Assessment of the marine renewables industry in relation to marine mammals: synthesis of work undertaken by the ICES Working Group on Marine Mammal Ecology (WGMME)

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INTRODUCTION

Marine renewables is a rapidly developing industry. In past meetings, the ICES Working Group on Marine Mammal Ecology (WGMME1) looked at the effects of construction and operation of windfarms (ICES WGMME 2010), tidal devices (ICES WGMME 2011) and wave energy converters (ICES WGMME 2012) on marine mammals[1]. This included an overview of some of the features of renewable energy devices and the distribution and scale of developments in the ICES Area. Further information on these can be found in the respective reports. In addition, in 2010 the WGMME presented an overview of each country's guidelines on monitoring and mitigation of the effects of the offshore wind renewable energy sector. Preliminary guidelines for the wet renewable energy sectors were reviewed in 2011 and 2012. As wet renewable devices are at a relatively early stage of development, so are their guidelines and knowledge of the potential interactions with marine mammals is limited; based purely on first interactions and inferences derived from comparisons with other industries such as offshore wind, fisheries, and oil and gas developments.

This current synthesis summarizes the known and proposed effects of construction, operation and decommissioning of renewable energy devices on marine mammals, highlights information data gaps and presents the main recommendations of the ICES WGMME.

RENEWABLE ENERGY DEVICES

The extraction of energy from the marine environment has many parallels between all three renewable energy sectors; offshore wind, tidal-stream and wave energy. For example, developments will involve the placement of substantial structures into the marine environment,

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[1] Reports can be found at http://www.ices.dk/workinggroups/ViewWorkingGroup.aspx?ID=32

and they require large investment and specialized equipment to place and service them. While there are many parallels there are also fundamental differences between these technologies when considering the potential interactions with large vertebrates in the marine environment. The most obvious difference is that the moving structures that capture energy by tidal-streams and some wave energy converting (WECs) devices are submerged below the water surface. A more subtle difference is that the wet renewable sectors are at a much less advanced stage, and there are currently many different concepts (device types) being simultaneously developed: the technologies being progressed are extremely diverse in size, shape, method of fixing and many other characteristics. This latter point means that it is difficult to be sure of the future relevance of current evaluations of impact and proposals for mitigation. Also the sites required for tidal and wave energy extraction are much more specific than those available for offshore wind. Furthermore, as the water column moves at speed relative to the benthos, they are also fundamentally different in nature for animals operating in these areas compared to other marine areas.

During the construction and operation of renewable energy devices many activities can be identified which may, due to their noise emissions, have an effect on marine mammals; these are among others bottom profiling (seismic surveys and side-scan sonar), ship traffic, pile driving and/or drilling (depending on the device) and other construction activities, and the operation itself. These can possibly cause disturbance to marine mammals by eliciting behavioural responses and habitat exclusion. Pile driving may cause hearing damage at close range and during the operational phase, noise from devices may cause masking of biological significant signals. Long-term effects of chronic exposure of marine mammals to anthropogenic noise are of considerable current interest but research in this field still remains limited (Tyack 2008). Levels of turbation (re-suspension of sediments) or pollution are likely to increase during periods of construction and decommissioning. There is a misconception that the probability of cetaceans failing to detect and avoid a large static structure is extremely low, as they echolocate and are agile and quick moving. However, collision risk is considered to be a key potential effect during wet renewable device operation (Wilson *et al.* 2007) and, looking at the wide range of devices that may be deployed, all species of marine mammals are at some risk of collision impacts. In addition, recently there have been an increasing number of unusual seal mortalities reported in UK waters, consistent with injuries expected from animals being drawn through a ducted propeller (Thompson *et al.* 2010a), and concerns have been raised that harbour porpoises might also be affected (Deaville and Jepson 2011). Vessels involved in renewable device installations need to be able to manoeuvre accurately at small spatial scales, which is typically achieved by using ducted propellers such as Kort nozzles or some types of Azimuth thrusters. Removal of marine renewable devices may involve the use of explosives, which carry an acute risk of hearing damage or mortality, or cutting machinery that may generate high levels of noise. Apart from lethal interactions and potential hearing damage, negative impacts on marine mammals could be identified by changes in parameters such as fecundity, calf/pup survival, and juvenile and adult mortality. The impacts mentioned here are not comprehensive, but are considered of the greatest concern at the present point in time.

