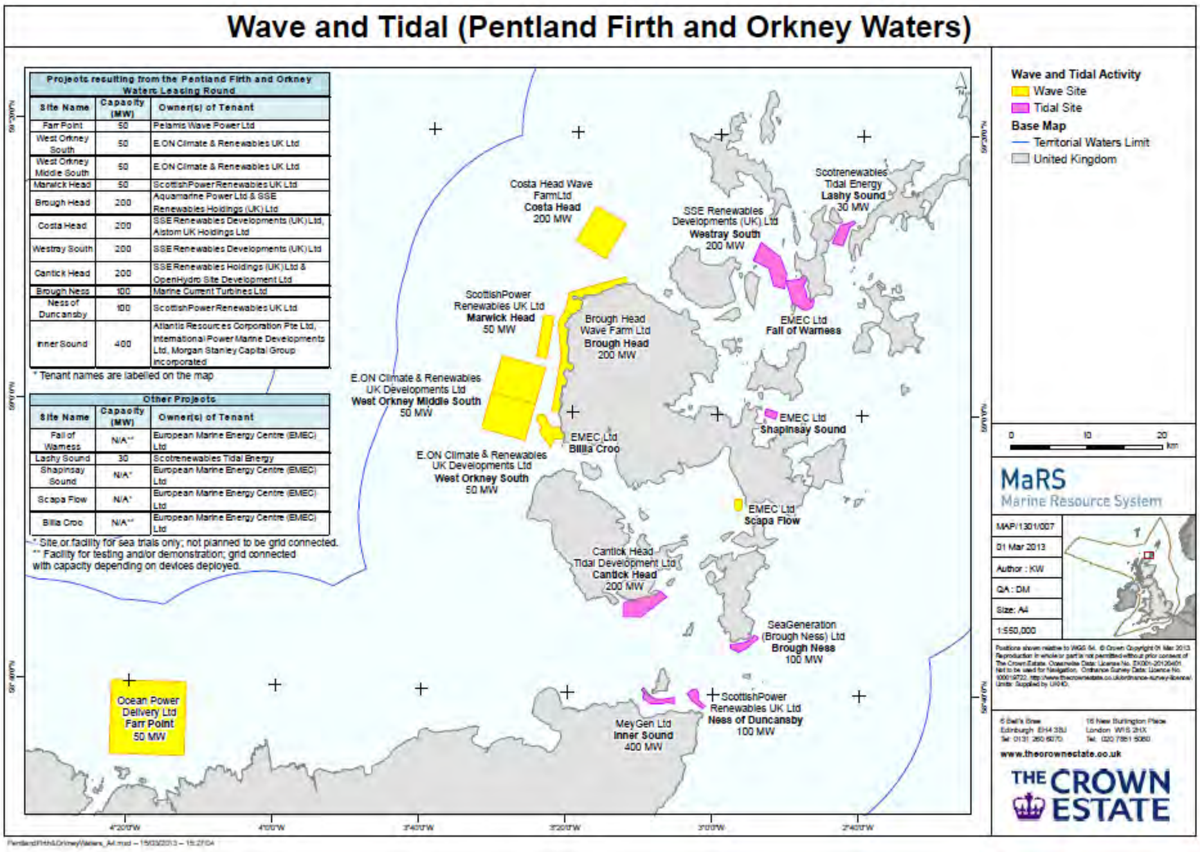
During the project, input has also been sought from staff of the European Marine Energy Centre (EMEC) and Dr Ben Wilson of Scottish Association for Marine Science (SAMS).

1.1 BACKGROUND

In 2008, The Crown Estate announced the first commercial leasing round for wave and tidal stream projects in the Pentland Firth and Orkney Waters (PFOW) Strategic Area. The Crown Estate entered into agreement for lease for six wave project development sites and five tidal stream sites, with a potential capacity of up to 1,600 MW (see Figure 1). In addition, an Agreement for Lease was awarded for a 30 MW demonstration project in Lashy Sound (Orkney) in 2012. Other than the Inner Sound project (MeyGen) having submitted an application for consent in 2012, the PFOW projects are currently at varying stages of development, mostly between pre-scoping/scoping and baseline surveying.

Offshore wave and tidal stream energy are novel types of renewable energy development, with the PFOW representing the largest area of water made available for commercial scale leasing of wave and tidal stream energy devices worldwide. The Crown Estate's Enabling Actions programme was created to accelerate and de-risk the development of the projects and thus to facilitate successful and timely consent, construction and operation of the wave and tidal devices. This Project forms part of The Crown Estate's Pentland Firth and Orkney waters (PFOW) Enabling Actions programme. This project is a general scoping study, but the information stemming from the project may be used to aid individual consent applications for wave and tidal stream developments in the PFOW area and elsewhere in the UK.

This study is specifically focused on the consequences of noise radiated by wave and tidal stream energy devices, and complements other studies that form part of The Crown Estate's PFOW Enabling Actions programme, such as those on Cumulative Impact Assessment (CIA) [Crown Estate 2013a] and on the potential for impact on specific species such as salmonids [Crown Estate 2013b] and ornithological species [Crown Estate 2013c].



Projects resulting from the Pentland Firth and Orkney Waters Leasing Round		
Site Name	**Capacity (MW)**	**Owner(s) of Tenant**
Farr Point	50	Pelamis Wave Power Ltd
West Orkney South	50	E.ON Climate & Renewables UK Ltd
West Orkney Middle South	50	E.ON Climate & Renewables UK Ltd
Marwick Head	50	ScottishPower Renewables UK Ltd
Brough Head	200	Aquamarine Power Ltd & SSE Renewables Holdings (UK) Ltd
Costa Head	200	SSE Renewables Developments (UK) Ltd, Alstom UK Holdings Ltd
Westray South	200	SSE Renewables Developments (UK) Ltd
Cantick Head	200	SSE Renewables Holdings (UK) Ltd & OpenHydro Site Development Ltd
Brough Ness	100	Marine Current Turbines Ltd
Ness of Duncansby	100	ScottishPower Renewables UK Ltd
Inner Sound	400	Atlantis Resources Corporation Pte Ltd, International Power Marine Developments Ltd, Morgan Stanley Capital Group Incorporated

* Tenant names are labelled on the map

Other Projects		
Site Name	**Capacity (MW)**	**Owner(s) of Tenant**
Fall of Warness	N/A**	European Marine Energy Centre (EMEC) Ltd
Lashy Sound	30	Scotrenewables Tidal Energy
Shapinsay Sound	N/A*	European Marine Energy Centre (EMEC) Ltd
Scapa Flow	N/A*	European Marine Energy Centre (EMEC) Ltd
Billia Croo	N/A**	European Marine Energy Centre (EMEC) Ltd

* Site or facility for sea trials only; not planned to be grid connected.
** Facility for testing and/or demonstration; grid connected with capacity depending on devices deployed.

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Figure 1. Pentland Firth and Orkney waters Development Sites

1.2 SCOPE OF THE STUDY

With the increasing deployment of wave and tidal stream energy devices, and the plans for extensive deployment of arrays of such devices at various locations around the UK, The Crown Estate requires an improved understanding of the nature and likely environmental consequences of the associated changes in underwater noise. To date, there has been limited deployment of the actual devices. The variety of device designs will have a range of associated noise spectra, and this study is aimed at reviewing the existing noise data, drawing conclusions about its use in assessing the impact on marine receptors, and making recommendations for future work. As such, the study focuses on the acoustics rather than the biological questions with regard to the impact on specific species.

The scope of the study was to:

- Assemble and review the available public domain evidence of the nature of the noise emitted or likely to be emitted by wave and tidal stream energy devices, both from the UK and abroad;
- Review any non-publically available noise data on wave and tidal stream energy devices which can be sourced (without commercial objections);
- Review the characteristics of this emitted noise and place in context with other sources (for example with naturally occurring background noise from wave action, shipping, etc) and in the context of the environment in wave and tidal stream lease areas;
- Indicate the potential for impact of the noise emitted from devices on a broad range of receptors, again in the context of other sources of underwater noise;

- Indicate the current knowledge gaps, and the likely routes to future standardisation of methodologies for noise measurement;
- Provide a prioritised programme of noise measurements that could reasonably be undertaken at this time to inform future applications for regulatory approval for the deployment of such devices.

1.3 METHODOLOGY USED FOR THE STUDY

1.3.1 Collating the data

For the review of existing data, the authors firstly assembled the data available in the public domain. There have been few examples of measurements reported in the open scientific literature of radiated noise (and background noise) during operation of wave and tidal stream energy devices. Such data as exists often appears in scientific reports. However, the area is clearly of growing interest and has been the subject of several scientific papers presented at recent international conferences.

A number of *commercial* measurements have been made, often solicited by manufacturers, and where the data is not in the public domain. Because of the commercial nature of the reports, it has not been possible to cite the results explicitly in this review. However, it has been possible to view many of these commercial reports with permission from regulators and developers. Although the noise data for individual trials cannot be disclosed here, it has been possible in most cases to review and cite the reports, and acknowledge the existence of the work. This means that the contents of reports may be used to inform the generic conclusions of this review even though the specific noise data are not revealed here.

With regard to the available data from the UK, the following organisations have been approached and have supplied information for this review:

- Marine Scotland
- Scottish Natural Heritage (SNH)

As part of the study, the authors also consulted extensively with staff of the **European Marine Energy Centre** (EMEC), where a number of the noise data sets described here originate. At EMEC, invaluable assistance was provided by Dr Jenny Norris, Dr David Cowan, and Dr Matthew Finn.
The authors are also grateful for invaluable discussions with Dr Ben Wilson of Scottish Association for Marine Science (SAMS).

During the study, the following developers were contacted to request information (PFOW site name in parentheses).

- MeyGen (Inner Sound)
- Pelamis (Farr Point)
- SPR (Marwick Head and Ness of Duncansby)
- Aquamarine (Brough Head)
- SSER (Costa Head, Westray, Cantick Head)
- OpenHydro (Cantick Head)

- MCT (Brough Ness)
- E-On (West Orkney South and West Orkney Middle South)

In some cases, the developer was able to provide some information directly particularly on background noise surveys, but in most cases the developers had no data on operational noise. In some cases, data were available from reports sourced from Marine Scotland, SNH and EMEC.

Where relevant data were available from non-UK sources, these were also incorporated into the review. Data were obtained from non-UK sources in the USA, Canada, Ireland, Sweden, Norway, Denmark and Portugal.

1.3.2 Review of data and recommendations

As will become clear from Section 2 of this report, there is a paucity of reliable data for the noise radiated by wave and tidal stream energy devices. For the few data that do exist, a review was undertaken of the characteristics of the reported radiated noise. The data were rarely reported in a common manner using similar metrics, making it difficult to compare the noise data for different devices. However, as far as is possible, the noise levels reported have been placed in context with the noise levels from other sources, such as shipping. There are considerably more data available for background noise levels in wave and tidal stream lease areas, and these have been reviewed in the context of typical background noise levels reported elsewhere, and have been used to put the radiated noise levels reported for the wave and tidal stream devices into context.

Without data for the source levels of wave and tidal stream devices, it is very difficult to make definitive statements in this report about the likely impact of the radiated noise, for example in terms of zones within which specific exposure criteria are likely to be exceeded, and such an assessment is outside the scope of this study. However, it is possible to examine how the radiated noise levels reported compare to other noise sources, and thereby give a general indication of the potential for impact on a range of receptors.

In the light of the above review, it has been possible to indicate the current knowledge gaps, and to provide a prioritised programme of noise measurements that could reasonably be undertaken to inform future applications for regulatory approval for the deployment of such devices. In so doing, a description has been given of the likely routes to future standardisation of methodologies for noise measurement.

Appendix A provides a summary of basic underwater acoustics and (in addition to referring to the glossary and list of abbreviations, see above) will assist with understanding of any of the terminology used in the review. Appendix B provides a very basic summary of the effects of noise on marine fauna.

2. SUMMARY OF EXISTING DATA

2.1 UK-BASED NOISE STUDIES

2.1.1 Noise surveys based around the EMEC test sites

Much of the information included in this section originates from reports that have been provided by Marine Scotland and by SNH. In addition, many of the PFOW developers have taken advantage of the facilities at EMEC for testing of renewable energy devices, and some of the testing has included a noise survey. The staff of EMEC provided a summary of the work undertaken which includes a noise survey, and this is included in the summary provided here.

The following is a summary of the noise surveys undertaken at the EMEC site.

Fall of Warness Tidal Energy Test Site

Initial work intended to characterise the baseline noise present at the site in the absence of any Tidal Energy Converter (TEC) devices was carried out by the Scottish Association for Marine Science (SAMS) [SAMS 2011a, SAMS 2011b]. This work quantified the ambient sound levels at the site in both ebb and flood conditions, and captured the noise levels due to the presence of a jack-up barge and a cable laying operation. Investigating the origins and sources of the background sound was outside the scope of the SAMS studies, but this has been further addressed in a more recent study, which was undertaken by Chickerell Bioacoustics Ltd with TEC devices in place [Harland-SNH 2013]. For the recent work, three surveys were carried out using drifting acoustic recorders - initially using the existing EMEC drifting hydrophone equipment, with later surveys using a modified drifting system (the Drifting Acoustic Recorder and Tracker (DART) system developed by Chickerell Bioacoustics Ltd and EMEC). The three surveys were carried out in September and November 2011, and in March 2012. The author reports some of the spectral and temporal characteristics of the noise radiated by the TEC devices from data acquired as the recorders drifted close by, but no attempt was made to derive source level spectra for the TEC devices. Analysis by the author indicates that noise induced by turbulent flow is a significant contributor to the ambient noise field within the test site, with other significant contributions from local shipping. The tentative conclusion of the study was that noise detected from the TECs operating on site during the survey period is unlikely to significantly impact marine mammals using the area. Recommendations for further work include deployment of a fixed cabled hydrophone within the test area to acquire continuous acoustic data, survey at higher sea states to give a more complete characterisation, carry out a more detailed analysis of individual noise sources and their locations in order to characterise their noise spectra, and differentiate shipping and TEC machine noise at frequencies below 1kHz in order to characterise noise spectra of their components.

Previous noise measurements undertaken at the Fall of Warness test site include environmental monitoring undertaken during jack-up operations, undertaken by Aquatera for Voith Hydro in the summer of 2010 [Aquatera 2010]. This was followed by measurements undertaken by the same authors of the drilling noise associated with the installation of a monopile at the Voith Hydro test berth [Aquatera 2011]. SPL received levels were varied, ranging from approximately 135 – 140 dB re 1 µPa at around 100 m to approximately 120 – 130 dB re 1 µPa at around 500 m. A simple spreading law of “$16.62.\log_{10}(R)$” was fitted to the measured data to derive a broadband “effective source level” of 168 dB re 1 µPa referred to 1 m. The authors note that the thrusters of the drilling vessel had contributed to the noise levels measured. The estimated background noise level ranged from 122 to 126 dB re 1 µPa (for frequencies up to 22 kHz), with strong contribution from local ship traffic.

Other data for installation noise for tidal turbines tested at the Fall of Warness test site include a unit from Scotrenewables Tidal Power Ltd, a 250 kW tidal turbine [Beharie and Side, 2011]. Measurements of the installation noise for the north-west mooring leg showed variable levels of noise radiated by the vessel thrusters. A simple spreading law was fitted to the measured data to derive a maximum broadband “effective source level” of 162 dB re 1 µPa referred to 1 m for the thrusters. Impulsive sounds were recorded associated with the anchor block and clump weight, and the “effective peak-peak source level” for these sounds was estimated by the authors to be between 154 and 173 dB re 1 µPa (peak-peak).

Shapinsay Sound Tidal Energy Test Site

The noise measurement work here is limited to background noise assessment, which involved carrying out a number of surveys through autumn and winter 2011-2012, with each survey covering a range of tidal and weather conditions. Initial surveys were carried out using the existing EMEC ‘Drifting Ears’ hydrophone equipment, but later surveys used the modified DART system. The surveys were carried out in September and November 2011, and in February and May 2012 [EMEC 2013a]. The collected data show that ambient noise levels were in line with that which could be expected for this type of shallow water site, with anthropogenic noise (from shipping and a ‘seal scarer’) being the major contributors to the ambient noise field. Other significant contributions to the noise field include noise from aircraft, chains, rain, wind, and waves. No sources of noise associated with strong tidal flow across bathymetric features were identified, though measurements were not made in very strong tidal flows, and no geographical variation in noise level was observed. Recommendations [in EMEC 2013a] for future studies include investigation of the relationship between tidal flow and noise levels and how these vary with location within the site, and to explore the ambient noise signature at higher sea states in order to understand how noise levels increase with increasing wind speed and wave height

Scapa Flow Wave Energy Test Site

Again, the noise measurement work here is limited to background noise assessment, which involved carrying out a number of surveys through autumn and winter 2011-2012, with each survey covering a range of tidal and weather conditions. Acoustic data were gathered using a self-contained hydrophone and recorder package deployed on the seabed. One unit was available for use in the surveys. The surveys were carried out in September and December 2011, and March 2012 [EMEC 2013b]. The collected data were used to establish the acoustic levels under quiet conditions, and this shows that the background noise levels were in line with that which could be expected for this type of shallow water site. Contributions over and above these conditions were then identified, with the major contribution being the natural sounds from wind/waves and precipitation. The major anthropogenic source was shipping noise from distant static and mobile sources. Local shipping traffic also contributed to the sound field, although this was only present for around 7% of the time. Other sounds identified included a thunderstorm, aircraft and various biological sources. Recommendations from this [EMEC 2013b] include that further surveys covering spring/summer periods would be required in order to fully characterise the site, after improvements are made to the mounting arrangement for the hydrophone.

Billia Croo Wave Energy Test Site

Some of the work at Billia Croo was in some respects the most comprehensive of all the measurements undertaken at EMEC with regard to noise assessment. The work has involved measurement of both background noise and radiated noise. Initially, an assessment of available measurement techniques for background noise measurement was undertaken, followed by the development of a methodology appropriate to EMEC’s Billia Croo wave test site to enable acoustic data collection and analysis to be performed. The methodology was used to collect data from which an acoustic baseline description of the test site was formed [EMEC 2012a]. Subsequently, a methodology was developed for measurement of operational noise of Wave Energy Converter (WEC) systems at the test site. The methodology considers the temporal and spatial variation of the radiated noise field, the potential for near-field effects, and the requirement to test the WEC under differing operational conditions, and the differing methodology that may be required for different WEC devices (for example surface floating devices compared to distributed water column systems). The need for longer term monitoring is also recognised. The data analysis options are described, and the potential for dependence of metrics on averaging time is acknowledged. A methodology is presented for deriving the monopole source level spectrum by use of an appropriate acoustic propagation model is also described, along with sources of uncertainty from positional errors.

The methodology was used to conduct an operational noise assessment on the Pelamis P2 WEC system [EMEC 2012b]. This is a large surface deployed attenuator system, which provides many challenges for characterisation of the radiated noise. For example, the Pelamis consists of a distributed series of noise sources that are not easily represented by a single value of source level, or by one acoustic centre. For the measurements, four seabed mounted autonomous recorder units were deployed on orthogonal transects on the beam and end-fire positions of the Pelamis system for a period of around 30 hours. Four broadband boat-based drift trials were conducted with a maximum measurement range from Pelamis of 2.4 km. Additionally, a sub-surface buoy recorder system was deployed close to Pelamis to operate in parallel with drift deployments and measure the temporal variation of the radiated sound.

Source level estimates are difficult to relate to one acoustic centre position, but if a position is chosen at the device midpoint, the 10 minute averaged third octave band (CPB) level was observed to be around 120 dB re 1 μPa^2/Hz referred to 1 m for components in the band 10 Hz to 2 kHz and for sea-states of between 1 and 2. At higher sea states (3-4), levels were generally higher, with the maximum observed average level being in the 1 kHz band at around 181 dB re 1 μPa^2 /Hz referred to 1 m. Both the frequency of occurrence and the level of some of the noise sources from the Pelamis system are likely to be higher at increased sea-states as the system becomes more energetic. This may be seen as the increase in the average operational noise levels with increasing sea state. The data sets suggest not only increased operational noise levels at higher sea state but also increased background noise levels. The variation between baseline and operational level is likely to be highly dependent on sea-state, local propagation conditions, other noise sources, and device status.