The construction and operation of renewable energy devices should ultimately be evaluated in terms of their effects on marine mammal populations, or relevant management units. As the cumulative impacts of renewable energy technology may lead to a decrease in population size, regulations must be population based and take on-board that marine mammals are, on the whole, migratory species. In addition, the deployment of marine renewable energy devices is but one of many concurrent activities that might take place within a given marine area. As this industry is likely to expand (both geographically and in terms of numbers of devices) in the coming years, it will become increasingly important to consider the effects of a number of large marine renewable energy sites being constructed relatively close together in space and time (e.g. southern North Sea) and within the range of the same marine mammal populations; bearing in mind that these populations are also being affected by other local anthropogenic activities and the large-scale impacts of climate change. When passing through multiple areas with marine infrastructure animals will be exposed to a variety of stressors, varying widely in their nature and impact. Those stressors can impact the animals directly (*i.e.* first order effects) or impact animals as secondary order effects (*e.g.*, by changes in abundance of prey). The numerous potential ways (e.g. cumulative and synergistic) in which such multiple stressors can interact remain poorly understood. However, to date research has been limited to within national boarders and therefore it has been difficult to assess the cumulative impacts at the population level.

Most marine mammals are highly mobile and are therefore likely to spend only a small proportion of their time within the effective range of a device or even within an array of these devices. Placement of arrays and subsea cable infrastructure in previously fished areas may result in improved conditions for those marine mammals that choose to enter such areas once they are closed to certain types of fishing, but could result in displacement of fishing effort leading to changes in the wider spatial distribution of bycatch. The effects of an array could potentially be more severe if it were sited in specific areas of habitat of vital importance to particular populations or species of marine mammals. Appropriate marine spatial planning is essential in order to avoid or minimise such conflicts and their potential negative effects on marine mammals.

OFFSHORE WIND TURBINES

Offshore wind farms are amongst the largest offshore engineering projects ever undertaken. They present a range of potential impacts and threats to marine mammals, which may be felt over long periods. They take a considerable period of time to plan and construct, and they should then be operational for several decades before decommissioning or refurbishment is required. Although offshore wind technologies are at a relatively advanced stage compared to other marine renewable energy sectors in terms of their design, knowledge of areas of impact on species in the marine environment and the information required for environmental consenting, there are still significant gaps in our knowledge on their effects.

Each wind farm site is unique. The number and arrangement of devices and the physical characteristic of the site (e.g. sediment type, water depth) vary considerably between projects. They also occur in areas with different populations and densities of marine mammals. Different foundation types require different construction operations producing different types and levels of noise, and levels of turbation (re-suspension of sediments) or pollution. Each device type will vary in requirements and strategies for maintenance and decommissioning. These factors all have implications for environmental impact and underline the need for a case by case evaluation of projects until a more general understanding of effects is available.

By the end of 2009, within western and northern European waters, 36 windfarms were operational in 9 countries, with a total of 796 wind turbines. An overview of the current distribution of windfarms in the North-East Atlantic can be obtained from the OSPAR Database on Offshore Wind-farms. This database is annually updated by the OSPAR Working Group on the Environmental Impact of Human Activities (EIHA), and is available on the OSPAR website (www.ospar.org). See Annex 1 for an overview of the operational, authorized, planned wind-farms in the OSPAR maritime area (correct as of 2011). Within the database, the largest windfarm proposed to date is for German waters, and is composed of 800 tripod turbines.

EFFECTS ON MARINE MAMMALS

When evaluating the impact of windfarms it is useful to separate the assessment into the three phases: construction (including site surveying prior to construction), operation and decommissioning. Decommissioning is fundamentally similar to the removal of other types of offshore structures, such as oil and gas platforms, and will not be covered here in detail; except for mentioning that offshore wind farm developers and licensing authorities should be encouraged to consider decommissioning within the design phase. In UK waters, pile removal is likely to involve excavating the entire pile or cutting off the exposed parts, with the use of explosives unlikely to be approved except under exceptional circumstances (Scottish Marine Renewables SEA 2007, DECC 2011). This review was undertaken in April 2010 and consequently does not include any publications/reports published after that date. For further information on some of the impact studies undertaken in the 2000s see Tables 1 and 2.

CONSTRUCTION

Among the methods currently used for construction, there is little doubt that pile driving constitutes the single most important source of impact. The majority of offshore turbines are monopiles. The foundation is usually a steel tube of 2 to 5 m in diameter (with larger diameter piles being planned for future farms) which is driven into the seabed. Occasionally, alternative constructions such as tripod, jacket or gravity foundations are used. Piles are driven into the bottom by some thousand strokes of strong hydraulic hammers, produced at a rate of 30–60 pulses per minute. The ramming operation lasts from less than one hour to a number of hours per pile, depending on the seabed type. The levels of noise emissions depend on a variety of factors including pile dimensions, seabed characteristics, water depth, as well as impact strengths and duration (Diederichs *et al.* 2008).

PILE DRIVING-CETACEANS

Studies were undertaken during the construction phase of both **Horns Reef I** and **Horns Reef II windfarms** in the Danish North Sea (Brandt 2009, Tougaard *et al.* 2009); see Tables 1 and 2). Both studies measured the acoustic activity of harbour porpoises using passive acoustic detectors (T-PODs) located within the windfarm sites and at stations situated at various distances from the piling events. Both studies demonstrated a decrease in acoustic activity following an individual pile driving event at all stations, including stations located up to 20–25 km from the piling event. The duration of the impact was assessed differently in the two studies and thus may not be directly comparable. For **Horns Reef I** the impact persisted for up to c.6 hours following the completion of an individual pile driving (Tougaard *et al.* 2009), whereas longer-term impacts of up to c.48 hours were detected at **Horns Reef II** (Brandt 2009). These results were corroborated by a T-POD study undertaken at the **Alpha Ventus** test field in the German Bight, which demonstrated an effect extending to c. 20 km from the windfarm site, and lasting for 1–2 days after the completion of each individual pile driving event (Diederichs *et al.* 2009). The large impact area was confirmed by aerial surveys conducted before and during pile driving (Lucke 2010). A smaller study in Moray Firth, Scotland (**Beatrice offshore wind farm**) demonstrated a decrease in acoustic activity of harbour porpoises and also dolphins (bottlenose dolphins and common dolphins) during the month when pile driving was undertaken, compared with periods without pile driving (Thompson *et al.* 2010b). This study did not evaluate the effects of individual pile driving events and the temporal extent of the impact of each pile driving was thus not established.

The study at **Beatrice** had only two stations, one very close to the piling site, the other 40 km away. No reduction in the acoustic activity of small cetaceans was observed at the far station, indicating that the extent of the impact zone was less than 40 km (Thompson *et al*., 2010). There seems little doubt that pile driving of turbine foundations affects the behaviour of harbour porpoises at distances of at least 25 km from the piling site (Brandt 2009, Diederichs *et al.* 2009, Tougaard *et al.* 2009). To date, the extent of the impact zone is thus unknown, but among other factors is likely to be related to the emitted noise energy, which is strongly correlated with pile diameter (Betke 2010). The piles used at **Beatrice** are among the smallest at 1.8 m in diameter, followed by **Alpha Ventus** at 2.5 m and Horns **Reef I and II** at c. 4 m.

While the existence of a behavioural reaction to pile driving noise is well documented for porpoises (i.e. a reduction in echolocation clicks recorded), no work so far has addressed the important questions of what the nature of this behavioural reaction is, and what the consequences may be for the long-time survival of individuals. It is thus relevant to elucidate for example the energetic consequences of the disturbance. Pile driving can disturb animals during their feeding activities, and therefore the degree to which their food intake, and ability to nurse calves, declines during the construction period will determine the true energetic cost of the impact. Even though the disturbance itself, i.e. a single pile driving event, is fairly short term (in the order of maximum 2 hours), it may take 1–2 days following an individual pile driving event before porpoises gradually return to the impact area. However this depends on the number of foundations being piled, and also the intervals between piling.