In addition to the above work with the Pelamis device, during the summer of 2011 at Billia Croo, preparations were made for the subsequent installation of an Oyster 801 wave energy device currently under development by Aquamarine Power Ltd. The Oyster is a hinged device (oscillating wave surge converter) that moves under the action of passing waves, and it was secured to the seabed by means of a foundation pile, which was grouted into a foundation socket drilled into the seabed. The drilling noise was measured by Kongsberg Maritime Ltd and reported in a paper at an international conference [Ward and Needham 2012]. The measured noise levels during the drilling at ranges from 400 m to 5 km were in the range 100 to 120 dB re 1 μPa^2/Hz. Operational noise data is not yet available.

Reliable Data Acquisition Platform for Tidal (ReDAPT)

With funding by the Energy Technologies Institute (ETI), the ReDAPT project aims to demonstrate near commercial scale devices in real sea-state conditions. The project has installed a 1 MW tidal generator at EMEC and will test the performance of the tidal generator in different operational conditions. As part of the project, a detailed assessment of the acoustic environment around the Tidal Generation Ltd (TGL) tidal energy converter will be undertaken. This involves collecting acoustic data from two different systems: (i) drifting hydrophones, using the DART equipment, and (ii) fixed hydrophones housed within a cabled seabed pod. Acoustic data are not yet available from this project.

Table 1 shows a summary of recent noise measurement activity at EMEC test sites, the data being provided by EMEC. Note that not all the entries have resulted in noise data being made available, and not all the data have been available for review in this study.

Table 1. Summary of recent noise measurement activity at EMEC test sites

Organisation	Site	Date	Survey Type
EMEC	EMEC Wave Test Site, Scotland	2011	Ambient noise baseline surveys
			Operational noise survey of Pelamis Wave Power
	EMEC Nursery Wave Test Site, Scotland	2011/12	Ambient noise baseline surveys
	EMEC Tidal Test Site, Scotland	2008/11/12	Ambient noise baseline surveys
		2011	Noise surveys of cable installation using a Dynamic Positioning vessel
		2012/13	Operational turbine noise surveys of Tidal Generation Ltd (ReDAPT)
	EMEC Nursery Tidal Test Site, Scotland	2011/12	Ambient noise baseline surveys
OpenHydro	EMEC Tidal Test Site, Scotland	2010	Operational turbine noise survey using drifting ears
Voith Hydro	EMEC Tidal Test Site, Scotland	2010	Acoustic characterisation survey of Dynamic Positioning vessel for installation
Aquamarine Power	EMEC Wave Test Site, Scotland	2011	Installation and operational noise characterisation surveys

2.1.2 Environmental Statements by developers in UK waters

There are a number of Environmental Statements (ESs) prepared by developers which consider the likely impact of the noise during construction and operation of wave and tidal stream energy devices. In general, these are prepared in advance of any deployments, and therefore can only make use of the data available already in the public domain or available from other developments. The following ESs were made available for review in this project by The Crown Estate:

- Inner Sound tidal stream array **[MeyGen 2012]** "MeyGen Tidal Energy Project Phase 1 Environmental Statement", MeyGen, 2012.

- Kyle Rhea tidal stream array **[KRTSA 2013]** Kyle Rhea Tidal Stream Array Environmental Statement, Appendix 12.6: Assessment of underwater noise from construction and operation of the Kyle Rhea Tidal Array, 2013.
- Sound of Islay Demonstration Tidal Array **[Scottish Power 2010]** Sound of Islay Demonstration Tidal Array Environmental Statement, Scottish Power Renewables, 2010.
- Isle of Lewis wave energy array **[Lewis Wave Power 2012]** 40MW Oyster Wave Array Environmental Statement, Lewis Wave Power, 2012.
- Anglesey Skerries tidal stream array **[Skerries Tidal Stream Array 2012]** Skerries Tidal Stream Array, Supplementary Environmental Information, Prepared by Marine Current Turbines Ltd on behalf of SeaGeneration (Wales) Ltd, 2012.

Typically, the background noise is considered, and in some cases measured using deployed recorders. However, all the ESs make estimates of the likely noise radiated during construction and operational phases based on existing data in the scientific literature, or using data measured at previous deployments. For construction noise, sources such as small motor vessels, jack-up barges and dynamically positioned vessels are considered. Drilling is the typical method assumed for fixing the foundation pieces, and reported noise data from other drilling operations are used in the assessment (e.g. from drilling in the Fall of Warness), sometimes with a simple scaling factor applied to account for differences in drill head size or power. Similarly, for operational noise, the little existing data that have been measured (for example for tidal turbines at Strangford Lough or Lynmouth) are re-used, sometimes with a simple scaling factor to account for larger turbine size. Ranges for injury are typically estimated to be negligibly small, and strong disturbance/aversion is predicted only within a few hundred metres. Comparing the background levels to the predicted levels during drilling operations shows that drilling noise levels should reach background noise levels at range of between 300 m and 3 km depending on the ambient conditions (wave height, tidal flow, etc).

Though these ESs are relatively comprehensive considering they have so few measured data on which to base predictions, they do not contain new measured data for operational noise or construction noise, and so do not add to our knowledge base of measured data.

2.1.3 UK noise surveys based outside the EMEC test sites

There have been a number of deployments to measure background noise at sites such as the Sound of Islay, and at WaveHub in north Cornwall. However, in addition to background noise measurements, there have been a number of noise measurements reported during either installation or operation or WEC and TEC devices.

Lynmouth, Bristol Channel

One of the earliest measurements of sound made in the vicinity of an *operating* wave or tide energy device was carried out at the site of the Marine Current Turbines (MCT) tidal current generator near Lynmouth, in the Bristol Channel. The results of the measurements were the subject of a confidential report for the client [Parvin *et al* 2005], but have since been reported extensively elsewhere in the public domain [Richards et al 2007, Faber Maunsell & Metoc 2007]. In the study, sample measurements were taken at a sampling rate of 192 kHz both while the turbine was operational and also when it was not running to give an indication of the local ambient noise. The distance of the measurement locations from the device ranged from 100 m to more than 1 km, with all measurements taken within a period of about four hours on the 9th March 2005. It was therefore not possible to capture the variation in ambient noise over time. The measurements of operational noise show significant variation in the sound pressure level measured at similar distances from the device. In some cases, particularly at greater distances from the device, the background noise level is higher than the noise level from the turbine (the background noise consisting of a large amount of shore and surf noise and local shipping noise). At a range of 250 m, the operational noise is higher than the background noise by typically 10-15 dB in the frequency range 300 Hz to 10 kHz [Richards et al 2007]. A simple spreading law was fitted to the measured data to derive a broadband "effective source level" of 166 dB re 1 µPa referred to 1 m.

Strangford Lough, Northern Ireland
The tidal turbine development at Strangford Lough is Marine Current Turbine's SeaGen tidal stream energy device, which consists of two 16 m open-bladed rotors, attached to a pile in the seabed in 26 m of water. The device on the surface includes a turret supporting an observation platform. The deployment site is in the centre channel of the Narrows in Strangford Lough, where tidal currents reach up to 4.8 m/s. Measurements were made of pin pile drilling noise during the construction phase, and these were compared to measurements of background noise [Nedwell and Brooker 2008]. Measurements were made at ranges of 28 m to 2,130 m from the drilling operation showing one second RMS sound pressure levels varying from 105 to 139 dB re 1 µPa. Again, a simple spreading law was fitted to the measured data to derive a maximum broadband "effective source level" of 162 dB re 1 µPa referred to 1 m. Such levels are comparable with noise radiated by small vessels and are considerably lower than the levels of noise generated by other piling techniques such as marine percussive piling on large monopoles for offshore windfarms. Measurements of background underwater noise during periods when no drilling was being carried out indicated high levels of high frequency background noise are present in the Strangford Narrows region of Strangford Lough, considered by the authors to be due to the high speed of tidal flow in the region generating noise by interaction of turbulent water with the sea bed and at the water surface. Data from operational noise measurements made on the SeaGen turbines at Strangford Lough have not yet been made available in the public domain.

Ramsey Sound, Wales
Ramsey Sound is located in the south west of Wales and is an open channel 2.5 km long by 1 km wide. The depth varies between 25 and 70 m at Lowest Astronomical Tide (LAT). Ramsey Sound is subject to high currents and the flow can reach up to 4 ms^{-1} during spring tide. It is planned that the company Tidal Energy Ltd will test its DeltaStream tidal turbine in Ramsey Sound. This will allow Swansea University (Marine Energy Research Group) to monitor the underwater noise impact and to assess the potential for disturbance to the marine mammal population (mainly harbour porpoise and grey seals). So far only background noise measurements have been reported [Willis *et al* 2011a, Willis *et al* 2011b, Broudic *et al* 2012, Broudic *et al* 2013].

Falmouth Bay, Cornwall
Passive acoustic monitoring devices were deployed in 2012 at FaBTest in Falmouth Bay (a marine renewable energy device testing facility) during trialling of a wave energy device. Noise monitoring occurred during i) a baseline period, ii) installation activity, iii) the device in situ with inactive power status and, iv) the device in situ with active power status. Two Autonomous Multichannel Acoustic Recorders (AMAR Generation 2; Jasco Applied Sciences) were deployed at a distance of about 200 m from the WEC. The highest sound levels were found to occur during installation activity, where the local sound levels were increased with a median difference of 8.5 dB in the spectral density level in the frequency range 10 Hz to 5 kHz. It is considered unlikely that weather sound contributed to the difference in sound levels, but it is possible that other sources of sound could have contributed, such as shipping activity. An "effective source level" was derived for the 95% percentile received level using a transmission loss of 15.log10(r) to give a level of 154.5 dB at 176 Hz at 1 m for 5% of the time. During operation, no acoustic signature was detected from the WEC at FaBTest. The hydrophone was about 200 m from the WEC in the study, and it is possible that the sounds from the WEC are undetectable above the background noise at this distance [Garrett *et al* 2013].

Table 2 shows a summary of recent UK-based noise measurement activity outside of EMEC test sites. Note that not all the entries have resulted in noise data being made available, and not all the data have been available for review in this study.

Table 2. Summary of UK noise measurement activity excluding EMEC test sites

Organisation	Site	Date	Survey Type
Scottish Association of Marine Science	Sound of Islay, Scotland	2009	Ambient noise baseline survey
Aquamarine Power	Lewis, Scotland	2012	Noise modelling undertaken along with desktop studies to assess potential impact WEC
Wave Hub	Cornwall, England	2012	Long term hydrophone deployment for research purposes
Swansea University	Ramsey Sound	2011/12	Ambient noise measurement
Exeter University	Falmouth Bay	2012	Operational noise and installation noise WEC
Marine Current Turbines	Lynmouth, England	2005	Baseline and operational noise measurements TEC
Marine Current Turbines	Strangford Lough, Northern Ireland	2008	Baseline and operational noise measurements TEC

2.1.4 NERC-funded research projects

The following projects are currently funded by the Natural Environment Research Council, Marine Renewable Energy Research Programme, and are directly concerned with marine renewable energy and its impact. Note that although the projects do not aim to determine the level of noise radiated by marine renewable energy devices, some of the projects will require such data as an ***input*** to the research.

FLOWBEC (FLOw, Water column & Benthic ECology 4D)
A project aimed at using developments in high resolution physical modelling and state of the art observation systems to identify the physical conditions influencing the behaviour of fish and their predators and also benthic communities by concurrently measuring hydrodynamics and biology at 3 different wet MRE test sites – EMEC, WaveHub & Strangford Lough. [Blondel and Williamson 2013]

EBAO (Optimising Array Form for Energy Extraction and Environmental Benefit)
A project aimed at developing a robust procedure in which large scale marine energy developments can be designed to comply with environmental (and social) constraints including defining criteria from which array optimisation procedures can be judged and through which project upscaling becomes feasible.

QBEX (Quantifying benefits and impacts of fishing exclusion zones on bioresources around Marine Renewable Energy Installations)
A project aimed at quantifying changes in distribution and abundance of commercial species (fish, crustaceans) using novel methodologies, in relation to environment (waves, current, habitats) around Marine Renewable Energy Installations.

RESPONSE (Understanding how marine renewable device operations influence fine scale habitat use and behaviour of marine vertebrates).
A project aimed at understanding the fine scale distribution of marine wildlife in high tidal and wave energy sites to understand how seals, cetaceans, birds and large fish use such areas; characterising acoustic, visual and electromagnetic signals that wave and tidal stream

produce and assessing the reactions of marine wildlife to those cues; using the results and habitat preference models to infer zones of influence and/or avoidance associated with wave and tidal stream at both small and large scales; developing effective mitigation methods.

2.1.5 Modelling radiated noise

One approach to estimation of radiated noise from underwater structures is to develop a physical model of the radiation mechanisms that provides some predictive utility. Even though accurate acoustic field prediction from vibrating underwater structures is a difficult problem, such models also assist when extending the validity of experimental data to regimes that are substantially different to those pertaining to the measured data. Use of a physical model enables extrapolation of empirical data based on physical principles rather than just fits to empirical data. For example, this can help with extrapolation to larger structures, or different material properties.

With regard to underwater construction noise, there have been recent attempts to model the radiation from marine marine percussive piling, with the result that there has been considerable progress in understanding how the acoustic radiation is transmitted into the water column, and what are the important constraining factors [Reinhall and Dahl 2011, Zampolli et al 2013].

There have also been some initial attempts to model some of the noise radiation mechanisms for underwater turbine operation, including cavitation noise [Wang *et al* 2007], and inflow turbulence [Lloyd *et al* 2011]. The latter study predicted sound pressure levels due to inflow turbulence for a typical turbine, estimating the third-octave-bandwidth pressure levels of 119 dB re 1 µPa at a range of 20 m from the turbine at individual frequencies. This preliminary estimate reveals that this noise source alone is not expected to cause permanent or temporary threshold shift in the marine animals studied (Harbour seal, harbour porpoise, cod). Finite element models that describe the vibration of the entire structure of a marine turbine, including blades, gearbox and generator noise have been developed by Xi Engineering [Carruthers and Marmo 2011, Marmo 2013]. Such models have been coupled to the surrounding fluid to predict the pressure field around the turbine to predict the far-field acoustic pressure. However, the outputs of these models are not available in the public domain at the time of this review.

2.2 NON UK-BASED NOISE STUDIES

2.2.1 North America

There are a number of US studies that have recently reported on the underwater noise radiated by wave and tidal energy devices. Examples of the most recent include a Technical Report by NOAA [Polagye *et al* 2011], and a review undertaken by the Pacific Northwest National Laboratory (PNNL) for the US Ocean Energy Systems Initiative, Annex IV: Assessment of Environmental Effects and Monitoring Efforts for Ocean Wave, Tidal and Current Energy Systems [Copping *et al* 2013]. This provides a comprehensive review of the activity in the USA and Canada

Cobscook Bay Tidal Energy Project

Ocean Renewable Power Companyis planning a commercial installation of three cross-axis TECs in 26 m of water in Cobscook Bay in coastal Maine, USA. Phase I, a single TEC, began commercial operation in September 2012. Two years prior to installation, a demonstration TEC was fixed on a barge to test the turbine and acquire environmental data that would help guide the permitting process and future modifications of the turbine. Monitoring carried out by Scientific Solutions, Inc. was performed to demonstrate the measurement of noise in a strong tidal current using drifting hydrophones, establish ambient noise levels in Cobscook Bay prior to turbine deployment, and measure the radiated noise from the barge-mounted TEC, as a measurement of the noise expected from the commercial array of bottom-mounted turbines. For the measurements, a buoy system was used to suspend two hydrophones to measure underwater sound. A series of experiments were carried out under varying tidal current speeds and a range of operating conditions for the turbine. The buoy was released by a research vessel and recovered some distance downstream in the area where the barge-mounted turbine was normally operated to measure ambient noise. This was repeated upstream once the barge-mounted turbine was in place. All other sources of noise were made quiet in the vicinity of the experiment while the hydrophones were collecting data. Instrumentation mounted on the turbine allowed for correlation of the measured sound with the operating speed of the turbine. The results reported indicated that sound from the barge-mounted turbine was less than 100 dB re 1 $\mu Pa^2/Hz$ at a range of 10 m from the turbine; at ranges of 200 m to 500 m, the turbine sound was undetectable above ambient noise within the bay [CBTEP 2012].

Roosevelt Island Tidal Energy Project

Verdant Power deployed six tidal turbines in 10 m of water in the East River of New York as a demonstration for the Roosevelt Island Tidal Energy project (RITE). The turbines are three-bladed unducted turbines mounted on the seabed. The Verdant team set out to establish the ambient underwater sound signature for the East River and for the array of tidal turbines. At the time the turbine acoustic measurements were made, blades on one of the six turbines were broken and another turbine was failing, resulting in more noise generation than would be expected in normal operating mode. Using hydrophones, transects were made parallel to shore, surrounding the turbine array footprint, before and after the array was deployed, to gather data on the ambient and turbine noise. Noise from the subway travelling under the East River dominates the ambient noise signature, and is comparable to the sound of the array (reported source level of up to 145 dB re 1 µPa referred to 1 m). Verdant scientists compared the turbine noise to the hearing thresholds of 14 fish species known to be in the area (four species with narrow hearing ranges and 10 species that hear across a broadband range). For 13 of the fish species, the sound measured from the damaged turbine array did not reach levels known to cause injury in fish [Copping et al 2013].

Sea Ray Wave Energy Converter, Puget Sound

Columbia Power Technologies (CPT) tested its SeaRay 1/7th scale wave buoy in West Point, Puget Sound, near Seattle, Washington, for 14 months, from March 2011 to April 2012. The purpose of the deployment was to test the survivability, tuning, and power potential of the device in a sheltered environment with small waves before progressing to a full-scale deployment in the open ocean. More information about the CPT trials can be found on the company website at http://www.columbiapwr.com. To characterize the acoustic signature of the SeaRay and compare it to the ambient acoustic environment, researchers from the University of Washington Northwest National Marine Renewable Energy Center (NNMREC) measured the sound signature of the wave device and the surrounding waters. NNMREC researchers conducted a series of experiments using a cabled drifting array of hydrophones at two depths (5 m and 15 m) and one autonomous drifter at 1 m depth in the vicinity of the wave device. Ships in the area were identified using ship's Automatic Identification Systems and from hydrophone data. The NNMREC researchers measured ambient levels to be approximately 116 dB re 1 µPa, peaking at 132 dB re 1 µPa in a frequency band of 20 Hz to 20 kHz when ship traffic was close to the SeaRay deployment site. They were able to acoustically identify the wave device within a range of 500 m when there was no ship traffic in the area. However, when ships were present, the high ambient noise levels appear to have masked the wave device sound. SPL received levels for the SeaRay were "measured to be 126 dB re 1 µPa", which the authors compare to a tugboat passing at a range of 1.25 km. In addition, the sound from the SeaRay was closely correlated with the wave period [Copping *et al* 2013, Basset *et al* 2011].

Admiralty Inlet Tidal Energy Development

A major utility in the Puget Sound region is planning to deploy two 6 m OpenHydro tidal turbines in 55 m of water in Admiralty Inlet in 2013. Information being collected prior to deployment includes significant site characterization that will be used to support the consenting process. University of Washington NNMREC researchers characterized the acoustic environment of Admiralty Inlet and evaluated the potential addition of the noise of two turbines to the location. Bottom-mounted Acoustic Doppler Current Profilers and hydrophones were used to determine the tidal current movement and noise at the proposed turbine deployment location. Vessel traffic (commercial ships and a passenger ferry) in the region was tracked using the Automatic Identification System and traffic noise was recorded by hydrophone. The researchers found that the low-frequency ambient noise (<1000 Hz) in Admiralty Inlet is dominated by vessel traffic and by sediment transport at high frequencies (>1000 Hz), particularly during periods of strong tidal currents. Breaking waves and rain on the surface of the water also contribute to the ambient high-frequency noise, but do not significantly contribute to the ambient noise budget at this location. To estimate the sound that the turbines are likely to contribute to the environment, NNMREC researchers used measurements conducted by SRSL (SAMS) of a 6 m OpenHydro turbine deployed at the EMEC Fall of Warness site in the UK. Over 5 hours of recordings were made during both flood and ebb tides using ‘Drifting Ear’ systems. These results were re-analysed to estimate the acoustic output in Admiralty Inlet. Using this technique, the maximum noise source level from the two turbines in Admiralty Inlet was estimated to be 172 dB re 1 µPa referred to 1 m, at a tidal current level of 3.6 m/s. The authors state that this maximum acoustic output is expected to occur less than 0.01% of the time that the turbine is operating [Copping *et al* 2013]. The researchers also estimated that the probability that marine mammals will detect the noise of the turbine is likely to fall below 25% within a kilometre of the site. For the same planned deployment, a study was undertaken on juvenile Chinook salmon (*Oncorhynchus tshawytscha*). After they were exposed to simulated tidal turbine noise, the hearing of juvenile Chinook salmon was measured and necropsies performed to check for tissue damage. Experimental results indicate that non-lethal, low levels of tissue damage may have occurred but that there were no effects of noise exposure on the auditory systems of the test fish [Halvorsen et al 2011].

Bay of Fundy Tidal Energy Demonstration

For this Canadian study, an estimate of the anticipated operational radiated noise level was obtained by use of data for the OpenHydro device tested at the EMEC in the UK. For the EMEC tests, with broadband acoustic signals observed (up to 120 kHz), received sound pressure levels ranging from 140 dB re 1 µPa at 50 m to 140 re 1 µPa at 790 m. Based on these measured data, the source level noise was calculated to be 162 dB 1 µPa referred to 1 m. At distances beyond 200 m, the turbine noise was difficult to identify above the ambient noise. As such, the extent of behavioural interaction with marine species was considered (by OpenHydro) to be limited to this range. The EMEC study concluded that unless marine organisms were in the immediate vicinity of the unit, behavioural interaction is unlikely [AECOM 2009]. More recently, work has begun to measure long-term ambient noise levels in the Bay of Fundy [Martin et al 2012].

Oregon Wave Energy Trust

The research facilities at Oregon State University (OSU) are ideal to act as a WEC test bed for research and development. To meet OSU’s requirements, JASCO Applied Sciences undertook to devise a noise assessment framework for the development of wave energy converters in the area. The study is quite comprehensive but the development was still at the planning stage, and the report does not contain any measured data [Austin *et al* 2009].

2.22 Europe

Wave Energy Centre, Portugal

In Portugal, the Wave Energy Test Centre has carried out a number of tests on wave energy devices in recent years [Patricio 2009, Patricio *et al* 2009]. An example is a study carried out at the European Pilot Plant of Wave Energy Oscillating Water Column device, at the Pico, Azores Island, which presents one of the first acoustic assessments made on a Wave Energy Converter. In May 2010 the first monitoring campaign was undertaken at the Pico Wave Plant. The data obtained during WEC operation show the existence of harmonic acoustic components associated with the rotational speed of the turbine and impulsive noise associated with increased air pressure within the air chamber. The harmonics are related to the natural frequency of turbine blades, corresponding the eighth harmonic to the passage frequency of the 8 turbine blades. When analysing the harmonics for various rotational speeds, the received SPL values did not exceed 126 dB re 1 µPa at a position 10 m in front of the device [Patricio and Soares 2012]. The Simple Underwater Renewable Generation of Electricity (SURGE) project aims at the demonstration of the Waveroller - a Wave Energy Converter (WEC) that is in an advanced stage of development. During the SURGE project a Waveroller device will be installed near the shore in front of the town of Peniche (Portugal). The background noise measurement has already been carried out in 2010, and a protocol for measuring the radiated noise has been developed [Soares, C. *et al* 2012].

Smart Bay, Galway, Ireland

In Ireland, SmartBay is responsible for the establishment and development of a national research, test and demonstration facility to support the application and translation of research and provide platforms for the testing and demonstration of new technologies and solutions in the marine and related sectors. The proposed test bed will be deployed at the existing ¼-scale wave energy test site. The test and demonstration facility will provide a test bed for Marine ICT and will also provide wave energy developers with a facility to assess the performance of wave energy converters. The project is currently at the planning stage, in advance of procurement and installation. Initial focus has been on innovative instrumentation, including particle velocity sensing [Kolar et al 2011, McKeown 2011, McKeown et al 2012].

Sweden

Acoustic measurements have been reported of the noise from Wave Energy Converters (WECs) in the Lysekil project at Uppsala University and the Project WESA (joint effort between Uppsala University (Lead Partner), Ålands Teknikkluster r.f. and University of Turku). The study examined the noise from full scale operating WECs in the Lysekil and project WESA, with submersible recording devices (SM2-recorder from Wildlife Acoustics and hydrophones from High Tech Inc. - HTI 96 MIN and HTI 99 HF) deployed at typically 20-40 m from WECs at a depth of approximately 24 meters. Both WECs are full-scale point absorbers with a directly driven linear generator, placed on gravitation foundations at the seabed with a connected buoy at the surface that absorbs energy from the heaving waves. Measurements at the Lysekil project were carried out in the spring of 2013 and in the project WESA in Jan-Feb of 2012. Preliminary results show that the main operating noise radiated from the WEC are short transients with instant rise time when the translator moves past the stator and when the stator hits the end stop springs of the generator. Most of the energy in the noise is in the frequency range 20 – 1000 Hz. Peak amplitude was found at 145 Hz with "an average value" of 126 dB re 1 µPa. The SPL for an entire pulse at 20 m from a WEC was 133 dB re 1 µPa (max SPL value) and 129 dB re 1 µPa (average SPL value). Broadband SPL received levels were "corrected" to a range of 1 m to derive an "effective source level" using a transmission loss of 15.log$_{10}$(r). Occasional transient sounds caused by the device end stop being struck were as high as 181 dB re 1 µPa (corrected to a range of 1 m from the device), but these transient signals are atypical and would not generally occur in normal operation. The authors report that the results indicate that a number of marine organisms (fish and mammals) will be able to hear the operating WECs of a distance of 20 m. [Haikonen *et al*, 2013a, Haikonen *et al*, 2013b].

Norway
Akvaplan-niva AS reported the characterization of a 300 kW Hammerfest Strøm tidal turbine at Kvalsund, in Norway. Operational noise was measured using a drifting boat based deployment. The third octave band SPL **received levels** in the vicinity of the device ranged from 130 dB to 150 dB re 1 µPa [Akvaplan-niva, 2009].

Denmark
Underwater noise was recorded in October 2012 from the Wavestar wave energy converter, a full-scale hydraulic point absorber, placed on a jack-up rig and located at Hastholm, Denmark (57°7.73´N, 8°37.23´E). For measurements, an autonomous data-logger (DSG-marine, Loggerhead Instruments, Sarasota, Florida) was used with a HTI-96 hydrophone connected to a 35 kHz low-pass filter, with the acoustic signal continuously digitized with 16 bit resolution at 80 kilosamples/s. The data-logger was attached to an anchor and moored in 7 m deep water, about 2 m above the seabed, and between 10 and 20 m from the converter. During recordings, significant wave height 1.9 m, and wave period 4.2 s. Median sound pressure levels in third-octave bands during operation of the converter were 106-109 dB re. 1 µPa in the range 125 Hz to 250 Hz, with statistically significant levels of typically 1-2 dB above ambient noise level. A more powerful tone at 150 Hz (sound pressure level 121-125 dB re 1 µPa) was present from the hydraulic pump during start-up and shut-down of the converter. The author reports that the measured noise levels were so low that the potential negative effects on marine mammals appear minimal [Tougaard 2013].

Table 3 shows a summary of recent non-UK-based noise measurement activity. Note that not all the entries have resulted in noise data being made available, and not all the data have been available for review in this study.

Table 3. Summary of non-UK noise measurement activity

Organisation	Site	Date	Survey Type
Uppsala University	Lysekil, Sweden	2011, 2012, 2013	Baseline noise monitoring at one location and operational noise monitoring with of Lykesil L12 and WESA devices. WEC
Cobscook Bay Tidal Energy Project	Maine USA	2010	Demonstrator project with turbine deployed from barge. Radiated noise level measured. TEC
RITE TEC project	New York, USA	2011	Three turbines deployed. Radiated noise level measured while operational. TEC
SeaRay WEC	Puget Sound, USA	2011/12	Scale model demonstrator Operational noise measured WEC
Admiralty Inlet TEC	Puget Sound, USA	2011/12	Used OpenHydro data from EMEC to estimate noise levels. Study undertaken on fish sensitivity TEC
Oregon Energy Trust WEC	Oregon, USA	2009	Planning stage – no data available at that time WEC
Bay of Fundy TEC	Bay of Fundy, Canada	2009, 2012	Demonstrator project. Background noise. OpenHydro data from EMEC used for estimates of operational noise. TEC
Wave Energy Centre	Pico plant, Portugal	2010	Operational noise measurements for EIA WEC
AW Energy SURGE	Peniche, Portugal	2010	Ambient noise baseline survey
Akvaplan-niva AS	Kvalsund, Norway	2009	Characterization of a 300 kW Hammerfest Strøm tidal turbine TEC
IBM Research and the Marine Institute Ireland	SmartBay, Galway, Ireland	2012	Ambient noise baseline survey
Wavestar WEC	Hastholm, Denmark	2012	Operational noise and background noise measured. WEC.

3. REVIEW OF NOISE SOURCES FROM WAVE AND TIDAL STREAM ENERGY

3.1 SUMMARY OF ABSOLUTE MEASURED DATA FOR RADIATED NOISE

The review in Section 2 established that there are a total of 17 studies in the scientific literature which report the absolute levels of noise radiated by wave and tidal stream energy devices. Many other studies report only data for background noise at the site, or report only the protocol for planned measurements to be undertaken in the future.

Where absolute levels of radiated noise are reported, some of the data reported are in the form of received levels at specified ranges (though on occasion, the exact range for each received level is not quite clear). Such data are useful in estimating the noise level in the proximity of the specific source, but make comparisons between sources difficult because the received noise level depends not just on the source output, but also the range from the source and the environment through which the sound is propagating.

To compare the noise level radiated by sources, a metric is needed which describes the sound output of the source independently from the environment and the range from the source. In underwater acoustics, the quantity commonly used to describe the source output is termed the Source Level (SL), a term derived from sonar engineering. It can be related to the sound energy or power generated by the source, and is calculated by measuring the sound pressure in the acoustic far-field and “correcting” the sound pressure to account for the propagation of the sound wave from source to receiver position. To derive a true Source Level requires the use of a propagation model that can account for all of the relevant transmission phenomena, including the spreading of the sound wave, the sound absorption, and the interaction of the sound wave with the medium boundaries (these latter phenomena will in general depend on the acoustic frequency). Another benefit of calculating a Source Level is that it has a predictive utility - it can be used as an input to appropriate propagation models to predict the sound field around the source even if the source were placed in a different environment. Appendix A has more information on how sources are commonly described in underwater acoustics.

For some of the measured data reviewed here, an attempt has been made to derive an acoustic output measure for the source by use of a simple spreading loss formula (eg N.log(R) where R is the range and N is a constant), with the resultant metric described as an “effective source level”, or sometimes erroneously as a “source level”. The quantity so calculated is not really a true Source Level, and although it is still a measure of the acoustic output of the source, it retains some dependence on the environment (water depth, seabed type, etc). In the ISO standard, ISO PAS 17028, which describes the procedure for measuring noise radiated by ships in deep water, the quantity obtained using back propagation by a simple spreading formula is termed “Radiated Noise Level”, or RNL. However, for ship noise the value of the spreading term constant N is always 20, whereas for the studies reviewed here, a different value for the constant has been used. Sometimes the value of N is derived from an empirical fit to the measured levels as a function of range, but often it is simply assumed to be a value of 15. In order to avoid confusion with true Source Level, for the remainder of this section an output measure calculated using such a method has been termed “Effective Radiated Noise Level”, or ERNL. Note that this term is not commonly used in underwater acoustics, but is used here to avoid any confusion with true SL or RNL.

Acoustic output measurements expressed as Received Levels at specific ranges, or corrected to Effective Radiated Noise Levels, do not allow easy comparison of different sources, and the data cannot be used to predict the noise field around the source when it is placed in another location.

The noise data from the reports reviewed here are summarised in Table 4 for tidal energy devices and Table 5 for wave energy devices. Where no radiated noise levels have been stated, the study has been omitted from these tables. Note that in source material summarised in Table 4 and Table 5, there is a range of noise metrics quoted, and it is not always clear to this project team what the units are intended to be (some educated guesswork has been used to complete the table). As far as possible, the data are quoted as they appear in the report that is cited, with the exception that “Effective Radiated Noise Level” (ERNL) is used instead of “Effective Source Level”

Table 4. Summary of available measured data for Tidal Energy Converters.

Tidal Energy Converters (TEC)			
Organisation/Owner	Methodology used	Measurements	Details
SeaFlow (MCT) Lynmouth	Boat based drifts at ranges 100m to 1km; simple spreading law was fitted to the measured data to derive ERNL	Operational noise. Broadband "Effective Radiated Noise Level" of 166 dB re 1 μPa referred to 1 m	[Parvin *et al* 2005] but has since been reported extensively elsewhere in the public domain [Richards et al 2007, Faber Maunsell & Metoc 2007].
SeaGen (MCT) Strangford Lough	Boat based measurements over range 150 m - 2,937 m.	Operational noise. Broadband Received Level of 141 dB re 1 μPa (SPL) at a range of 311 m Broadband "Effective Radiated Noise Level" of 174 dB re 1μPa referred to 1m	[Kongsberg, 2010] [Götz *et al*, 2011].
OpenHydro, Fall of Warness, EMEC	Multiple deployments of drifting autonomous recorders on flood and ebb tides. Geometric spreading law used in ERNL estimate	Operational noise. Broadband SPL Received Levels ranged from 116 to 127 dB re 1 μPa Third octave band "Effective Radiated Noise Level" 125 to 148 dB re 1 μPa referred to 1 m	Below ambient at ranges greater than 200 m [Wilson et al , 2010]
Cobscook Bay Tidal Energy	Buoy based hydrophone	Operational noise. Broadband Received Level at range of 10 m: <100 dB re 1 $\mu Pa^2/Hz$	Demonstrator project with tidal turbine. [OES, 2013]
Andritz Hydro Hammerfest (*HS300)* Kvalsund, Western Finnmark, Norway	Drifting boat based deployment	Operational noise. Third octave SPLs Received Levels ranged from 130 to 150 dB re 1 μPa	[Akvaplan-niva, 2009]
East River, New York	Transect deployments of hydrophones	Operational noise. 145 dB Received Level measured at 1 m	Array of three devices [OES, 2013]
Voith / Aquatera, Falls of Warness, EMEC	Drifting boat based measurements at different ranges from drilling operation. ERNL derived from simple spreading laws	Construction noise Broadband "Effective Radiated Noise Level" for pin drilling of 168 dB re 1 μPa referred to 1 m Background noise levels of 115-125 dB re 1$\mu Pa^2/Hz$	Drilling noise for pin pile and background noise levels [Aquatera 2010, 2011]
Admiralty Inlet, Puget Sound 2 x 6m Openhydro TEC		Operational noise (estimate). "Estimated maximum noise level" of 172 dB re 1 μPa	Used OpenHydro data from EMEC to estimate operational noise. [Copping *et al* 2013]

Scotrenewables, Falls of Warness, EMEC,	ERNL derived using a simple spreading law.	Construction noise Broadband “Effective Radiated Noise Level” of 162 dB re 1 µPa referred to 1 m including noise from thrusters. Impulsive sounds from anchor block and clump weight with reported effective peak-peak “Effective Radiated Noise Level” between 154 and 173 dB re 1 µPa referred to 1 m.	[Beharie and Side, 2011].
SeaGen (MCT) Strangford Lough	Boat based survey at ranges 28m-2130m ERNL derived using a simple spreading law.	Construction noise Mean SPL Received Levels of 136 dB re 1 µPa at range of 28 m. Broadband “Effective Radiated Noise Level” of 162 dB re 1 µPa referred to 1m for pin pile drilling.	[Nedwell and Brooker, 2008]

Note: All values and units are quoted in this table as stated in the original reports as far as possible. Note that varying methodologies, metrics and notations have been used by different authors making direct comparison of values difficult. The term “Effective Radiated Noise Level” has been used instead of “Effective Source Level” where authors have derived an acoustic output metric by back-propagating received levels using a simple spreading law model.

Table 5. Summary of available measured data for Wave Energy Converters.

Wave Energy Converters (WEC)			
Organisation/Owner	Methodology used	Measurements	Details
Pelamis P2 Billia Croo, EMEC, UK	Multiple autonomous loggers and boat based survey. Source Level derived using range dependant propagation modelling (in TOB)	Operational noise. Broadband Source Level 120 dB re 1 μPa^2/Hz referred to 1 m in low sea state Broadband Source Level 180 dB re 1 μPa^2/Hz referred to 1 m in high sea state	Maximum levels in 1 kHz TOB, measurements made of mean and variance of 10 minute sequences. Source Level calculated for assumed acoustic centre of device. [EMEC 2012b]
Wave Energy Pico Plant, Algarve, Portugal		Operational noise. SPL Received Levels did not exceed 126 dB re 1 μPa measured at 10 m.	[Patricio and Soares 2012]
SeaRay, West Point, Puget Sound, USA		Operational noise. SPL Received Level of 126 dB re 1 μPa observed	1/7th scale device demonstrator [Copping *et al* 2013, Basset *et al* 2011].
L12 Lykesil, WESA project, Uppsala University, Norway	Two systems measured using autonomous loggers in various sea states	Operational noise. Received levels SPL at 20 m from a WEC was 133 dB re 1 μPa (max SPL value) and 129 dB re 1 μPa (average SPL value). Peak amplitude was found at 145 Hz with “an average value” of 126 dB re 1 μPa.	SPL also “corrected” to range of 1 m to derive ERNL using a transmission loss of 15.log10(r). [Haikonen *et al*, 2013]
Aquamarine Oyster Billia Croo, EMEC UK	Received Levels measured in range 400 m – 5 km	Construction noise Received levels from 100 to 120 dB re 1 μPa^2/Hz	Drilling for foundation pile installation [Ward and Needham 2012]
Exeter University Falmouth Bay, UK	Received Levels measured at range of ~200 m from device using recorder/logger	Construction and operational noise Typically ~8.5 dB increase in spectral level during installation, leading to “Effective Radiated Noise Level” of 154.5 dB at 176 Hz at 1 m (5% of the time).	No detectable increase in level during operation at range of ~200 m. [Garrett et al 2013]
Wavestar A/S, Hastholm, Denmark. *Aarhus University, Denmark*	Received Levels measured at range of 10-20 m from device using autonomous recorder/logger	Operational noise. Median SPL Received Level of 106-109 dB re. 1 μPa in the range 125-250 Hz A more powerful tone at 150 Hz (SPL of 121-125 dB re 1 μPa) occurred during start-up and shut-down.	SPL measured in third-octave bands during operation was typically 1-2 dB above background. [Tougaard 2013]

Note: All values and units are quoted in this table as stated in the original reports. Note that varying methodologies, metrics and notations have been used by different authors making direct comparison of values difficult. The term “Effective Radiated Noise Level” has been used instead of “Effective Source Level” where authors have derived an acoustic output metric by back-propagating received levels using a spreading law model.

Some of the data presented in the reports reviewed here indicate both broadband and tonal characteristics of the noise field. Some data have indicated additional temporal effects such amplitude / frequency modulation of tones (cyclic whines), chattering, etc. These effects are not well captured by the reporting mechanisms typically used in the reports reviewed here, where broadband levels are quoted, or at most third-octave band frequency analysis is undertaken. These signals are better described by a spectrogram-type plot (time-frequency analysis). Such signals are worthy of study because it is possible that these types of characteristic sounds may well enhance the capability of marine mammals to detect marine renewable energy devices compared to other noise sources in the environment.

3.2 COMPARISON WITH BACKGROUND NOISE DATA

Figure 2 shows a plot of the typical ambient noise levels that are observed in deep water, showing the dependence on distant ship traffic noise, wave noise (sea state) and precipitation noise. Of interest here is the fact that these spectral levels are somewhat less than the values cited for ambient noise at the sites of wave and tidal stream energy in the reports. This is because there are additional local sources of noise in the vicinity of the wave and tidal deployment areas from severe wave action, local (rather than distant) shipping, sediment transport, etc. This increases the background noise compared to those expected in deep water.