PILE DRIVING-SEALS

Two studies addressed the impact of pile driving on seals. This study was conducted during the driving (by vibration and not impact driving) of sheet piles in connection to the installation of gravitational foundations at **Nysted offshore windfarm** in the Baltic Sea (Edrén *et al.* 2010). Daily counts of hauled out seals made by remotely operated video cameras showed that 20–60% fewer grey and harbour seals hauled out on days when pile driving was conducted, compared with days without piling. Furthermore, the proportion of the seals in the region which hauled out on the nearby sandbank during the harbour seal pupping period in July (coinciding with pile driving) was significantly lower than both the preceding year and the following year. The most likely explanation is that seals were partly displaced to other haulout sites in the region during pile driving (Edrén *et al.* 2010). Construction coincided with the outbreak of a phocine distemper epizootic. However, the harbour seal population in the western Baltic was not severely affected

(Härkönen *et al.* 2006) and because all haulout sites in the management area were surveyed, this additional factor was taken into account in the analysis.

Research undertaken on the **Egmond aan Zee offshore windfarm** fitted seals with satellite-relayed data loggers (SRDLs), and results indicated an effect from pile driving. During the construction period seals did not approach within 40 km of the windfarm area, whereas they were recorded within the windfarm area both before and after construction.

Table 1. A summary of impact studies undertaken during the construction and operation phases of offshore wind farms. Taken from ICES WGMME (2010).

Name	Locat-ion	Constr-uction year	Foundati-on type	Pile diam-eter	Water depth	No of turbines	Turbi-ne type	Monito-ring	Comments
Horns Reef I	Danish North Sea	2002	Monopiles	3.8 m	6–12 m	80	2 MW	Construction and operation	
Nysted	Western Baltic, Denmark	2002–2003	Gravitational foundations	n.a.	5–10 m	72	2.2 MW	Construction and operation	Sheet piling conducted during construction
Beatrice	Outer Moray Firth, Scotland	2006	4-legged jacket	1.8 m	42 m	2	5 MW	Construction	4 piles per foundation
Egmond aan Zee	Dutch North Sea	2006–2007	Monopiles		18–20 m	36	3 MW	Operation	
Horns Reef II	Danish North Sea	2008	Monopiles	4 m	5–15 m	95	2.3 MW	Construction	Located 15 km from Horns Reef I
Alpha Ventus	German Bight	2009	4-legged jacket and tripod	2.6 m	25 m	12	5 MW	Construction and operation	Transformer platform

ACUTE DAMAGE FROM PILE DRIVING NOISE

Noise levels emitted during pile driving are very high, with sound pressures reaching 200 dB re. 1 µPa peak-peak at 100 m and sound exposure levels of single pulses reaching 180 dB SEL 100 m from the foundation. Such high levels have the potential to inflict temporary or permanent damage to the auditory system of marine mammals (Nachtigall *et al.* 2003, Finneran *et al.* 2005, Kastak *et al.* 2005, Lucke *et al.* 2009). There are no commonly adopted exposure criteria for marine mammals and thus no consensus on which exposure levels are considered safe. The criteria suggested by Southall *et al.*, 2007 are based on permanent threshold shifts (PTS) and levels are thus higher than what others have suggested. Nevertheless, modelling of cumulated sound exposure over the duration of a single pile driving event suggests that levels sufficient to elicit PTS could be reached for both seals and porpoises at distances of around 1 km from the piling site (Brandt 2009). For this reason mitigation measures in the form of ramp up (soft start) procedures and use of acoustic deterrent devices (pingers and seal scarers) immediately prior to piling have been introduced in order to deter animals out of the impact area before piling commences.

The exposure criteria of Southall *et al.* (2007) did not include information about harbour porpoises as this was not available at that time. However, recent results indicate that harbour porpoises may be more susceptible than other odontocetes tested and have significantly lower thresholds for eliciting TTS (temporary threshold shift, Lucke *et al*., 2009).