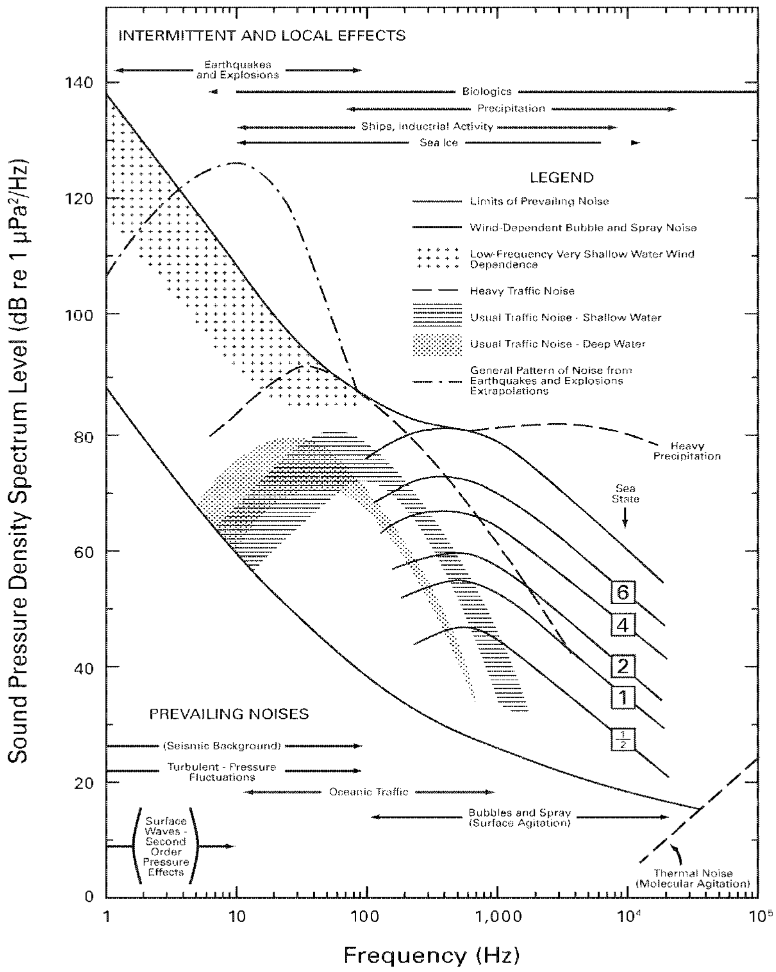

Figure 2. Classic deep water ambient noise spectra for the ocean (re-drawn from Richardson *et al*, 1995)

Figure 3 shows the results of measurements of background noise taken from the Billia Croo test site at EMEC (reproduced from reference EMEC 2012a). As can be seen, the background noise is considerably higher than classic deep-water background noise data under similar sea conditions (Beaufort scale 3-4). The plots shown were taken on separate occasions, and the left hand plot shows the influence of a cable-laying vessel present during the measurements (elevated levels at the 63 Hz and 80 Hz third-octave band frequencies). In general, the levels are higher than for the classic deep-water spectra even when the vessel is not present.

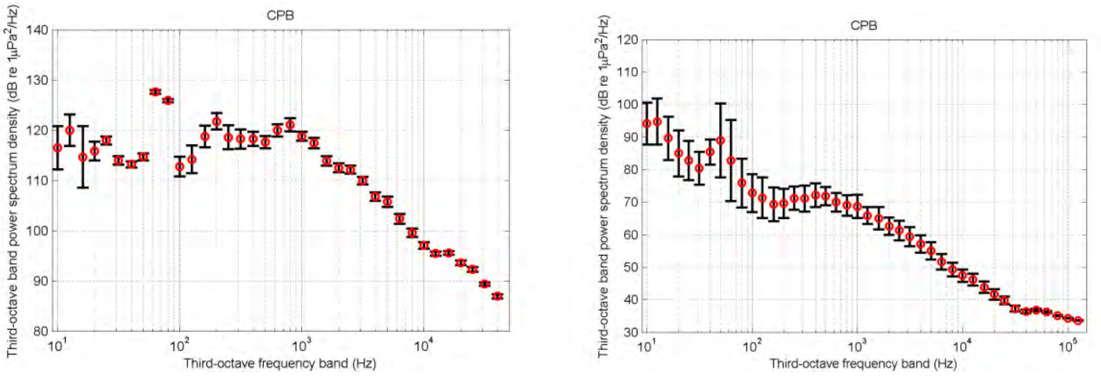

Figure 3. Measured background noise level in third-octave bands measured on two separate occasions at the Billia Croo test site at EMEC (reproduced from EMEC 2012a).

The high levels of background noise present will mean that devices with relatively low operational noise output may not be audible to marine receptors even at surprisingly short ranges. This is borne out by some of the reported findings from operational noise surveys where, on some occasions, the received level from the device was below the background noise level once the measuring hydrophone was more than few hundred metres from the device [AECOM 2009].

The noise radiated during operation is likely to be strongly correlated with the background noise level, since both (at least to a degree) depend on environmental conditions. An example would be wave energy converter systems as they become more energetic in higher sea states, and where the increased surface agitation (creating surf, wind and wave related noise) would also lead to a commensurate increase in background noise levels. Similarly, for tidal stream devices, the acoustic output levels are likely to depend on revolution speed and operational mode, this being related to the tidal flow. Conditions of high tidal flow will cause increased background noise levels due to increased turbulence and sediment agitation.

In summary, with regard to the comparison with background noise:

- background noise at the sites of wave and tidal stream energy devices will typically be higher than expected from classic deep-water noise spectra due to additional local sources of noise from severe wave action, local (rather than distant) shipping, sediment transport, high tidal flow, etc;
- the radiated noise from the device will be correlated with the background noise and may not be much higher than the background levels at relatively modest ranges from the device. This has implications for perception capability of marine mammals, and therefore the collision risk.

There is, however, currently not a good understanding of the potential influence of the changes in radiated noise relative to background noise on the risk of impact. In particular, the relative signal-to-noise ratio will influence perception capability, and therefore the collision risk.

3.3 COMPARISON WITH OTHER NOISE SOURCES

3.3.1 Comparison of Source Levels

In the absence of data for the true Source Level spectra of the wave and tidal stream energy devices, it is difficult to make a direct comparison with other noise sources. Any data for Radiated Noise Level (this applies to most of the data reported) are at least partially dependent on the environmental conditions in which the sources are placed, and so cannot easily be compared with other sources not measured in the same conditions. Nevertheless, it is instructive to attempt some comparison, even if a fully quantitative comparison is not possible.

In a number of studies reviewed here, the operational noise (and sometimes the noise of drilling during construction) is likened to that of a modest vessel. Vessel noise is probably a good example to choose for a comparison because the noise generation mechanisms have some similarities: in both cases the noise is continuous in nature, with some broadband noise but with occasional superimposed tonal components, and with the possibility of short impulsive transients. The mechanisms generating the noise in both cases include reciprocating machinery, gearboxes, and potentially cavitation and hydrodynamic noise. Furthermore, the frequency range of the two types of noise source bear some similarity (with most sound energy typically in the range 10 Hz to 10 kHz).

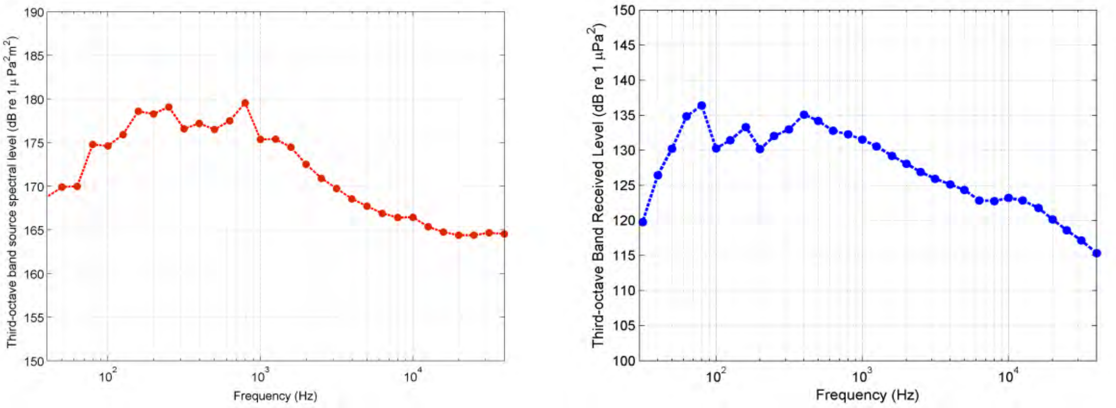

Figure 4. Data for third-octave band source level spectra for a commercial vessel travelling at modest speed (a dredger during operation on light sand) and the received level for the same vessel at a range of approximately 125 m (from Robinson *et al*, 2011).

Figure 4 shows data for third-octave band source level spectra for a commercial vessel travelling at modest speed (a dredger during operation on light sand transiting at a speed of less than 5 knots) and the received spectral level for the same vessel at a range of approximately 125 m. The data are for a trailing suction hopper dredger (TSHD) used to extract marine aggregate [Robinson *et al*, 2011, Wang *et al* 2013]. While it is not possible to make a direct comparison to the variety of Radiated Noise Levels quoted in Tables 4 and 5, it can be seen that the vessel source level is of a similar order of magnitude and sometimes substantially higher than the values typically quoted for wave and tidal energy devices.

Another example of an underwater noise source for comparison is that of personal watercraft (water scooters, jet skis). These are common in coastal recreational areas. Examples have been recorded under water in Bramble Bay, Queensland, Australia and reported by Erbe [Erbe 2013]. Underwater noise emissions consisted of broadband energy between 100 Hz and 10 kHz due to the vibrating bubble cloud generated by the jet stream, overlain with frequency-modulated tonals corresponding to impeller blade rates and harmonics. Broadband monopole source levels were 149, 137, and 122 dB re 1 µPa referred to 1m (5th, 50th, and 95th percentiles).

Recent data have also been reported for noise radiated by container ships [McKenna *et al* 2013]. A 54 kGT container ship had the highest broadband source level at 188 dB re 1 µPa referred to 1m; a 26 kGT chemical tanker had the lowest at 177 dB re 1 µPa referred to 1m. Recently reported data for ice-breakers showed source levels reached 190–200 dB re 1 µPa referred to 1m (full octave band) during icebreaking operations [Roth *et al* 2013].

Other recently reported radiated noise data are for six Floating Production Storage and Offloading (FPSO) vessels of the type commonly found in the offshore oil and gas industry. Monopole Source Level spectra were computed for use in environmental impact assessments, and given that operations on the FPSOs varied over the period of recording, and were sometimes unknown, a statistical approach to noise level estimation was adopted. The 5th, 50th (median), and 95th percentile Source Levels (broadband, 20 to 2500 Hz) were 188, 181, and 173 dB re 1 µPa referred to 1 m, respectively. [Erbe *et al* 2013]. This puts these platforms in a similar category to merchant ships of reasonable size.

Another example for comparison is perhaps underwater operational noise from offshore wind turbines. An example of measured data is for three different types of wind turbines in Denmark and Sweden (Middelgrunden, Vindeby, and Bockstigen-Valar) during normal operation. The results showed that wind turbine noise was only measurable above ambient noise at frequencies below 500 Hz. Total broadband SPL was in the range 109-127 dB re 1 µPa, measured at distances between 14 and 20 m from the foundations (not dissimilar to some of the values quoted for wave and tidal stream devices). Audibility was low for harbor porpoises extending 20-70 m from the foundation, whereas audibility for harbor seals ranged from less than 100 m to several kilometers. Behavioral reactions of porpoises to the noise appeared unlikely except if they were very close to the foundations. However, behavioral reactions from seals could not be excluded up to distances of a few hundred meters. It was however considered unlikely that the noise would reach levels capable of causing injury at any distance from the turbines, and that masking effects were highly unlikely. Similar conclusions are not unreasonable for wave and tidal stream energy developments, as has been pointed out in several studies [Tougaard 2013].

Table 6 provides a summary of the recently available Source Levels data for the vessels and platforms discussed above.

Table 6. Summary of Source Levels for a variety of vessels and platforms.

Source type	**Broadband Source Level (dB re 1 µPa referred to 1 m)**	**Details**
TSH Dredger loading soft sand	180 – 188	Frequency range: 20 Hz – 40 kHz [Robinson et al 2011]
Jet-ski, water scooters	122 - 149	Frequency range: 100 Hz – 10 kHz [Erbe 2013]
Container ships	177 - 188	Frequency range: 20 Hz – 1 kHz [McKenna *et al* 2013].
Ice breaker ships	190 - 200	Frequency range: 20 Hz – 2 kHz [Roth *et al* 2013]
FPSO oil and gas platforms	173 - 188	Frequency range: 20 Hz – 2.5 kHz [Erbe *et al* 2013]
Offshore wind operational noise	N/A	Frequency range: 20 Hz – 500 Hz Broadband SPL: 109-127 dB re 1 µPa at range of 14 – 20 m. [Tougaard *et al* 2009b]

Of course, it should be borne in mind that the data from the studies reviewed here have acoustic output metrics calculated in different ways and in different units, so making a truly quantitative comparison difficult if not impossible. Nevertheless, the values for the acoustic output of the wave and tidal stream devices are rarely as high as those quoted for vessels, and often an order of magnitude less than thee values. This means that, to provide a broad analogy, the noise from wave and tidal stream energy devices may reasonably be described no more than that of a modest size vessel at moderate speed.

3.3.2 Range of detection

The range that the source can be detected above background noise can be an important consideration. If the received level is sufficiently high in amplitude, a specific marine species may show aversion to the noise and the noise may cause displacement of the animals within the vicinity. At the noise levels reported for wave and tidal energy devices, it is unlikely that any significant displacement would occur over a significant range. This view is borne out by the common observations made in several studies that the radiated noise falls below the background noise within a relatively short range from the source (the device “cannot be heard above the background” after a modest range, etc). In some cases, these ranges are little more than a few hundred metres, but in some cases can be a few kilometres.

As a comparison with regard to range of detection, consider another source: large-scale marine percussive piling, for example for offshore windfarm construction using large monopiles. This would seem an extreme comparison, because such piling introduces a large amount of energy into the structure with a hammer strike of up to 2,000 kJ. Although less than 3% of this energy escapes as acoustic energy, nevertheless this is an anthropogenic source with a very high acoustic energy source level. It is not easy to compare source levels with continuous sources because for an impulsive source it is more useful to talk in terms of energy source level than in terms of sound pressure level [Ainslie *et al* 2012, Robinson *et al* 2013], but if the detection range is considered then the piling noise may be detected tens of kilometres away from the source (depending on the background noise and the propagation loss, possibly many tens of kilometres). Figure 5 illustrates this by showing the third-octave band spectra for a single piling pulse as a function of range from the pile being driven. Even at 5 km range, the signal is still 10-15 dB above background noise. Some studies have reported aversion to piling noise for harbour porpoises at ranges of 20 km [Tougaard *et al* 2009a].

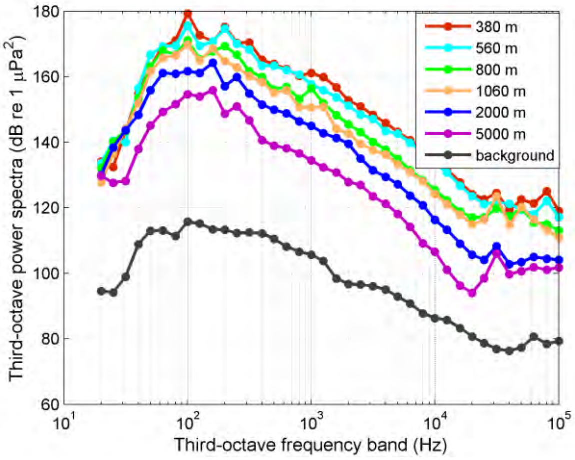

Figure 5. The third-octave band spectra for a single piling pulse as a function of range from the pile being driven, with the background noise level also shown (data measured for a 5 m diameter pile driven by a 1,400 kJ hammer strike).

Realistically, significant displacement due to the level of radiated noise is highly unlikely unless percussive piling is used in the construction phase for wave and tidal stream projects rather than drilling. Of note for wave and tidal energy devices is whether the detection range is so short that the risk of collision is not reduced. This is of more concern than for wind turbines because of the dynamic nature of the devices compared wind turbine foundations. This is also exacerbated by the high levels of background noise at sites for wave and tidal energy development. Where large arrays of devices are deployed in a confined area (for example, in narrow straits), the potential for barrier effects is evident. The lack of accurate radiated noise data for the devices is a significant obstacle to determining the optimum spatial array pattern which will minimise interaction with marine receptors.

3.4 REVIEW OF NOISE GENERATION MECHANISMS

There are a variety of designs of wave and tidal stream energy technologies, each of which have sources of noise, some of which will be unique to specific designs. Therefore, the radiated noise is likely to differ between different designs [Faber Maunsell & Metoc 2007, Copping *et al* 2012].

As indicated earlier, the noise associated with wave and tidal stream energy devices may be categorised as:

(i) Construction noise

This is likely to be relatively short term, occurring during the installation phase. This may involve some or all of:

- drilling (or possibly percussive piling) to fix the device (or its moorings) to the seabed;
- shipping and machinery noise;
- dredging;
- cable burial, which may require the use of trenching or jetting machinery in soft sediments, rock cutting machinery in hard sea-beds, or rock or concrete mattress laying may be used to protect cables in areas where they cannot be buried.

The noise source of most concern in the above list is that of marine percussive piling. This is a significant source of impulsive noise in other constructions projects, for example for offshore wind farms and oil and gas platforms. However, it should be noted that, for wave and tidal stream devices, fixing to the seabed is mostly done by drilling. This is partly due to the rocky seabed locations for most wave and tidal stream developments. In such conditions, it is impossible to carry out percussive pile driving because the strong wave and tidal regimes present in most PFOW locations means that there is very little sediment present to accept the pile (see also Crown Estate 2013b). This is possibly not definitive for all PFOW developments - some offshore wave developments may be over areas of sediment, but even here gravity based anchors are being considered as foundation methods. Pile drilling is generally a much less noisy activity than percussive pile driving, and consists of a large, heavy drill bit rotating slowly on the seabed and grinding the rock. Though there are only a few data sets of noise measured during pile drilling, the levels reported indicate that the radiated noise is similar to a vessel of modest size.

A major contribution to the noise during construction is the caused by the presence of the vessels and machinery associated with the activity. Although these noise sources would not be present without the renewable energy development, in general they are not in themselves of sufficient acoustic output or duration to cause injury to marine receptors.

(ii) Operational noise

Long-term noise generated during operation will depend on the design of the device, and could include some or all of:

- noise generated by turbulence and vortex shedding;
- noise from hydraulics, joints and hinges;
- noise from moorings;
- impact of surface waves;
- rotating machinery;
- movement of air or water;
- noise in all operational modes (start-up, braking, stationery, overrunning etc.)

One point worth mentioning is that some of the above noise generation mechanisms are not well characterised, with very little data available describing their spectral content and likely source level.

Another fact worth remembering is that noise levels can also increase when there is some kind of mechanical failure or fault conditions. Such occurrences of faults are clearly undesirable, but in the hostile marine environment, it is inevitable that fault conditions will sometimes occur. A faulty bearing in rotating machinery can produce increased levels of broadband noise, worn gear boxes can become progressively noisier, and anti-vibration mounts can become worn and less efficient. A fault in a flexing joint can produce tonals at the flexing cycle and joints can partially or fully seize resulting in a change in the way the unit interacts with the waves and thereby increasing wave noise. Rubber seals eventually become worn and start squeaking. With moorings, as parts wear they will generally become noisier. Listening for the characteristic acoustic signatures of the above noise sources does offer the potential for monitoring the structural health of the energy converter, and so acoustic sensors could provide a secondary purpose as a diagnostic tool.

4. REVIEW OF MEASUREMENT METHODOLOGIES

4.1 CHALLENGES FOR METHODOLOGIES

There are a number of challenges with regard to measuring the radiated noise from wave and tidal stream energy devices, and these will influence the quality of the available data.

Harsh environments

These include severe wave action, mooring noise, self-noise of the deployment platform, electrical pick-up, and cable strum. Perhaps the most difficult to deal with is fast currents which can be destructive to acoustic measurement equipment, and which can generate substantial flow noise at the hydrophone (a form of sensor self-noise caused by pressure fluctuations in the turbulent boundary layer around the hydrophone). Drifting deployments can minimise flow noise and offer a solution to a number of the problems, but introduce other issues that require addressing.

High background noise

The background noise in the vicinity is often relatively high, for example due to substantial surface agitation (wave action). Since radiated noise is at least partially generated by moving parts within the energy device, and since the device motion increases with increased wave action or current flow, the radiated noise and the background noise are likely to be correlated (as happens for operational noise for offshore wind turbines). This makes accurate measurement of radiated noise more difficult (although this does mean that the high background noise may tend to mitigate the noise impact by masking the noise generated by the renewable energy device).

Variety of designs to be measured

The large variety of designs of wave and tidal stream energy devices place considerable challenges on the measurement methodology. These include [Crown Estate 2011]:

Wave Energy Converters
- Attenuator
- Point absorber
- Oscillating water column
- Overtopping device
- Oscillating wave surge converter
- Pressure differential device

Tidal Stream Energy Converters
- Horizontal axis turbine
- Vertical axis turbine
- Oscillating hydrofoil

Some devices are on the water surface, some on the seabed, and some span the water column. Some devices are physically very large with a number of potential noise sources spatially distributed along the device. The acoustic output of such a device is difficult to characterise in terms of a simple monopole source level. There may also be significant acoustic near-field effects, or the individual noise sources may require individual characterisation.

Complex acoustic propagation

In deep water, the variations in depth due to tides are not significant. However, in inshore waters the effect is much more pronounced and can alter noise fields through the tidal cycle. Bathymetric changes that are a significant fraction of the water column have a significant effect on propagation. Sand banks that dry out at low water can block acoustic paths so a receiver hearing a noise source across a sand bank at high tide may not receive it at all at low tide.

In the calculation of source level, or source level spectra, a propagation model is required. Ideally this should be capable of accounting for all the key propagation phenomena, including: (i) interaction with the seabed; (ii) interaction with the sea surface; (iii) dependence on acoustic frequency (for example, for absorption in the water and seabed); (iv) dependence on bathymetry. Many of the studies reported here used a simple spreading model to propagate the acoustic signals, with the value of the spreading constant derived from a fit to empirical data. Such a model can have sufficient accuracy for propagating between two points in far-field in conditions of flat bathymetry, but does not account for the interactions noted above, and cannot be used to derive a true monopole source level (see Appendix A). An argument put forward in mitigation is that if the same model is used to propagate outward to calculate the impact zones for the purposes of an EIA or ES, the error is minimised, but this is not true if the source level is to be used to predict the acoustic field when the source is in another location. The use of simple models is tempting for a number of reasons, but it is necessary to know what the limitations are of any technique [Duncan and Parsons 2011].

Particle motion and vibration

Some marine species are sensitive to particle motion rather than acoustic pressure. This is particularly true of some species of fish. Wave and tidal stream energy devices have the potential to generate complex particle velocity fields in the near-field and to cause the seabed to vibrate. Neither seabed vibration nor particle velocity are typically measured, and little is known about the fields generated by renewable energy devices (nor is much known about any other source in this regard). This topic is certainly worthy of further study.

Calibration and system performance

Many commercial recorder systems and hydrophones are not supplied with a calibration. For the studies reviewed here, a number of the studies described problems with calibration issues. A calibration is essential and should consist of a full system calibration (including hydrophones, amplifiers, *and* digitisation system). Ideally, a traceable calibration should be obtained from an accredited source, rather than simply relying on nominal figures from manufacturer's data. For a hydrophone/system which is required to work over a wide frequency range (at frequencies approaching the hydrophone resonance), the calibration should cover the full frequency range of interest (the sensitivity will not be invariant with frequency when close to resonance).

For a system designed to measure in a low noise situation, the EU TSG 2012 report [Van der Graaf *et al* 2012] recommended maximum self-noise of 47 dB re 1 μPa^2/Hz at 63 Hz and 43 dB re 1 μPa^2/Hz at 125 Hz. These self-noise values are not achieved by all of the commercial systems available, and where the signal level is sufficiently high, the self-noise requirement can be relaxed somewhat. Self-noise can originate from poor choice of hydrophone and amplifiers, or from pick-up of electrical noise generated by the electronics and data storage system.

Some commercial systems suffer from relatively poor dynamic range so that the large amplitude signals that can be detected at low frequencies can sometimes saturate the recorders. This is challenging, and many systems will not achieve the dynamic range in combination with the self-noise requirements, but in any case the actual dynamic range should be known so that the maximum undistorted signal level can be estimated, and any saturated signals eliminated during analysis of the data.

Data analysis

When analysing noise data, it is necessary to average the results. A simple metric such as Sound Pressure Level (SPL) is defined as an average quantity because it relies on estimation of the mean value over a specific time window and bandwidth (see Appendix A). When reporting the SPL, the averaging time must be stated. For analysis of long-term deployments, it will be necessary to break down the data into segments for analysis and averaging. Again, the duty cycle and averaging time (or “snapshot” time) should be stated with the results. The only metric that does not depend for its final value on the snapshot or averaging time (in other words how the data is broken up) is the *arithmetic mean*. This requires that the average be calculated in linear units (pascals) and only converted to decibels afterwards for display purposes. For this reason, the arithmetic mean is the best choice as a metric if compatibility with results of data analysis from other researchers is required. However, when comparing noise data, it is necessary to establish the statistical significance of a difference in the observed data. This requires the distribution in the form of percentiles (probability density function). The 50th percentile is also called the “median”. For the establishment of the statistical significance of the difference in two values for the noise level computed from different data sets, the distribution in the form of percentiles is required. The difference between the arithmetic mean and median may be regarded as a measure of the influence of outliers, or the how skewed the distributions are [Merchant *et al* 2012, Van der Schaar *et al* 2013].

Noise is typically analysed in aggregated bands. Third-octave band spectra are good for general appraisal of EIAs and for ambient noise; narrow-band spectra are good for diagnosis of noise source components and tonal frequencies.

4.2 THE USE OF DRIFTING SYSTEMS

Drifting systems have the potential to solve (or at least alleviate) a number of problems caused by fast flowing environments. In particular, they can reduce flow noise dramatically and also reduce other sources of parasitic signals such as cable strum (worse when the mooring ropes/cables are in tension, as is the case if the mooring is fixed in a tidal flow). However, care must be taken to eliminate mooring noise due to chafing and rubbing on the drifting system itself [Wilson *et al* 2011, Carter and Wilson 2011, Carter *et al* 2012].

Drifting systems have proven popular for use in the measurement of tidal energy converters for these reasons. However, there are some disadvantages. The drifting systems are not suitable for long-term deployments – they can drift out of the region of interest and must be picked up and re-deployed repeatedly. In addition, there is less control over where the hydrophone is located, since the system is at the mercy of the tide. Therefore a GPS tracker is a beneficial feature, so that there is a record of where the system is at any time.

Drifting systems make measurement of source level more difficult when undertaking radiated noise measurements. Ideally, a fixed system is also needed so that any temporal changes in the source output are captured (otherwise it is difficult to know whether the change in signal is because of the changed receiver position or because the source output has changed). Also, a drifting system may not drift in transect directly away from the source, requiring that the correction for propagation loss be made over different bearings. This latter issue is more difficult than for usual static receivers, but it is not impossible to solve – the situation is rather like ship noise ranging but here the receiver is moving and not the source. Other issues with drifting systems are that there is sometimes little control of where the receiver drifts to, and this can lead to collisions with debris, or the shoreline.

Having said this, drifting systems nevertheless have a great deal to offer when measuring both wave and tidal energy systems because the difficulties with the harsh environment for static systems can be very severe. Deployment of static boat-deployed systems or bottom-mounted systems is much more difficult in these harsh environments than in open water. A bottom-mounted system will reduce many of the problems encountered by boat-deployments, but it must avoid being moved by tides and storms. Flow noise can be significant even close to the seabed, and it is difficult to moor in high tidal flow. There may also be sediment noise if the system is on the bottom in a strong tidal flow. The logistics of deployment and retrieval are also difficult and should not be underestimated. Ideally, the system needs communication to shore via cabled system or telemetry (mobile phone or satellite or wi-fi). A fixed system does provide a check on the temporal stability of the source, but range-dependent data are needed if an empirical check of propagation loss is desired. Therefore, several systems should be deployed, or used in combination with vessel-deployed or drifting systems. If more than one fixed system can record simultaneously, the data can be used to localise the position of noise source on a large device as well as ambient noise mapping.

4.3 ROUTE TO STANDARDISATION

Standard methodologies for measuring the noise from wave and tidal stream energy devices do not currently exist, and researchers have used a variety of approaches in making and reporting the measurements made so far, even with respect to the units used for the quantities reported. This is perhaps to be expected for a field that is relatively immature (such noise sources have only recently been developed, and it will take a little time for the metrology to catch up with the advances in technological development). With the variety of types of device and the harsh environmental conditions, some flexibility and a range of methodologies are likely to be needed. However, the results must be reported in a standard format if meaningful comparisons are to be made. The variety of formats and metrics made it difficult to compare the existing data for this study.

There are two main aims in standardisation. One is to achieve a consensus about the best approach to a problem – the one that provides the closest estimate to the “right” answer. The second is to achieve harmonisation, such that there are common methodologies used by all, ensuring that measurements made by different researchers are comparable. In marine acoustics, it is essential that we achieve some common international standards. Sound in the ocean has no boundaries, and noise generated in the waters of one country can be heard in the waters of a neighbouring country.

Standardisation within ISO and IEC

Work is being undertaken by the International Organisation for Standardisation (ISO) to develop standards for measurement of underwater noise. The work is underway in two separate Technical Committees: TC43 (Acoustics) and TC8 (Shipping and Maritime Technology).

In TC43, a new Sub-Committee with the title *Underwater Acoustics* has been established. Three Working Groups have begun work on: WG1: measurement of ship noise; WG2: terminology and definitions; WG3: measurement of marine piling noise. In TC8, there is a Joint Working Group with TC43 on standards for measurement of noise radiated from commercial ships. The first standard to be produced is an adoption of an ANSI standard (S12.64) as a Publically Available Specification as ISO PAS 17028

Another relevant committee, this time within the International Electrotechnical Commission is IEC TC114: Marine Energy – Wave and Tidal Energy Converters. This committee does not currently have a work item on acoustic noise radiated by wave and tidal energy, but the topic is under active consideration.

Nationally, the UK has mirror committees with the British Standards Institute that feed into the international standards arena. For ISO TC43, the relevant BSI committee is designated EH/1/7 which has 15 UK underwater acousticians as members, and is chaired by NPL. In the case of IEC TC114, the BSI mirror committee is designated PEL 114, and John Griffiths of EMEC is the Chairman until September 2014.

American National Standards Institute (ANSI)

A US standard is also available for the measurement of noise radiated by commercial vessels in deep water: ANSI/ASA S12.64-2009/Part 1. This standard was the first non-military standard of its type. ISO PAS 17028 is based on this standard.

Interim national guidance

International standards take time to develop because each national committee has the opportunity to contribute to the process. The work of TC43 has only just begun and will take close to three years to be completed. In such cases, where there is a more urgent need, it can be beneficial to produce documents that provide interim guidance at a national level. In the Netherlands, the Dutch government sponsored work led by TNO to develop national guidance on physical quantities and units [TNO 2011a], and on the measurement of noise in connection with offshore wind farms [TNO2011b].

With regard to the UK situation, any initiative should take full account of the existing work underway in ISO and IEC. Standards produced by these bodies are automatically adopted as UK national standards by BSI, and there would be little point in introducing standards that are idiosyncratic and unlikely to be supported by the international community since these will eventually be superseded. Regarding generic guidance on making acoustic measurements in the marine environment, there are some relatively simple directions that can be provided, and initiatives have already begun within The Crown Estate, Marine Scotland and the Department for Business Innovation and Skills (BIS).

With regard to measuring the noise from wave and tidal energy devices, there are still some significant technical difficulties to overcome, and this would benefit from a strategic approach where the lessons learned by the researchers undertaking the earliest measurements are passed on, and where the measured data is more freely available and where the successes (and failures) are shared so that best practice is promoted and mistakes are not repeated.

5. KNOWLEDGE GAPS, RECOMMENDATIONS AND CONCLUSIONS

5.1 KNOWLEDGE GAPS

There have been several other reviews in the last five years into the environmental effect of wave and tidal stream energy developments, and it can sometimes seem that there are more questions than answers when considering the gaps in the knowledge base. For the purposes of the discussion here, we will confine ourselves to issues with the acoustics rather than the biological aspects of the problem. Of course, this does not mean that the biological issues are any less important – in fact the reverse is probably true. Indeed, the sensitivity of individual species to the noise and physical presence of the energy device is a key issue, especially with regard to how the animal reacts in close proximity to the device where the likelihood of significant impact is perhaps greatest. Unlike for other high-energy low frequency impulsive sound sources such as large-scale marine percussive piling, there seems little likelihood of the radiated noise from the construction and operation of wave and tidal stream causing injury to the hearing of marine receptors at substantial range from the source, or causing large displacements of animals over many kilometres.

A number of the studies reviewed as part of this project conclude that the operational noise (and in some cases the construction noise) is analogous to that of a modest vessel and is very unlikely to cause hearing damage, and there would seem no reason to disagree with that conclusion for the devices tested in those studies. However, there are still a number of questions, and some of these relate to the acoustics [Robinson and Lepper 2013].

The following knowledge gaps have been identified during this study:

Source levels

In underwater acoustics, the concept of source level is used instead of acoustic power or energy, but it often causes confusion. Most of the studies reviewed here calculated what is sometimes called an “effective source level” by use of a simple spreading formula applied to the measured data. Such a metric does not just depend on the acoustic output of the source, but also the environment in which the source is placed. The resulting quantity is not “portable” and in general cannot be used to predict the noise field if the source were moved to a new location. The objective when characterising an acoustic source is to calculate a quantity that represents the acoustic output independent of the environment, and this requires the use of a propagation model that accounts for the effect of the environment sufficiently to derive a source level that represents the source output alone. A more sophisticated model requires more input parameters with regard to the local environment (seabed, etc). An alternative would be to “calibrate” the environment by placement of a known characteristic (calibrated) source.

Measurement methodology

The measured methodologies have evolved to adapt to the harsh environments surrounding the wave and tidal energy devices. For example, the use of drifting recorders has proved very effective. However, these can have difficulties of their own when trying to determine source level, and the methodology would be more effective if the drifting systems were augmented by static recording systems, which can measure the temporal stability of the source output. Some standardisation in the methodology would be desirable, to increase the comparability of noise surveys by different researchers (for example, in terms of the use of range-dependent and static recorders/hydrophones and their relative positioning). An example of what is possible was shown by EMEC [2012a].

Source characterisation

Not all individual noise sources present in wave and tidal stream energy devices have been sufficiently well characterised yet in terms of their amplitude and frequency content. The same is true of some of the construction activities (cable trenching, etc). If such sources are low amplitude, then they may not be a significant omission, but until they are measured they will remain an unknown. With such a variety of different designs, any new design should be measured quickly to provide the necessary acoustic characterisation.

Particle velocity and vibration

As with many other sources, little is known about the particle velocity field around the device, or about the vibration of the seabed. Since some fish species are sensitive to particle motion, this may be important. Any effects are likely to be more significant close to the device (in the acoustic near-field).

Scaling up to full arrays

Scaling up the measured data for one device to simulate arrays of devices is challenging. Firstly, the total acoustic output of the array must be calculated, a calculation which will require validation by measurement when the array is deployed. But, new issues begin to emerge, such as the problem of producing a barrier effect in a narrow channel if the overall noise from the array is high enough to deter the animals. The opposite effect would occur if the array devices are so quiet that the animals cannot detect them and avoid them, potentially leading to animals swimming into the array.

The acoustics of collision avoidance – should the devices be noisier?

In order to avoid collision, an animal must be able to detect the device, and this will be easier if the devices are audible. Just how “loud” do they need to be audible enough to deter animals from swimming into the array is an interesting question [Wilson *et al* 2007]. When trying to answer this question, a crucial factor will be the ability to accurately measure the device source level. In the case of collision avoidance for a relatively “quiet” device, the interesting region might actually be the acoustic near-field close to the device. In addition, the directional properties of the source may become important. When close to the device, some species may be able to detect the water movement rather than relying on an acoustic stimulus.

Directivity of radiated noise

The source directivity (or directionality) will start to become important when scaling up device characteristics to simulate an entire array. This is not a parameter that has been considered often before, though some consideration was given to it in by EMEC [2012b].

Background or ambient noise

The background noise at the deployment site is important for determining audibility ranges, and collision mitigation by deterrent through acoustic radiation. Rarely is the background noise sampled over a sufficient timescale to represent the variation of ambient noise at the site. With the advent of commercial-off-the-shelf recorders that can be programmed with an appropriate duty cycle, longer-term deployments are more viable, and the recorders themselves are gradually improving in quality, so longer term deployments are now increasingly achievable.

Uncertainties

Rarely are uncertainties quoted for the measurements made. Impact assessments sometimes consist of drawing lines on the ocean for impact zones without any indication of the likely uncertainty. Partly, the uncertainty comes from the transmission loss, but also it originates with the source level estimate. When measurements are taken of the radiated noise (or ambient noise) the dispersion of measured values should be indicated (eg by use of percentiles) so that the probabilistic nature of the noise is understood.

5.2 RECOMMENDATIONS AND CONCLUSIONS

From the review of the existing data, it is possible to make the following observations:

- There was a lack of a common approach to measurement by different researchers, with a range of methodologies applied;
- The data were rarely reported in a common manner using similar metrics, making it difficult to compare the noise data for different devices, and accurate data for Source Levels were rarely provided;
- The harsh environments (fast tidal flow, strong wave action, etc) pose severe problems for accurate measurements, motivating the need to explore novel measurement techniques.

There are relatively few high quality data sets describing the noise radiated by wave and tidal stream energy devices. Without accurate data for the Source Levels of wave and tidal stream devices, it is very difficult to make *definitive* statements about the likely impact of the radiated noise, for example in terms of zones within which specific exposure criteria are likely to be exceeded. However, it is possible to examine how the radiated noise levels reported compare to other noise sources, and thereby give a general indication of the potential for impact on receptors. In a number of studies reviewed, the operational noise (and sometimes the noise of drilling during construction) is likened to that of a modest sized vessel. This is probably a good analogy to choose, though the operational noise levels quoted in some of the studies are actually lower than the values quoted for other activities such as the transiting of a modest sized vessel, or marine aggregate extraction. It should be noted that marine percussive piling (a high energy, low frequency impulsive source of underwater sound) was not used during construction for any of the studies reviewed here.

In general, background noise levels at sites of wave and tidal stream energy described in the reports are typically at higher levels than classic ‘deep water’ noise curves. The development sites appear to be *naturally* noisier than deeper water sites. This is due to a variety of reasons including additional local sources of noise in the vicinity, severe wave action, local (rather than distant) shipping, sediment transport, etc. The high levels of background noise present will mean that devices with relatively low operational noise output may not be audible to marine receptors even at surprisingly short ranges. This is borne out by some of the reported findings from operational noise surveys where, on some occasions, the received level from the device was below the background noise level once the measuring hydrophone was more than few hundred metres from the device.

The noise radiated during operation is likely to be strongly correlated with the background noise level, since both (at least to a degree) depend on environmental conditions. An example would be wave energy converter systems as they become more energetic in higher sea states, and where the increased surface agitation (creating surf, wind and wave related noise) would also lead to a commensurate increase in background noise levels. Similarly, for tidal stream devices, the acoustic output levels are likely to depend on revolution speed and operational mode, this being related to the tidal flow. Conditions of high tidal flow will cause increased background noise levels due to increased turbulence and sediment agitation. Currently, there is not a good understanding of the potential influence of the changes in radiated noise relative to background noise on the risk of impact. In particular, the relative signal-to-noise ratio (the amplitude of the radiated noise level compared to the background noise) will influence perception capability, and therefore the collision risk.

From the data that were reported in the studies reviewed here, it is possible to draw some conclusions with regard to the likely impact of the radiated noise from wave and tidal stream developments:

- The radiated noise during operation of wave and tidal stream devices is not at a level likely to cause injury to the hearing of marine receptors, even at relatively close range;

- Similarly, the radiated noise during the construction phase of wave and tidal stream devices, though sometimes of greater amplitude than during operation, is also unlikely to cause injury to the hearing of marine receptors;

- Radiated noise during operation and construction is unlikely to cause significant behavioural effects at long ranges from the site development site;

- Accurate data for radiated noise from wave and tidal stream energy devices is important for assessing behavioural response in the vicinity of individual devices and for scaling up to large scale commercial arrays;

- There is currently not a good understanding of the potential influence of the changes in radiated noise relative to background noise on the risk of impact on a range of receptors. In particular, the relative signal-to-noise ratio will influence perception capability, and therefore the collision risk.

From the review, it has been possible to indicate current knowledge gaps and key areas of uncertainty. These include:

- Operational noise source characteristics (acoustic and vibrational) of new and emerging technologies under different operating conditions and modes;

- Relative importance of device noise relative to background noise, particularly in terms of behavioural response;

- Unknown behavioural response of marine receptors to ‘novel’ acoustic signatures provided by these emerging technologies both in terms of individual devices and large scale array development.

Recommendations

Finally, as part of the review, a prioritised list of recommendations has been identified. These provide a program of noise measurements that could reasonably be undertaken to inform future applications for regulatory approval for the deployment of wave and tidal stream energy devices. Where relevant, a description has been given of the likely routes to future standardisation of methodologies for noise measurement.