Table 2. An overview of sources of impact, relevant impact studies, research needs and mitigation measures. Taken from ICES WGMME (2010).

IMPACT	PILE DRIVING	CONSTRUCTION IN GENERAL	OPERATION	SERVICE ACTIVITIES	CHANGES TO HABITAT
Observed effects	Harbour porpoises: Decrease in acoustic activity out to at least 20 km (2; 3; 4; 10) Decreased abundance well beyond construction site in visual surveys during pile driving (6). One study showed decreased porpoise acoustic activity at the piling site (Beatrice), but no significant change at a control site 40 km away (8). Seals: Decreased numbers at a nearby haulout site during piling (5). Indication of avoidance out to 40 km by animals fitted with SRDLs tags (Egmond aan Zee wind farm)	Harbour porpoises: Decreased abundance during construction phase (2; 3; 9; 11). Seals: Limited information. No general effect of construction on haul out behaviour, except a partial displacement to alternative haulout sites in the pupping season (e.g July in harbour seals) (5).	Harbour porpoises: Three studies indicate no negative effect during operation (1; 11; 13). A study from Nysted windfarm demonstrated decreased abundance two years after construction (3). However, a subsequent study did not report variations in abundance between the Nysted windfarm site and adjacent areas (1). Seals: No effect detected in satellite tagged animals, though very few animals were tagged (Egmond aan Zee wind farm)	No evidence of effect but limited information available	Limited information available. One study (13) observed increased harbour porpoise abundance inside an operating windfarm, which may be related to exclusion of fisheries and/or ships.

Impact	Pile driving	Construction in general	Operation	Service activities	Changes to habitat
Significance of impact	Significant risk of hearing damage to seals and harbour porpoises, even under current mitigation schemes. Nature of behavioural impact is unknown, but could be significant.	Partial or complete habitat loss during period of construction. Significance depends on scale of project, abundance of animals and nature of surrounding habitats. Impact beyond the construction site is possible if migration routes are affected but no studies are available on this. Indirect effects through altering local prey abundance have not been assessed to date.	Significance for small cetaceans likely to be low (7; 12). Significance for other species with better low frequency hearing (e.g. baleen whales and seals) is unknown, though could be greater. Impact could be significant if migration routes are affected.	By nature similar to impact from other ship and boat traffic activities. Cumulative effects should be considered, i.e. taking into account other non-construction boat traffic.	Introduction of hard substrata will change prey species composition. Reduction of fishing activities will affect prey abundance and size distribution. Effects on marine mammals have not been assessed. Though significant changes to ice habitats (Baltic Sea) may occur due to foundations and service vessel traffic. This may affect the distribution and abundance of seals.
Research needs	Cumulative effects of several simultaneous pile driving operations in the same area. Elucidation of the nature of behavioural response of seals and cetaceans. Establishment of links between behavioural response and impact on fitness (reduced survival and/or fecundity). Determination of possible links between spectral properties of noise and size of impact area.	Determination of population level effects by temporary habitat loss. Assessment of effects from individual activities during construction.	Determination of extent of habitat loss (if any). Assessment of effect on migration routes (if relevant). Determination of population level effects of partial habitat loss	Establishment of link s between service activities and alterations in abundance /behaviour. Determination of population level effect of disturbance.	Investigation of fine-scale habitat use inside the wind farm to address whether marine mammals exploit the artificial reefs. Determination of net population level effects (positive or negative) of changes in habitat.

Impact	Pile driving	Construction in general	Operation	Service activities	Changes to habitat
Mitigation (if required)	Visual observers only detect some animals and therefore this method alone is not efficient. Ramp up/acoustic deterrent devices partially address acute hearing damage. Reducing impact on behaviour can be undertaken by reducing radiated energy at relevant frequencies or by limiting installation to periods with low marine mammal abundance and/or by changes in methodology.	Construction should occur during periods with low abundance. Further, noise emission from other sources (e.g. ships, boats etc.) should be reduced.	Modification of turbines and foundations to reduce noise emission at relevant frequencies.	Selection of service vessels based on minimizing impact. Larger maintenance operations should be located in periods with low marine mammal abundance.	Changes to design of foundations and scour protection.

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2. Brandt, M. J., Diederichs, A., and Nehls, G. (2009) Harbour porpoise responses to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Final report to DONG Energy. Husum, Germany, BioConsult SH.

3. Carstensen, J., Henriksen, O. D., and Teilmann, J. (2006). Impacts on harbour porpoises from offshore wind farm construction: Acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). Mar.Ecol.Prog.Ser. 321, 295-308.

4. Diederichs, A., Brandt, M. J., and Nehls, G. (2009) Auswirkungen des Baus des Umspannwerks am Offshore-Testfeld „alpha ventus" auf Schweinswale. Husum, Germany, BioConsult SH.

5. Edrén, S. M. E., Andersen, S. M., Teilmann, J., Carstensen, J., Harders, P. B., Dietz, R., and Miller, L. A. (2010). The effect of a large Danish offshore wind farm on harbour and grey seal haul-out behaviour. Mar.Mammal Sci. 26, 614-634

6. Lucke, K. Potential effects of offshore windfarms on harbour porpoises - the auditory perspective. Talk at Pile driving workshop at the European Cetacean Socity meeting, Stralsund, 21th March 2010. 2010.

7. Madsen, P. T., Wahlberg, M., Tougaard, J., Lucke, K., and Tyack, P. L. (2006). Wind turbine underwater noise and marine mammals: Implications of current knowledge and data needs. Mar.Ecol.Prog.Ser. 309, 279-295.

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9. Tougaard, J., Carstensen, J., Bech, N. I., and Teilmann, J. (2006) Final report on the effect of Nysted Offshore Wind Farm on harbour porpoises. Annual report to EnergiE2. Roskilde, Denmark, NERI.

10. Tougaard, J., Carstensen, J., Teilmann, J., Skov, H., and Rasmussen, P. (2009). Pile driving zone of responsiveness extends beyond 20 km for harbour porpoises (Phocoena phocoena, (L.)). J.Acoust.Soc.Am. 126, 11-14.

11. Tougaard, J., Carstensen, J., Wisz, M. S., Teilmann, J., Bech, N. I., and Skov, H. (2006) Harbour porpoises on Horns Reef in relation to construction and operation of Horns Rev Offshore Wind Farm. Technical report to Elsam Engineering A/S. Roskilde, Denmark, National Environmental Research Institute.

12. Tougaard, J., Henriksen, O. D., and Miller, L. A. (2009). Underwater noise from three offshore wind turbines: estimation of impact zones for harbour porpoises and harbour seals. J.Acoust.Soc.Am. 125, 3766-3773.

13. Tougaard, J., Scheidat, M., Brasseur, S., Carstensen, J., Petel, T. v. P., Teilmann, J., and Reijnders, P. Harbour porpoises and offshore development: increased porpoise activity in an operational offshore wind farm. Proceedings of the 24th conference of the European Cetacean Society. 63. 2010. Stralsund, Germany, European Cetacean Society.

OTHER CONSTRUCTION ACTIVITIES

During the entire construction phase at **Horns Reef I**, **Horns Reef II** and **Nysted offshore wind farms** there was a pronounced general decrease in abundance of harbour porpoises (Carstensen *et al.* 2006, Tougaard *et al.* 2006b, Brandt 2009). However, no attempts were made to assess the effects of other construction activities, which included acoustic bottom profiling, dredging, deposition of boulders for scour protection and installation of turbines. The disturbance caused by the installation of gravitational foundations without associated pile driving is thus not known. Neither have any studies documented effects of ship noise (due to increased boat traffic associated with construction) in general on the abundance and behaviour of harbour porpoises.

OPERATION

Operational effects of offshore windfarms on harbour porpoises have been studied in three wind farms: **Horns Reef I** (Blew *et al.* 2006, Tougaard *et al.* 2006b), **Nysted** (Blew *et al*., 2006; (Tougaard *et al.* 2006a) and **Egmond aan Zee** (Tougaard *et al.* 2010). As these three windfarms are dissimilar in a number of characteristics, it would be expected that results and conclusions may differ between impact studies.