The main theme of the recommendations is that the approaches adopted should be proportional to the perceived risk, should aim to fill in key knowledge gaps, and should aim at the most cost effective solution. The prioritised recommendations are:

1 Strategic coordinated approach
A strategic coordinated approach should be adopted in devising a measurement programme for the radiated noise during installation and operation (including different operational modes, start up, full capacity, etc) of wave and tidal stream energy devices. This will lead to cost savings in the long-run, will avoid duplication, and allow comparison of data across projects. This would best be achieved if the noise measurement programme were coordinated by a central facilitating organisation, where best measurement practice could be adopted and testing could take place at well-characterised sites (where the acoustic environment is well understood).

2 Type-testing in combination with modelling
For operational noise assessment, consideration should be given to "type-testing" in combination with the use of theoretical modelling where appropriate. Type-testing would be an activity that takes place once at the design testing stage in order to accurately determine the acoustic Source Level and characterise the operational acoustic signature of the machine in differing environmental conditions. The measured data could then be used to validate theoretical models of the noise generation mechanisms, where these are available. Further acoustic measurement would then be required only if significant changes are made to the design, or in order to validate extensions to theoretical models (for example for scaling up to an array). On-going monitoring at each development site would not then be required. However, it is recognised that there are many different designs, particularly of wave energy devices, and each separate design may require initial assessment. With regard to construction, if specific construction activities are likely to cause concern (for example, if marine percussive impact piling is used), then a noise monitoring program may be required during the construction phase.

3 Standard measurement methodologies
Standardised measurement methodologies are needed to accurately derive an acoustic Source Level independent of the acoustic environment for use in predictive models, and to facilitate comparison between different sources measured in different locations. In the first instance, it would be beneficial if generic guidance were provided for making acoustic measurements in the marine environment. It should be possible to reach consensus among expert acousticians on the appropriate metrics to use to describe the acoustic fields, and on the basics of good measurement practice, including uncertainty estimates. There have already been some initiatives in this area, for example those begun by The Crown Estate and Marine Scotland. Secondly, agreed measurement methodologies must be developed for each wave or tidal stream device type. With the technical difficulties posed by the different design of device and the harsh environments, compromises may have to be made, but it should be possible to harmonise the approaches and converge on a common methodology. In the medium to long-term, standards will be provided by international standards committees such as ISO TC43 SC3 and IEC TC114, and the any work begun in the UK must be cognisant of these developments, and ideally the UK work should feed into the development of new standards.

4 Validated modelling capability
Modelling of energy devices, for example using finite element techniques, holds considerable promise and should be encouraged in order to gain a better physical understanding of the radiation mechanisms and contributions of different components of the devices. This approach also allows consideration of future variants or design options before construction and installation. Ultimately these models need to be validated by comparison with empirical data. Close collaboration, (data sharing, analysis feedback, etc) between device developer engineers, modellers and acoustic

measurement teams should be encouraged to quantify acoustic characteristics of new systems under development.

5 Improved measurement technology

Recent developments in acoustic technology have greatly increased the capability for measurement of ocean noise, and encouragement should be provided for new technology developments that address the specific difficulties encountered when making measurements of wave and tidal stream energy devices. Examples of further developments of measurement tools are long-term acoustic data loggers, drifting systems, and static systems designed to mitigate flow noise. The noise measurement technology should ideally be cost effective, robust, simple to install, and scalable to array sizes. The protocols developed under item (3) should not be so constraining that they stifle creativity and innovation – for example the use of new technologies and instruments.

6 Background noise assessment

Background noise at specific sites/locations should be measured by longer-term deployments using new autonomous recorders of sufficient acoustic performance. This could be limited to representative sites that could be used as a proxy for other sites (rather than every development site needing to measure background noise over the long-term). There is also need to consider array-scale spatial variations in ambient sound particularly in tidal areas. Where measurements are undertaken, they should cover the range of environmental conditions likely to be experienced (to match the different operational modes investigated during the radiated noise measurements).

7 Acoustic data exchange

Although commercial sensitivities may occasionally militate against it, regulators should encourage developers to share data and collaborate where possible allowing greater coordination across the industry as new devices and sites are developed. Where possible within commercial restraints, data collected to meet licence conditions should be made available in the public domain to allow developers and researchers to learn from existing work establishing an industry wide pool of data. Any publically-funded research programme should as a matter of course mandate that any data acquired be made public.

8 Acoustic near-field measurements

Where feasible, measurements should be encouraged to include the acoustic near-field of the energy device as well as the far-field. Ideally, these should include measurements of the particle velocity and seabed vibration, since some species show sensitivity to motion rather than sound pressure. However, it is recognised that the technology to undertake such measurements, and the knowledge of appropriate exposure criteria, is immature. In the future, developments in the technology may make such measurements viable, and progress with biological research may enable suitable exposure criteria to be developed

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7. REFERENCES

[AECOM 2009] “Environmental Assessment Registration Document – Fundy Tidal Energy Demonstration Project Volume I: Environmental Assessment”, Fundy Ocean Research Centre for Energy (Minas Basin Pulp and Power Co. Ltd.), prepared by AECOM Canada Ltd, Project Number 107405, June 2009.

[Ainslie *et al*, 2009] “*Assessment of natural and anthropogenic sound sources and acoustic propagation in the North Sea*”, M. A. Ainslie, C. A. F. de Jong, H. S. Dol, G. Blacquière, and C. Marasini, TNO Report TNO-DV 2009 C085, (2009).

[Ainslie *et al*, 2012] Ainslie, M. A., de Jong, C. A. F., Robinson, S. P. and Lepper, P. A. (2012) “What is the Source Level of Pile Driving Noise in Water?”, The Effects of Noise on Aquatic Life, Advances in Experimental Medicine and Biology, vol. 730, edited by A. N. Popper and A. Hawkins (Springer, New York), pp. 445-448.

[Akvaplan-niva 2009] “Operational noise of a 300 kW Hammerfest Strøm tidal turbine at Kvalsund, Norway” report by Akvaplan-niva, 2009.

[Aquatera 2011] “Environmental Monitoring Report- 2011 Installation of monopile at Voith Hydro test berth, Fall of Warness, Orkney”, undertaken by Aquatera for Voith Hydro, Report P362, November 2011.

[Aquatera 2010] “Environmental Monitoring Undertaken during Jack-Up Operations by Voith Hydro at Fall of Warness Test Site, Orkney, Summer 2010”, prepared by Aquatera on behalf of Voith Hydro Report P330, November 2010.

[Arveson and Vedittis, 2000] “Radiated noise characteristics of a modern cargo ship”, P. T. Arveson and D J Vendittis, *J. Acoust. Soc. Am.,* **107**, 118 – 129, 2000.

[Austin *et al* 2009] “Assessment of Underwater Noise Generated by Wave Energy Devices”, Austin, M., Chorney, N., Ferguson, J., Leary, D., O’Neill, C., and Sneddon., H. Technical Report prepared for Oregon Wave Energy Trust by JASCO Applied Sciences, 58 pp, 2009.

[Basset *et al* 2011] “Underwater noise measurements of a 1/7th scale wave energy converter”, Bassett, C., Thomson,J., Polagye B. and Rhinefrank K. in *OCEANS 2011*, pp. 1-6, 2011.

[Beharie and Side, 2011] “*Sub-Sea Acoustic Monitoring - North-West mooring leg installation for the Scotrenewables SR250”,* Beharie, R., and Side, J., Report commissioned by Scotrenewables from International Centre for Island Technology, Report No. 2011/04/SR, 2011.

[Blondel and Williamson 2013] “First analyses of long-term multibeam measurements of the environment around a tidal turbine test site in Orkney, Scotland”, Blondel, P. and Williamson, B. *Proceedings of 1st International Conference and Exhibition on Underwater Acoustics*, Greece, p 1633-1638, 2013.

[Broudic *et al* 2012] “Comparison of underwater background noise during spring and neap tide in a high tidal current site: Ramsey Sound”, Broudic M., Croft T.N., Willis M.R. and Cheong S-H. *Proceedings of the 11th European Conference on Underwater Acoustics*, p 518-525, Edinburgh, 2012.

[Broudic *et al* 2013] "Monitoring underwater ambient noise at marine renewable energy sites: issues and mitigations", Broudic M., Croft T.N., Master, I, and Willis M.R. *Proceedings of 1st International Conference and Exhibition on Underwater Acoustics*, Greece, p 159-170, 2013.

[Carruthers and Marmo 2011] "Device Modelling, Simulation & Vibration Analysis", Carruthers, B. and Marmo, B.A., *Proceedings of the 9th European Wave & Tidal Energy Conference*, Southampton, September 2011.

[Carter and Wilson 2011] "Mapping underwater ambient noise in the Sound of Islay tidal-stream: A potential tidal energy extraction area", Carter, C. and Wilson, B. *Proceedings of the Institute of Acoustics,* vol. **33**, part 5, ISBN 978-1-906913-09-0, 2011.

[Carter *et al* 2012] "Acoustic interactions between marine mammals and marine renewable devices: Mapping underwater ambient noise at Scottish tidal-stream energy sites", Carter C., Wilson, B. and Burrows, M. *Proceedings of the 11th European Conference on Underwater Acoustics,* p 159, Edinburgh, 2012.

[CBTEP 2012] Cobscook Bay Tidal Energy Project; Available online at: http://mhk.pnnl.gov/wiki/index.php/Cobscook_Bay_Tidal_Energy_Project

[Copping *et al* 2013] "Environmental Effects of Marine Energy Development around the World for the OES Annex IV", Copping, A., Hanna, L., Whiting, J., Geerlofs, S., Grear, M., Blake, K., Coffey, A., Massaua, M., Brown- Saracino, J. and Battey, H. 2013. [Online], Available: www.ocean-energy-systems.org.

[Crown Estate 2011] "Wave and tidal energy in the Pentland Firth and Orkney waters: How the projects could be built", Report commissioned by The Crown Estate, prepared by BVG Associates, May 2011.

[Crown Estate 2013a] "Cumulative Impact Assessment in Pentland Firth and Orkney Waters", prepared by AMEC Environment & Infrastructure UK Limited, Doc Reg No. Lea32898r-046, The Crown Estate, June 2013. Available: http://www.thecrownestate.co.uk/energy-infrastructure/wave-and-tidal/pentland-firth-and-orkney-waters/enabling-actions/projects-and-publications/.

[Crown Estate 2013b] "Pentland Firth and Orkney waters wave and tidal stream projects and migratory salmonids", Slaski, R.J., Hirst, D. and Gray, S. (Eplison Resource Management and Bidwells), The Crown Estate, July 2013. Available: http://www.thecrownestate.co.uk/energy-infrastructure/wave-and-tidal/pentland-firth-and-orkney-waters/enabling-actions/projects-and-publications/.

[Crown Estate 2013c] "Ornithological Cumulative Impact Assessment Framework, Pentland Firth and Orkney Waters, Wave & Tidal Projects", MacArthur, D., Furness, R., Trinder, M. and MacArthur, K., prepared by MacArthur Green Ltd, The Crown Estate, May 2013. Available: http://www.thecrownestate.co.uk/energy-infrastructure/wave-and-tidal/pentland-firth-and-orkney-waters/enabling-actions/projects-and-publications/.

[Duncan and Parsons 2011] "How Wrong Can You Be? Can a Simple Spreading Formula Be Used to Predict Worst-Case Underwater Sound Levels?" Duncan, A.J. and Parsons, M.J.G. *Proceedings of Acoustics 2011*, Australia, November 2011.

[EMEC 2012a] EMEC report "Acoustic Noise Measurement Methodology for the Billia Croo Wave Energy Test Site", Lepper, P., Harland, E., Robinson, S., Hastie, G., Quick, N. EMEC Project No: EMEC_ITT_007_09, 2012.

[EMEC 2012b] EMEC report "Acoustic Noise Measurement Methodology for the Billia Croo Wave Energy Test Site: ANNEX A: Summary of operational underwater noise tests for a Pelamis P2 system at EMEC May 2011" (Lepper, P., Harland, E., Robinson, S., Theobald, P., Hastie, G., Quick, N. EMEC Project No: EMEC_ITT_007_09, 2012.

[EMEC 2013a] "Shapinsay Sound Tidal Test Site: Acoustic Characterisation", Harland, E. J. EMEC Report ref. CBA044/12 Issue 4, January 2013.

[EMEC 2013b] "Scapa Flow Wave Test Site: Acoustic Characterisation", Harland, E. J. EMEC Report ref. CBA047/12 Issue 4, February 2013.

[Erbe 2013] "Underwater noise of small personal watercraft (jet skis)", Erbe, C. *J. Acoust. Soc. Am.* **133** (4), p. EL326-330, 2013.

[Erbe *et al* 2013] "Underwater noise from offshore oil production vessels", Erbe, C., McCauley, R., McPherson, C. and Gavrilov, A. *J. Acoust. Soc. Am.* **133** (6), p. EL465-470, 2013.

[Faber Maunsell & Metoc 2007] *Scottish Marine Renewables SEA: Environmental Report Section C Chapter C17: Noise,* Faber Maunsell & Metoc, Scottish Executive, March 2007.

[Garrett et al 2013] "Underwater Sound Levels at a Wave Energy Device Testing Facility in Falmouth Bay, UK", Garrett, J.K., Witt, M.J. and Johanning, L. *Proceedings of the Effects of Noise on Aquatic Life - AN2013*, Budapest, August 2013

[Götz et al 2011] "The impact of SeaGen operational noise on marine mammals and fish at Strangford Lough, Northern Ireland". Götz T., Hastie G., Sparling C., & Mundie D. Report to Marine Current Turbine Ltd. SMRU Ltd.

[Haikonen et al 2013a] "Characteristics of the Operational Noise from Full Scale Wave Energy Converters in the Lysekil Project: Estimation of Potential Environmental Impacts", Haikonen, K., Sundberg, J. and Leijon, M. *Energies,* **6**, p. 2562-2582, 2013.

[Haikonen et al 2013b] "Hydroacoustic measurements of the noise radiated from wave energy converters in the Lysekil project and project WESA", Haikonen, K., Sundberg, J. and Leijon, M. *Proceedings of 1st International Conference and Exhibition on Underwater Acoustics*, Greece, p 199-209, 2013.

[Halvorsen *et al* 2011] "Effects of Tidal Turbine Noise on Fish Hearing and Tissues: Draft Final Report - Environmental Effects of Marine and Hydrokinetic Energy", Halvorsen, M.B., Carlson, T.J. and Copping, A.E. Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830, Pacific Northwest National Laboratory Report PNNL-20786, September 2011.

[Harland-SNH 2013] "Fall of Warness Tidal Test Site: Additional Acoustic Characterisation", Harland, E.J. *Scottish Natural Heritage Commissioned Report No. 563, 2013.*

[Kolar *et al* 2011] "Stream analytical processing of acoustic signals for cetacean studies and environmental monitoring of ocean energy conversion devices", Kolar H.R., et al, *Oceans'11* Santander, 2011.

[KRTSA 2013] Kyle Rhea Tidal Stream Array Environmental Statement, Appendix 12.6: Assessment of underwater noise from construction and operation of the Kyle Rhea Tidal Array, 2013.

[Lewis Wave Power 2012] 40MW Oyster Wave Array Environmental Statement, Lewis Wave Power, 2012.

[Lloyd *et al* 2011] “Modelling techniques for underwater noise generated by tidal turbines in shallow waters”, Lloyd, T.P., Turnock, S.R. and Humphrey, V.F., *Proceedings of the 30th International Conference on Ocean, Offshore and Arctic Engineering OMAE2011,* Rotterdam, June 2011.

[Marmo 2013] “Acoustic modelling of a tidal turbine array – South West Islay”, report by Xi Engineering, 2013.

[Martin *et al* 2012] “Measurement of long-term ambient noise and tidal turbine levels in the Bay of Fundy”, Martin, B., Gerber, A., Whitt, C. and Scotney, M., *Proceedings of the 11th European Conference on Underwater Acoustics,* p 1083-1090, Edinburgh, 2012.

[McKenna *et al* 2012] “Underwater radiated noise from modern commercial ships”, McKenna, M.F., Ross, D., Wiggins, S.M. and Hildebrand, J.A. *J. Acoust. Soc. Am*. **131** (1), 2012.

[McKeown 2011] “Monitoring noise emissions from ocean energy devices”, McKeown, E. *Proceedings of the Institute of Acoustics,* vol 33, part 5, ISBN 978-1-906913-09-0, 2011.

[McKeown *et al* 2012] “Measurement of particle velocity levels at ocean energy sites”, McKeown, E., Yeatman, P., Akhriev, A., Hayes, J., Barry, M. and Purcell, M. *Proceedings of the 11th European Conference on Underwater Acoustics,* p 1091-1097, Edinburgh, 2012.

[Merchant *et al* 2012] “Averaging underwater noise levels for environmental assessment of shipping”, Merchant, N.D., Blondel, P., Dakin, D.T and Dorocicz, J. J. Acoust. Soc. Am. 132 (4), October 2012.

[MeyGen 2012] “MeyGen Tidal Energy Project Phase 1 Environmental Statement”, MeyGen, 2012.

[Nedwell and Brooker 2008] “Measurement and assessment of background underwater noise and its comparison with noise from pin pile drilling operations during installation of the SeaGen tidal turbine device, Strangford Lough”, Nedwell J.R. and Brooker A.G., *Subacoustech Report No. 724R0120* for COWRIE Ltd. ISBN: 978-0-9557501-9-9, 2008.

[Parvin *et al* 2005] “Assessment of Tidal Current Turbine Noise at the Lynmouth site and predicted impact of underwater noise at Strangford Lough”, Parvin, S. J., Workman R., Bourke P. and Nedwell, J.R., SubAcoustech Report No. 628 R 0102, 2005.

[Patricio 2009] “Wave Energy and Underwater Noise: State of Art and Uncertainties”. Patricio, S. *Oceans’09*, Bremen, 2009.

[Patricio *et al* 2009] “Underwater Noise Modelling of Wave Energy Devices”, Patricio, S., Soares C., and Sarmento A. *Proceedings of the Eighth European Wave and Tidal Energy Conference*, Uppsala, Sweden, pp. 1020-1028, 2009.

[Patricio and Soares 2012] “Analysis of underwater noise data from the PICO wave power plant as a complementary tool to analyse operational phenomena”, Patricio, S. and Soares, C. *Proceedings of the 11th European Conference on Underwater Acoustics,* p 289-296, Edinburgh, 2012.

[Polagye *et al* 2011] “Environmental effects of tidal energy development”, Polagye, B., B. Van Cleve, A. Copping, and K. Kirkendall (editors). U.S. Dept. Commerce, NOAA Tech. Memo. F/SPO-116, 181p. 2011.

[Reinhall and Dahl 2011] “Underwater Mach wave radiation from impact pile driving: Theory and observation”, Reinhall P.G. and Dahl P.H. *J. Acoust. Soc. Am.* **130** (3), p.1209-1216, 2011.

[Richards *et al* 2007] “Underwater Noise Study Supporting Scottish Executive Strategic Environmental Assessment for Marine Renewables”, Richards, S.D., Harland, E.J. and Jones, S.A.S. Report no. QINETIQ/06/02215/2, for Scottish Executive Contract No. 97262, January 2007.

[Robinson *et al* 2011] “Measurement of noise arising from marine aggregate dredging operations”, Robinson S. P., Theobald P. D., Hayman G., Wang L. S., Lepper P. A., Humphrey V. and Mumford S. MALSF Report MEPF Ref no. 09/P108, February 2011.

[Robinson *et al* 2013] “Underwater noise generated from marine piling”, Robinson S.P., Theobald P. and Lepper, P.A., *Proceedings of Meetings on Acoustics,* Vol. 17, 070080, p1-10, [DOI: 10.1121/1.4790330], 2013.

[Robinson and Lepper 2013] “Review of underwater noise emitted by wave and tidal stream energy devices”, Robinson, S.P. and Lepper, P.A. *Proceedings of 1st International Conference and Exhibition on Underwater Acoustics*, Greece, p 191-198, 2013.

[Roth et al 2013] “Underwater radiated noise levels of a research icebreaker in the central Arctic Ocean”, Roth, E.H, Schmidt, V., Hildebrand, J.A. and Wiggins, S.M. *J. Acoust. Soc. Am.* **133** (4), 1971–1980, 2013.

[Scottish Power 2010] Sound of Islay Demonstration Tidal Array Environmental Statement, Scottish Power Renewables, 2010.

[Soares, C. *et al* 2012] “Baseline measurement of underwater noise under the SURGE project”, Soares, C., Patricio, S., Zabel, F. and Moura, A. *Proceedings of the 11th European Conference on Underwater Acoustics,* p 401-408, Edinburgh, 2012.