The **Horns Reef I offshore wind farm** is located in shallow waters in the Danish North Sea and consists of 80 turbines mounted on monopile foundations. Studies undertaken using T-PODs (Tougaard *et al.* 2006b) monitoring porpoise acoustic activity before (baseline), during and after construction showed a clear decrease in acoustic activity inside the windfarm site during the construction phase. This was followed by a full recovery to baseline levels during the first year of operation. The results of this study were subsequently supported by a second fine-scale study by Blew *et al*. (2006) where a possible gradient in acoustic activity across the edge of the wind farm was investigated using T-PODs during the second year of operation. Results from Blew *et al*. (2006) suggested no evidence of such a gradient.

The **Nysted offshore wind farm** is located in the Baltic Sea in an area with comparatively low harbour porpoise abundance. It consists of 72 turbines mounted on gravitational foundations. Tougaard *et al*. (2006a) compared porpoise acoustic activity using T-PODs inside the windfarm site with a reference area located 10 km away. Data from this study showed a significant decrease in acoustic activity (and hence possibly porpoise abundance) during construction in both the windfarm and the reference area. During the second year of operation (2005) the acoustic activity in the reference area had attained baseline levels whereas acoustic activity inside the windfarm site was still significantly below baseline. However, in contrast to this are the results of a second study by Blew *et al*. (2006) where a gradient in porpoise acoustic activity (and abundance) was investigated by placing a number of acoustic loggers (T-PODs) inside and immediately outside the wind farm. This study did not demonstrate a gradient in acoustic activity (and possibly abundance) across the edge of the wind farm. It should be noted though that both studies were only partially overlapping in time ((Blew *et al.* 2006)conducted in 2005–2006) and they were looking at porpoise acoustic activity/abundance at two different scales (possible gradient over a few hundred meters vs. difference to a reference area 10 km away). Underwater noise measurements from Nysted did not indicate noise levels or spectral properties significantly different from what has been measured in other offshore wind farms (110 dB re. 1 µPa rms @ 100 m, dominant frequency 135 Hz, Blew *et al*., 2006).

The **Egmond aan Zee offshore wind farm** is located in the Dutch North Sea and consists of 36 turbines mounted on monopile foundations. A study using T-PODs located inside the windfarm site and at two nearby reference (or control) sites, reported that after construction, i.e. during the operational period, a significant increase in harbour porpoise acoustic activity was noted inside the windfarm site relative to baseline levels (Tougaard *et al.* 2010). The underlying cause of this increased acoustic activity (and possibly abundance) inside the operating windfarm site is unknown. It may be related to increased prey availability due to the artificial reefs created by the foundations or it may simply be due to the windfarm site providing shelter from other disturbing factors; as ships and trawling are not allowed inside the windfarm site.

TIDAL-STREAM DEVICES

There are a wide variety of tidal-stream energy extraction devices in development. These vary both in their basic energy extraction concepts (e.g. lift vs. drag devices) and in their specifics, including water depth requirements, flow speed tolerances, water column position, extent of surface piercing, methods of seabed mooring/attachment, deployment techniques, extent and velocity of exposed moving parts, size and seabed footprints, noise emissions, lubricants used and maintenance/ decommissioning requirements (Scottish Marine Renewables SEA, 2007). Although some environmental interactions such as removal of the tidal energy itself, cable runs, maintenance boat access, anchoring and fisheries exclusions are likely to be generic, it is anticipated that, given the variability between device types, the majority of issues relevant to marine mammals will vary depending on the particulars of the individual devices, and their deployment area.