[Skerries Tidal Stream Array 2012] Skerries Tidal Stream Array, Supplementary Environmental Information, Prepared by Marine Current Turbines Ltd on behalf of SeaGeneration (Wales) Ltd, 2012.

[TNO 2011a] “Standard for measurement and monitoring of underwater noise, Part I: physical quantities and their units”, TNO Report TNO-DV 2011 C235, ed. M. A. Ainslie, 2011.

[TNO 2011b] “Standard for measurement and monitoring of underwater noise, Part II: procedures for measuring underwater noise in connection with offshore wind farm licensing” TNO Report TNO-DV 2011 C251, de Jong C.A.F., Ainslie M.A. and Blacquière G. 2011.

[Tougaard *et al* 2009a] “Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (Phocoena phocoena (L.))”, Tougaard, J., Carstensen, J., Teilmann, J., Skov, H. and Rasmussen, P. *J. Acoust. Soc. Am*. 126 (1), p.11-14, 2009.

[Tougaard *et al* 2009b] “Underwater noise from three types of offshore wind turbines: estimation of impact zones for harbor porpoises and harbor seals”, Tougaard, J., Henriksen, O.D. and Miller L.A. *J. Acoust. Soc. Am*. 125 (6), p.3766-3773, 2009.

[Tougaard 2013] "Underwater noise from a wave energy converter is unlikely to affect marine mammals", Tougaard, J. *J. Acoust. Soc. Am.*, *submitted*, *in press*, 2013.

[Van der Graaf *et al* 2012] "European Marine Strategy Framework Directive - Good Environmental Status (MSFD GES): Report of the Technical Subgroup on Underwater noise and other forms of energy". Van der Graaf A.J., Ainslie M.A., André M., Brensing K., Dalen J., Dekeling R.P.A., Robinson S., Tasker M.L., Thomsen F., Werner S., 2012.

[Van der Schaar *et al* 2013] "Changes in 63 Hz third-octave band sound levels over 42 months recorded at four deep-ocean observatories", Van der Schaar, M., Ainslie, M. A., Robinson, S. P., Prior, M.K. and Andre, M. *Journal of Marine Systems*, vol. **116**, 2013.

[Wang *et al* 2007] "An experimental investigation on cavitation, noise, and slipstream characteristics of ocean stream turbines", Wang, D., Atlar, M. and Sampson, R., *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy,* vol. 221, p.219-231, DOI: 10.1243/09576509JPE310, 2007.

[Wang *et al* 2013] "Measurement of radiated ship noise", Wang, L., Robinson, S.P., Theobald, P., Lepper, P.A., Hayman, G. and Humphrey, V. *Proceedings of Meetings on Acoustics*, Vol. 17, 070091, p 1-10, [DOI: 10.1121/1.4792663], 2013.

[Ward and Needham 2012] "Modelling the vertical directivity of noise from underwater drilling", Ward, P.D. and Needham, K. *Proceedings of the 11th European Conference on Underwater Acoustics* p.1241-1247, 2012.

[Willis *et al* 2011a] "Ambient underwater noise in high and low energy flow conditions", Willis M.R., Broudic, M. and Masters I. *Proceedings of 4th International Conference on Wind Turbine Noise*, National Research Council of Italy (CNR), Rome, 2011.

[Willis *et al* 2011b] "A comparison of underwater noise at two high energy tidal stream sites", Willis M.R., Broudic, M. and Masters I. *Proceedings of EWTEC*, 2011.

[Wilson *et al* 2007] "Collision risks between marine renewable energy devices and mammals, fish and diving birds", Wilson, B., Batty R.S., Daunt F., and Carter C. Scottish Association for Marine Science, Report to the Scottish Executive, 2007.

[Wilson *et al* SAMS 2011a] "A baseline acoustic survey of the Fall of Warness tidal test site, and An on-site assessment of the acoustic output of jack-up barge *Pauline*", SAMS-RSL REF: 00104-09, Ben Wilson, Jim Elliott and Caroline Carter Scottish Association for Marine Science, March 2011.

[Wilson *et al* SAMS 2011b] "A baseline acoustic survey of the Fall of Warness tidal test site & assessment of the acoustic output of the vessel *CS Sovereign* during R.O.V. & cable laying operations", SAMS-RSL REF: 00104-09, Ben Wilson, Caroline Carter and Jim Elliott, Scottish Association for Marine Science, March 2011.

[Wilson *et al* 2011] "Going with the flow: A method to measure and map underwater sound in tidal-stream energy sites", Wilson, B., Carter, C. and Norris, J. *Proceedings of the Institute of Acoustics,* vol. **33**, part 5, ISBN 978-1-906913-09-0, 2011.

[Zampolli *et al* 2013] Zampolli, M, Nijhof M.J. J., de Jong C A. F., Ainslie M A., Jansen E H. W., and Quesson B A. J. "Validation of finite element computations for the quantitative prediction of underwater noise from impact pile driving", *J. Acoust. Soc. Am.* 133 (1), p.72-81, 2013.

Appendix A – Basics of Underwater Acoustics

This appendix introduces some basic underwater acoustic concepts for consideration when assessing and interpreting the potential for impact on marine life arising from underwater noise related to marine renewables.

Metrics and units
Two primary acoustic amplitude parameters have been widely used in the UK relating to impulsive sounds. These are peak-to-peak pressure, and Sound Exposure Level (SEL) (Southall *et al.* 2007). In addition, for some exposure criteria, the zero-to-peak pressure level has been used (Southall *et al.* 2007).

The peak pressure refers to the pressure amplitude of the pulse, often described as the peak positive pressure. Peak-to-peak pressure is also used which is usually taken to be the difference between the peak positive pressure and the peak negative pressure of the pulse. It is common to state these levels in decibels (dB) as a zero-to-peak pressure level (PPL) for peak pressure referenced to a zero-to-peak pressure of 1 μPa. Strictly, the use of decibels for peak levels of pulsed waveforms is controversial because decibels were originally used only for power-related quantities. However, the usage has become common practice.

The SEL is a measure of the pulse energy content and is calculated from the integral of the squared sound pressure over the duration of the pulse (Madsen 2005; Ainslie 2011). It is also used to express the overall exposure (hereafter SEL dose), which in this case is done by summation of sound exposure levels of the entire duration of the exposure. The SEL can also be expressed in dB notation, referenced to 1 $\mu Pa^2 \cdot s$.

It should be noted that the metric used for continuous sounds is different to those used for impulsive sounds. For continuous noise such as vessel noise or operational turbine noise, the Sound Pressure Level (SPL) metric would normally be used which by convention describes the root mean square (RMS) level over a one second interval referenced to an RMS pressure of 1 μPa.

Zero-to-peak pressure level (PPL)

For a specific pulse or waveform, the peak pressure level, *PPL*, is defined as the absolute value of the zero-to-peak pressure of the pulse and can be expressed as the zero-to-peak pressure level (or peak pressure level, PPL) in units of dB re 1 μPa:

$$PPL \quad = \quad 20 \log \left\lfloor \frac{P_{zero-to-peak}}{P_0} \right\rfloor$$

where P_0 is the zero-to-peak reference pressure of 1 μPa.

Peak-to-peak acoustic pressure

For a specific pulse or waveform, the peak-to-peak pressure, $P_{pk\text{-}pk}$, is calculated from the difference between the peak positive or maximum pressure p_{max} and the peak negative or minimum pressure p_{min}:

$$P_{pk-pk} \quad = \quad p_{\max} - p_{\min} \,.$$

Since the peak negative pressure has a negative value, the peak-to-peak pressure is equivalent to the sum of the magnitudes of the peak positive and peak negative pressures. The value is usually expressed as the peak-to-peak pressure level in dB re 1 μPa. This level is calculated from:

$$PL_{pk-pk} = 20\log\left[\frac{P_{pk-pk}}{P_{0\,pk-pk}}\right]$$

where P_0 is the peak-to-peak reference pressure of 1 μPa.

The use of peak-to-peak pressure has previously been adopted for UK marine piling measurements, especially for measurements reported on early wind farm projects. However, it should be noted that this metric has not been widely adopted outside of the UK or by the recently drafted EC Marine Strategy Framework Directive (MSFD), Descriptor 11 for underwater noise (MSFD, 2008). The MSFD has adopted the peak SPL (in addition to the SEL) defined as the zero-to-peak amplitude of the pulse (PPL).

Sound Pressure Level (RMS SPL)

The more common convention in underwater acoustics for expressing Sound Pressure Level (SPL) is for it to be expressed as a root mean square (RMS) value. The RMS value is a time-averaged pressure value, which allows the SPL to be related to the time-averaged acoustic power (the original use of the decibel notation is for expressing power ratios) (Carey 2006). This causes little problem for sinusoidal waveforms where there is a fixed relationship between the peak value of a sine wave and the RMS value. However, for pulse waveforms, there is no general relationship between the peak of the pulse and the RMS value (the RMS value for a pulse depends on the pulse length, which depends on the pulse shape, the decay time, *etc.*) (Madsen 2005; Ainslie 2011). *This can cause confusion and make comparisons between pulse type sounds and continuous type sounds meaningless even though they appear to be described using the same units.*

For this assessment, the root mean square of the sound pressure is used when considering continuous type noise sources such as turbine operational noise and can be expressed in units of dB re 1 μPa and is calculated from:

$$RMS\ SPL = 20\log\left[\frac{P_{RMS}}{P_0}\right]$$

where P_0 is the RMS reference pressure of 1 μPa.

Sound Exposure Level (SEL)

For a pulse of sound, SEL is related to the sound energy in the pulse and is calculated by integrating the square of the pressure waveform over the duration of the pulse. The duration of the pulse is defined as the region of the waveform containing the central 90% of the energy of the pulse. The calculation is given by:

$$E_{90} = \int_{t_5}^{t_{95}} p^2(t)\,dt$$

The value is then expressed in dB re 1 μPa^2·s and is calculated from:

$$SEL = 10 \log \left[\frac{E_{90}}{E_0} \right]$$

where E_0 is the reference value of 1 μPa^2·s.

Note that for a plane-wave in a free-field environment (an unbounded medium), the pulse pressure squared integral in μPa^2·s can be converted to units of energy flux density in J/m2 (joules per square metre) by dividing the cumulative squared acoustic pressure by the specific acoustic impedance, Z, of the medium, the specific acoustic impedance being the product of medium density and sound speed in the medium (ρc). When expressed in decibel notation, this means that 0 dB re 1 J/m^2 is equivalent to 182 dB re 1 μPa^2·s in water. Note also that the definition above uses the central 90% of the energy in the pulse, i.e. the pulse duration is defined as the time occupied by the central portion of the pulse, where 90% of the pulse energy resides. This is because it can be difficult to determine the exact start of the pulse when the waveform contains noise. For the 100% value of SEL, it would be necessary to add 0.45 dB to the 90% value.

The SEL for each impulsive noise event can also be aggregated by summation to calculate the total SEL (or SEL dose) for the entire sequence (Southall et al. 2007; Theobald et al. 2009). The concept of SEL dose is entirely analogous to the use in air acoustics to quantify the total noise dose for a subject receiver. The pulse duration is defined as the time occupied by the central portion of the pulse, where 90% of the pulse energy resides.

The calculation of the pulse duration and SEL are described graphically in Figure A.1. Figure A.1-A shows a typical pulse waveform (from a piling strike), and Figure A.1-B shows a plot of the normalised energy in the pulse waveform against time. Indicated on the plot are the 5% and 95% energy levels and the t5 and t95 times that define the pulse duration.

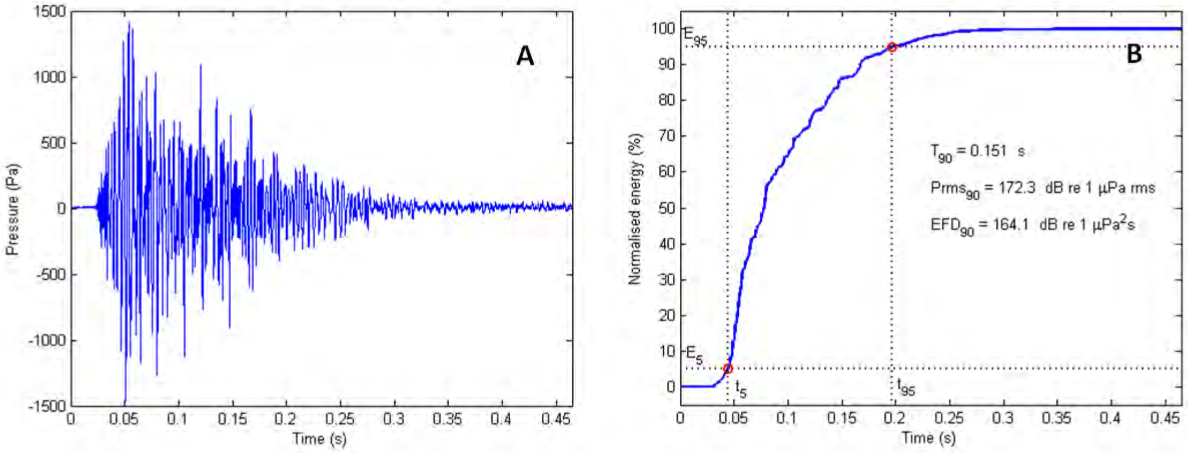

Figure A.1 – A: Example of pulse time waveform for analysis, and B: Calculation of SEL over pulse duration.

A SEL metric may also be used for continuous (non-pulsed) noise sources. In this case the energy across a frequency band is integrated across a fixed time period rather than an estimate of the pulse duration, often 1 second is used (Southall et al 2007). As with assessment of SEL from impulsive sources these can be aggregated by summation to calculate the total SEL (or SEL dose) across a longer exposure period.

In both cases (impulsive or continuous) a clear statement of the calculation methodology being used is required.

Source level

A metric used frequently in underwater acoustics to describe the source output amplitude is that of Source Level (SL), a term not commonly seen in air acoustics where the acoustic power or energy is commonly used. This term originates from sonar engineering, and as with acoustic power, the Source Level may be considered as a characteristic of the source that describes the acoustic output of the source itself independent of the environment into which the source is radiating. The decibel units for this quantity may sometimes be written as dB re 1 µPa·m; however, the unit is much more commonly seen expressed as dB re 1 µPa at 1m in spite of this not being an SI unit. This convention can appear confusing, and the units may more clearly be written as dB re 1 µPa referred to 1m. It should be noted that Source Level is an idealised acoustic far-field parameter and is not necessarily equal to the acoustic pressure or received level measured at a distance of 1 m (1 metre) from the source. Instead, it may be considered as the SPL that would exist at a nominal range of 1 m from the acoustic centre of an equivalent simple monopole source, which radiates the same acoustic power into the medium as the source in question (Ainslie 2011). However, for real sources which are acoustically large (such as occurs for marine piling), the value of the Source Level will not be equivalent to the SPL at the reference range of 1m.

In practice, for real sources, the Source Level is calculated by measuring the received level at a distance from source which is in the acoustic far-field and propagating the acoustic pressure back to the reference distance of 1 m from the acoustic centre of the source using an appropriate propagation model. The measurement distance is required to be in the acoustic far-field, which is related to both the dimensions of the source and the wavelength of the sound. Indeed, for large distributed sources, this reference distance of 1 m may be in the acoustic near-field (or sometimes even inside the source). In the near-field region, the sound field amplitude fluctuates due to interference between the waves that radiate from different parts of the source.

It should also be noted that propagation of sound in the ocean rarely corresponds to simple spreading laws. This is especially true in shallow water typical of marine renewable energy devices. In general, source level (SL) may be given by:

$$SL = RL + PL \,,$$

where RL is the received level in the acoustic far-field and PL is the propagation loss (dependent on frequency, seabed, bathymetry, etc).

Estimation of Source Level from sound pressure measurements in shallow reverberant channels is not straightforward since an estimate must be made of the true propagation loss (sometimes termed transmission loss), which is complicated by the interactions of sound with the seafloor and sea surface. An important fact to note is that the source levels for marine renewables (both construction and operational noise) reported in some previous studies, have often been obtained by extrapolation back to the source using simple spreading formulae. This means that these reported values are not true Source Levels and are generally not consistent with the accepted definition of source level by Urick (1983) and others (Ainslie 2011). This means that comparisons may not be possible with other sources measured in deep water. To distinguish between formats, data derived from simple spreading formulae are referred to as “Effective” Source Level.

Source level might be expressed in a number of ways, for example in terms of SPL (in units of dB re 1 µPa referred to 1 m), or for impulsive sound sources, in terms of energy or SEL (units: dB re 1 $\mu Pa^2 \cdot s \cdot m^2$).

Propagation/Transmission loss

Propagation Loss (PL) or Transmission Loss (TL) is the term used to describe the reduction of the sound level as a function of distance from an acoustic source. The mechanisms by which the sound intensity reduces are primarily geometrical spreading, sound absorption in the water and losses into the seabed or other boundaries. In shallow water, particularly with varying bathymetry, this can be quite complicated due to multiple interactions with the surface and seabed. In shallow water, the depth can also restrict the propagation of lower frequency.

It is normal for propagation/transmission loss to be stated as a positive number in dB representing the loss for the total range between the reference distance (1 m for Source Level) and the receiver location. The quantity is a function of frequency, and depends on seabed type, bathymetry, surface roughness, sound speed profile etc.

Received level

The received level (RL) is the acoustic pressure measured by a hydrophone at some distance away from a sound source. It is also considered to be the SPL that is “seen” by any acoustic receptor which is exposed to a sound.

The received level might be expressed in a number of ways, for example as a sound pressure level (dB re 1 µPa) or a sound exposure level (dB re 1 $\mu Pa^2 \cdot s$).

When predicting received levels from estimated source levels, the received level is simply determined by subtracting the transmission loss *or propagation loss* in dB from the source level in dB, RL = SL – TL, where the TL is estimated using a transmission loss model (see below). This calculation must be done at each frequency of interest (often this is done at third-octave frequencies). When the source level is estimated from measured received levels then the source level is simply found by addition of received level and transmission loss, SL = RL + TL. To calculate TL accurately requires an accurate model for the propagation of the sound and its interaction with the seabed and sea surface. Sometimes, the TL is empirically estimated from the measured received level data as a function of range. Ideally the TL should still be estimated by fitting an appropriate transmission loss model capable of accurately modelling propagation for a complex environment.

Sound propagation modelling

Environmental dependence
Perhaps even more so than for airborne sound, noise levels in the ocean produced by human activities are determined not only by the acoustic power output of the source, but equally importantly by the local sound transmission conditions. A moderate level source transmitting over an efficient propagation path may produce the same received SPL as a higher level source transmitting through a lossy propagation path. In deep water, variations in water properties strongly affect the sound propagation (for example, by leading to significant sound speed variation with depth). In shallow water, effects due to the surface and bottom become more influential. Variations in bathymetry (depth) can have a significant effect on the transmission of the sound, and for noise from marine renewable energy devices, significant proportions of the sound may be transmitted through the seabed itself.

The sound speed profile may be divided into several layers. Just below the surface is what is sometimes called the surface layer where the speed is susceptible to daily changes due to heating, cooling and wind action. This is followed by a seasonal thermocline, a region characterised by a negative sound speed gradient due to the decrease in temperature with depth. Below the main thermocline and extending into the deep ocean is the deep isothermal layer, which is roughly constant in temperature at about 4 ºC. In this layer, the sound speed increases with depth due to the increasing hydrostatic pressure. Between the thermocline and the isothermal layer is a sound speed minimum, toward which sound tends to be bent by the action of refraction. Some of the sound from a source placed in this channel can be trapped within the channel and travel great distances without suffering significant losses due to surface or bottom reflections. Whilst spreading losses will still occur, they are reduced from spherical spreading and in certain cases may approximate to cylindrical spreading. The variation with salinity is less of an influence in deep water, but can have a strong influence where water layers of different salinity are mixing, for example at the estuaries of fresh-water rivers.

In shallow water around the UK coast, the sound speed is less likely to vary strongly with depth due to the shallow conditions, and the often rapid tidal flow which leads to a mixed isothermal water column.

The sound speed is such an important oceanographic parameter that it is routinely measured as a function of depth. This may be done using an instrument such as a velocimeter, which measures the time for a high frequency pulse to travel over a known path. Alternatively, a measurement is made of the conductivity (to derive salinity), temperature and depth using a CTD meter with the sound speed calculated form empirically-derived relationships.

Shallow water specific environmental dependence

One effect not always appreciated is that shallow water channels do not allow the propagation of low frequency signals due to the wave-guide effect of the channel (Urick 1983; Jensen *et al.* 2000). This effect means that there will be a lower cut-off frequency, below which sound waves will not propagate (instead the sound generated propagates into the sea-bed).

For an idealised water channel consisting of a rigid bottom and a pressure-release surface, the cut-off corresponds to a quarter-wave resonance. However, for a realistic seabed, a slightly more complicated formula depending on the ratio of sound speed in the bottom to that in the water can be used (Urick 1983). The result of plotting this formula is shown in Figure A.2. The effect of the loss of sound from the water column due to shallow water is sometimes referred to as ‘mode-stripping’.

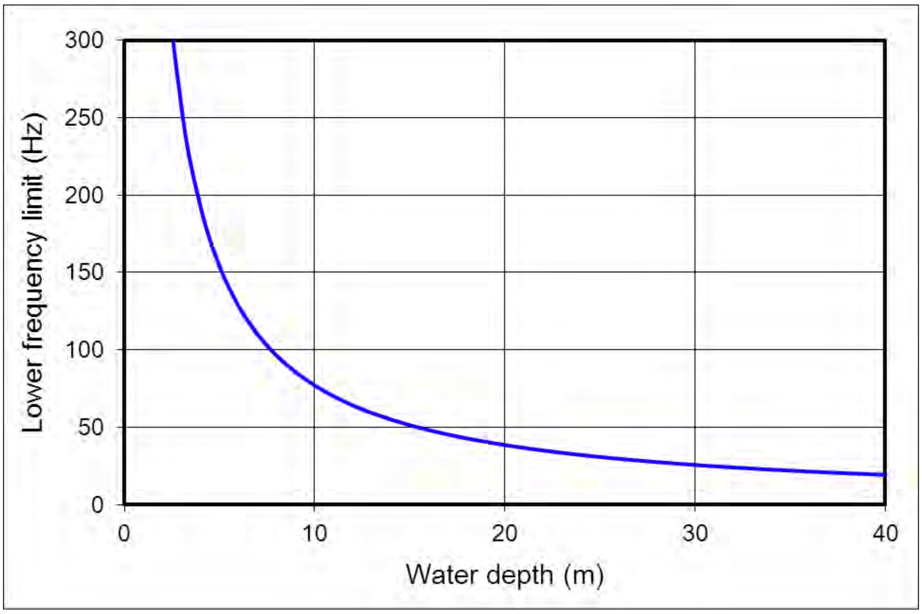

Figure A.2: The lower cut-off frequency as a function of depth for a shallow water channel with a seabed sound speed of 1702 m/s (sand) and water sound speed of 1490 m/s.

It can be seen from Figure A.2 that for an approximate water depth of 20 m, frequencies below around 40 Hz would not be expected to propagate through the water.

Types of propagation model

The wave equation describing the propagation of an acoustic field is often difficult to solve in real-world situations. A good model describing the propagation of sound in the ocean should take into account:

- The interaction with the sea-surface;
- The interaction with (and transmission through) the sea-bed;
- The refraction of the sound due to the sound speed gradient;
- Absorption of the sound by the sea-water and the sea-bed;
- The geometrical spreading of the sound away from the source; and
- Relative source and receiver depth.

One common approach is to use a method of normal modes, often applied in cases where the sound speed is stratified (changes vertically with depth but not horizontally with range). The normal mode method is useful to calculate the field in shallow water where the water column acts as a waveguide for a limited number of propagating modes. The theory can be expanded to account for different types of sea-bed (assuming the properties are known), and variations in sound speed gradients. The problem of solving the wave equation for range dependent conditions such as sloping or irregular bottoms and range-varying sound speed profiles has been overcome by a number of numerical methods including for normal mode methods. Another approximation which provides a range-dependent solution is called the parabolic equation. Here, small incremental changes in range and depth are used to accommodate changes in propagation parameters without the occurrence of large errors. However, in deep water with large numbers of modes propagating, the method is computationally demanding (Lurton 2003; Richardson *et al.* 1995). The Parabolic Equation method provides a frequency domain solution for transmission loss and can provide distance and depth dependent transmission loss predictions. An alternative approach which can prove useful for broadband impulsive sounds is to use a time-domain approach such as a finite-difference method. This method has been used extensively in the geophysical surveying industry.

In water deep enough for propagation of ten or more modes, ray theory may be used. This requires that the sound speed changes slowly, with little change over a distance of one acoustic wavelength, making it best suited to the higher frequencies (and thus smaller wavelengths). The sound field is calculated by tracing ray paths, starting from the source, at uniformly spaced angular intervals. For each increment in range, the ray direction is determined from the ray equations and the local gradient of sound speed versus depth. This method is useful in deep water, where a small number of rays transmit most of the acoustic energy from source to receiver, where there is a direct path from source to receiver, and where only a limited number of surface and bottom reflections contribute. For shallow water, the large number of reflected paths makes the method somewhat impractical (Lurton 2003; Richardson *et al.* 1995).

In simple cases, acceptable accuracy may be obtained by use of relatively simple geometrical spreading models. Commonly used models include spherical spreading (in decibel notation, this corresponds to a reduction in received level with range, r, of "20.log(r)"), or cylindrical spreading, (corresponding to a reduction in received level with range of "10.log(r)"). In practice, the spreading may lie somewhere between these two geometries and be described by "N.log(r)" where N typically has a value between 10 and 20. Such simple models do not include the effect of absorption in the medium. This may be included in a simplified manner by introducing an extra term, which describes the reduction due to absorption with range (leading to a term of the type "$\alpha.r$" where α is the absorption in dB per meter). A composite model of this kind would then be used to calculate the received level (RL) from the source level (SL) by: $RL = SL - N.\log(r) - \alpha.r$ (Nedwell *et al.* 2007a). This type of model can also be adapted to include frequency dependent attenuation (Thiele 2002; Thomsen *et al.* 2006). Such a model may be used to calculate the difference in propagation loss between two ranges in the far-field of the source, but in order to account for the propagation close to the source itself, a constant term must be added (a term which includes the water depth at the source position).

Comparisons of models

Simple "lumped parameter" spreading models which incorporate simplified absorption, and conform to the general type "$RL = SL - N.\log(r) - \alpha.r$", have been used in previous UK studies which attempt to estimate the likely noise levels generated by marine renewable energy developments (Nedwell *et al.* 2007a). These models have the advantage that they do not require a large amount of input data (only values of N and α), are simple to compute for measured values of received level versus range, and may be set up to replicate the apparent transmission loss of the sound measured during piling operations at other wind farm sites. However, the limitations of these models should be considered carefully. Such a model does not account for transmission loss effects due to changes in bathymetry, and so cannot (for example) predict the extra reductions in level caused by sand banks and shallow coastal areas (for example due to the effect of mode stripping). In addition, such models do not include reverberation or consider the sound transmitted through the sediment, except in a highly simplistic way (e.g. by use of a composite value of α). Such a model is also frequency independent if it is applied to a time-domain parameter such as peak-to-peak sound pressure. This means it will depend only on range from the source. In practice, the transmission of sound in shallow water will show a strong dependence on frequency due to the modal nature of the propagation and the frequency-dependent absorption in the water and in the sediment. These phenomena will cause the time waveform to distort during propagation away from the source, typically causing a dilation of the acoustic pulse (an increase in pulse duration) and a reduction in high frequency content.

For the very shallow water environments, the normal mode and Parabolic Equation approach outlined above has the potential to provide good accuracy. This method can be made to incorporate the effects of variable bathymetry, sound speed profiles and frequency dependent absorption. However, such models do require a large amount of input data to describe the bathymetry, sound speed profiles, and sediment properties in the local area. Such information may not always be available, and any model is only as accurate as its input data. In addition, to describe the propagation of short broadband pulses, typically this type of model would be run at a number of discrete frequencies in order to predict the transmission loss at all the frequencies present in the pulse, and this requires greater computational power (and time).

It should also be noted that the accuracy of any model depends on accurate representation of the source. The source in the case of WEC and TEC systems as with marine piling is likely very complex. In the case of piling with noise being radiated from the surface of the pile itself, and with noise also being launched directly into the sea-bed by the impact of the pile through the sediment. Currently, a perfect model does not exist for such complex distributed sources, and representations of the source in terms of simplified idealised sources such as point sources and line sources will inevitably limit the accuracy of predictions. This is particularly true for the acoustic field close to the source if the source is large (in the near-field), and possibly for greater ranges where sound propagating through the sea-bed re-enters the water column.

Appendix B - Effects of Sound on Marine Fauna

Potential effects of sound on marine fauna

Underwater sound can potentially have a negative impact on marine mammals and fish ranging from changing their acoustic habitat to scaring them away and even causing physical injury. In general, biological damage as a result of sound is either related to a large pressure change (barotrauma) or to the total quantity of sound energy received by a receptor. Barotrauma injury can result from exposure to a high intensity sound even if the sound is of short duration, such as an explosion. However, when considering injury due to the energy of an exposure, the time of the exposure becomes important. For example, a continuous source operating at a given sound pressure level has a higher energy and is therefore more damaging (Southall *et al.* 2007) than an intermittent source reaching the same sound pressure level. The harmful effects of high-level underwater sound can be summarised as lethal, physical injury and hearing impairment. Other ways in which sound or noise can be detrimental to the marine mammals and fish is by causing behavioural disturbance and auditory masking.

Injury and hearing impairment

High exposure levels from underwater sound sources can also cause hearing impairment. This can take the form of a temporary loss in hearing sensitivity, known as a Temporary Threshold Shift (TTS), or a permanent loss of hearing sensitivity known as a Permanent Threshold Shift (PTS). For transient and continuous sounds the potential for injury is not just related to the level of the underwater sound and the hearing bandwidth of the animal, but is also influenced by the duration of exposure. For example, for two separate piling events where the total energy expended inserting the pile is the same, but one with a lower blow energy but a higher number of strikes and one with a higher blow energy and fewer hammer strikes, the overall noise dose of the animal would be expected to be the same, assuming that the animal does not move and that the sound energy in each sound pulse is linearly proportional to the hammer energy. However, if the animal were to flee the sound at its onset, then the lower blow energy example would be expected to result in a lower overall exposure to the sound and thus reduce the likelihood of TTS or PTS.

Behavioural

At levels where the underwater sound wave may not directly injure animals or cause hearing impairment, the underwater sound may have the potential to cause behavioural disturbance. Studies of the behavioural response of marine species to sound describe a variety of different behavioural reactions, and a general consensus for criteria has been slow to emerge. However, there is general agreement that the hearing sensitivity of the animal should be taken into account with a frequency weighting applied to the received levels. This approach has been recommended by a Marine Mammal Noise Criteria Group, set up to review the subject in the USA (Southall *et al.* 2007). Some COWRIE funded work in the UK suggested the use of a similar approach using frequency weighting (Nedwell *et al.* 2007b). Frequency weighting provides a sound level referenced to an animal's hearing ability either for individual species or classes of species, and therefore a measure of the potential of the sound to cause an effect. The measure that is obtained represents the perceived level of the sound for that animal. This is an important consideration because even apparently loud underwater sound may have no effect on an animal if it is at frequencies outside the animal's hearing range.

Further work funded by COWRIE in the UK has considered the use of piling playback sounds to caged fish which has provided an indicator of levels which might provoke a behavioural response for both cod *Gadus morhua* and sole *Solea solea* species (Mueller-Blenke *et al.* 2010).

Lethality

Very close to the source, high peak pressure sound levels have the potential to cause death, or severe injury leading to death, of marine mammals and fish. Some of these effects may be considered to be barometric pressure effects due to the shock experienced by the animal, rather than acoustic effects *per se*. There has been considerable research into the levels of incident peak pressure and impulse (integral of the peak pressure over time) that cause lethal injury in species of fish and in human divers. The work of Yelverton *et al.* (1973; 1975 and 1976) on fish, highlighted that for a given pressure wave, the severity of the injury and likelihood of a lethal effect is related to the duration of the pressure wave- i.e. a pulse of the same peak pressure but with a longer duration would be more likely to cause injury. In the Yelverton model, smaller fish are generally more vulnerable than larger ones. Richardson *et al.* (1995) converted Yelverton's expressions for fish mortality into those representative of larger marine mammals.

Auditory Masking

Auditory masking occurs when an unwanted sound or noise may partially or entirely reduce the audibility of a signal which occurs in the same critical hearing band, even if the signal level is above the absolute hearing threshold. Auditory masking can reduce the ability of an animal to communicate or detect predators. For echolocating animals, masking can also reduce their ability to hunt and navigate. However, for example, the short pulse length and relatively low repetition rate of hammer strikes used for marine piling reduce the likelihood of this sound masking out the short, higher frequency vocalisations of marine mammals. Potential operational noise from WEC and TEC systems as from a wind turbine will likely generate continuous type noise signal but these are generally considered to be relatively low in level and such that impact is restricted to a relatively small area. For harbour porpoise specifically wind farm operational noise is believed to be too low in level and frequency to cause masking problems (Tougaard and Henriksen 2009).

Audibility

The audible distance or the physical range over which marine species can hear the noise will extend to the distance that the sound either falls below the ambient perceived sea noise level or the auditory threshold of the animal. Whether the sound is audible to an animal is not usually a consideration used for impact assessment, since impact is usually judged in terms of physical or behavioural effects triggered at levels that exceed mere audibility thresholds, which may already be within the ambient noise level. There may be no consequence, negative or otherwise, of the animal hearing the sound. An interesting extension to this currently being considered is the potential importance of *audibility* in presence of other risk factors such as collision risk. In this case ability to hear a system may be important in collision avoidance.

Audiograms

For an estimate to be made of whether an animal will be affected by an underwater sound, the hearing sensitivity of the animal must be considered. If the sound is composed of frequencies which do not lie within the reception bandwidth of the animal, the impact is likely to be negligible. For example, a sound at an ultrasonic frequency of 50 kHz will not be heard by a human observer.

It is therefore advantageous to apply weighting to the received sound pressure level according to the sensitivity of the exposed animal. This is most commonly done by making use of audiometric data for the animal of interest. For example, for humans in air, a frequency weighting which incorporates the relative frequency response of the human ear is commonly used to assess the effect of noise on humans. The most widely used metric in this case is the dB A-weighting which incorporates the frequency weighting and was originally based on the 40-phon Fl*etc*her-Munson human hearing curves (Burns, 1973). The A-weighting curve was most recently updated in 2003 and is the subject of an international standard (ISO 226:2003). It should be noted that in obtaining internationally agreed equal loudness curves which have resulted in the standardisation of the A-weighting curve, there have been several studies which in some cases vary to a large degree.

Audiogram techniques

Audiograms are a representation of the hearing sensitivity of a subject as a function of frequency. These are presented as the sound pressure levels required for the subject to just perceive the sound (hearing thresholds) or more commonly to perceive the sound with a certain loudness (e.g. for a loudness of 40 phon).

To determine an audiogram for an animal requires a technique which does not rely on direct cognitive compliance. The animal cannot be asked whether the sound is perceptible. Two principal techniques have been commonly used. The first often relies on behavioural response and requires the animal to be trained to perform a task in response to an aural stimulus. This can only be used for animals that can be trained. The second method involves measurement of the evoked auditory potential which is the electrical impulse in the auditory nerves that results from the sound being heard by the animal. In this approach, electrodes are attached to the animal to measure the electrical response to the sound directly.

Audiogram data

The audiogram data shown here has been chosen to match the data used in previous UK studies to estimate the impact of wind farm construction noise on marine life. Specifically, the data cited in the study by Parvin *et al.* (2006) have been used. A number of other audiometric studies have been undertaken, for example those by Finneran *et al.* (2000; 2002a and 2002b) which have not been used here although Finneran’s work has been used extensively in marine mammal exposure criteria. Audiometric data is very limited and where no audiometric data exists for a species, another species is often taken as a surrogate. For example, data does not exist for sole and so another flatfish, dab *Limanda limanda* is often used instead. Similarly, though striped dolphin *Stenella coeruleoalba* may not be prevalent in an area, good audiometric data is available and it may be considered (at least provisionally) as representative of other odontocetes for which no audiometric data currently exists. However, it should be noted that different species can exhibit significantly different hearing sensitivity, so this is a crude (though necessary) approximation.

Figure B.1 shows audiograms for selected species of cetaceans, Figure B.2 shows the audiograms for some example species of pinniped and Figure B.3 shows the audiograms for a selection of fish species.

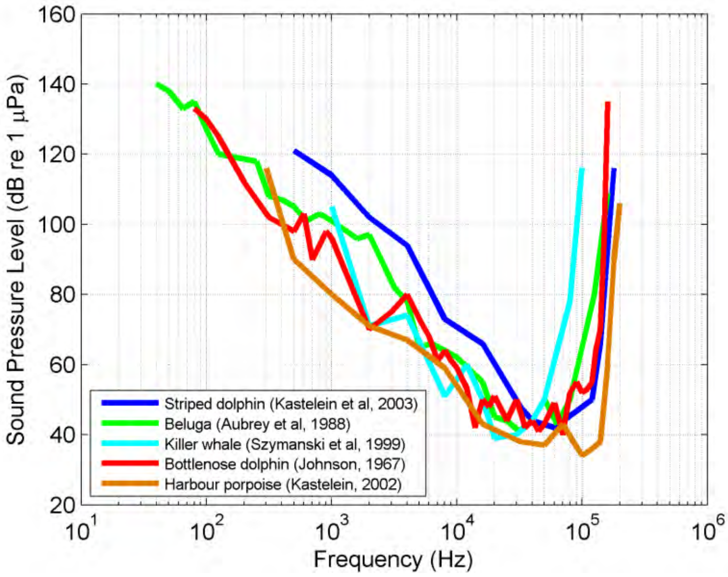

Figure B.1 – A: Hearing threshold data for a range of cetaceans.

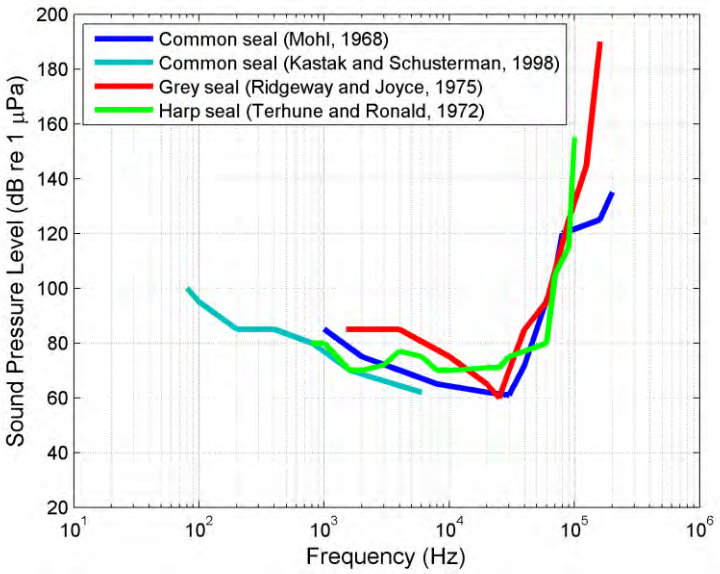

Figure B.2 – B: Hearing threshold data of a range of pinniped species.

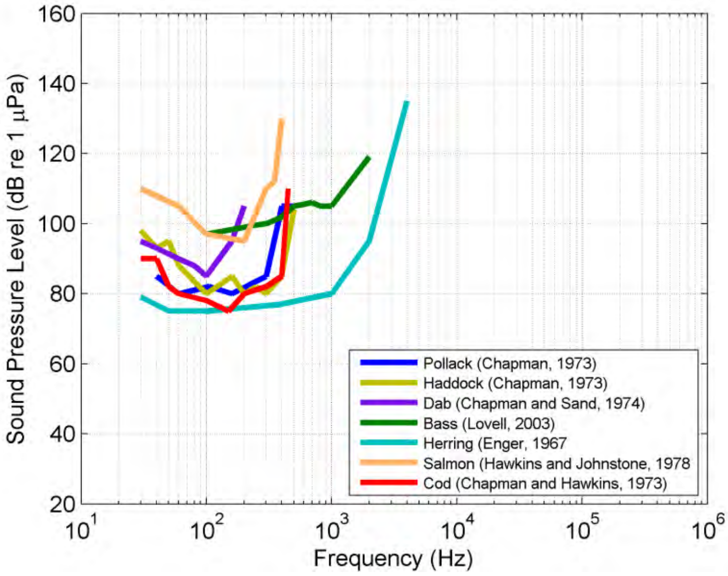

Figure B.3 – C: Hearing threshold data for a range of fish species.

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