Tidal-stream devices exploit the kinetic energy within the tidal flow itself (hence these devices are sometimes also called "hydrokinetic" technologies). Most devices exploiting the tidal-stream, work much like wind turbines but are driven by flowing water rather than air. Because water is much (800x) denser than air, equivalent amounts of energy can be extracted at lower flow rates but cavitation becomes an upper constraint on rotor-tip speeds. This phenomenon occurs when flow speeds around a device exceed a critical threshold and produce transient vapour bubbles. This cavitation can lead to significant mechanical damage. Consequently, tidal-stream devices are smaller and rotor tip speeds are lower (maximum ~ 12.5 $m.s^{-1}$ against the water) than conventional wind turbines (EMEC 2010)

There are currently two main types of tidal-stream devices, horizontal-axis turbines and vertical-axis turbines - though several other concepts are also under consideration including horizontal but transverse-to-flow rotation turbines combining both lift and drag energy extraction (e.g. the Aquascientific marine turbine), Venturi devices, oscillatory motion hydroplanes (EMEC, 2010) etc. (see ICES WGMME 2011). Horizontal axis turbines are the most common technology type being progressed and most look broadly similar to wind turbines - blades rotate around a horizontal axis to drive a generator. The turbine may be shrouded to increase tidal flow through the turbine and better align the presentation of water to the blades. Foundation strategies vary from gravity bases through to monopiles, hanging from surface barges or floating while tethered to fixed seabed anchor points. The number of turbine blades varies from two-to-many; with three currently the most common. There are many variants on these themes including devices with sets of counter-rotating blades mounted one in front of the other or blades supported by a doughnut-shaped structure with an open centre. Vertical axis turbines are generally in more basic stages of development and the number of blades and the configuration of the blades also vary between devices.

Depth requirements also vary between device types. Bottom-mounted devices can operate in depths of 40 to 50 m or deeper, and have the capacity for no surface expression. Conversely, devices hung from surface barges will have their clearance below them. Surface-piercing piled devices will occupy the entire water column with economic deployment depths currently in the 20 to 50 m depth range. Various anchoring options are available and will be dictated by the device requirements, the receiving environment (including need for slack water and seabed characteristics), environmental impact considerations and also infrastructure availability. Likely methods include piling, drilling, gravity structures (including caissons), anchors, weights and reverse hydrofoils.

Rotor blades on commercial scale horizontal-axis turbines will vary in their dimensions by device and site characteristics, being in the region of 2 to 23 m in diameter. Rotation speeds are likely to be from 10 to 30 revolutions per minute with an upper tip-speed of 10 to 12.5 $m.s^{-1}$ (RPS 2008, EMEC 2010). Blades may be exposed or shrouded within an open ended tube. By aligning and funneling water through the turbines, shrouding can make devices more efficient, but may also have an effect on the potential risk of submerged animals being struck by blades. Any shrouding will act to increase the visibility (visual or acoustic) of the entire devices and better indicate the arc of blade sweep but once entering the tube, the shroud itself creates a physical barrier reducing the manoeuvring options of the marine mammal and altering the chance of an enforced passage through/between the blades of the turbine. Current models of vertical-axis turbine diameters are likely to be in the regions of 3 m to approximately 6 m in diameter and up to 6 m in height.

At present, the bulk of the tidal-stream energy industry is focused on the deployment and improvement of single demonstrator devices, but to deliver useful electricity the industry will have to move into the next phase: the placement of multiple full-scale devices. Considerations of the appropriate geometry and spacing of such arrays for optimal energy extraction is still at an early stage and so it is difficult to extract generalities in terms of potential environmental impacts from such scale-ups. However, current discussions suggest that arrays will be composed of tens to hundreds of similar devices duplicated across discrete patches of the seabed.

This review was undertaken in February 2011 and consequently does not include any publications/reports published after that date.

POTENTIAL EFFECTS OF TIDAL-STREAM DEVELOPMENTS ON MARINE MAMMALS

Marine mammal species can potentially be impacted from installation and operation of tidal-stream devices in a number of ways. Most of the effects described below are considered probable or hypothetically feasible, but require database verification with any new device being built. Further information on possible impacts can also be found in Masts Marine Predator JRT (2010). The SeaGen turbine (twin 16 m diameter rotors connected to a generator through a gearbox, with a rotor system supported on the end of a cross beam, and the cross beam is, in turn, supported by a

3 m diameter pile) was used in the world's first commercial tidal-stream generator, sited in **Strangford Lough**, Northern Ireland. The turbine was installed in June 2008 and only a limited period of operation was available for analysis (ICES WGMME 2011), and preliminary results suggested:

- there was no evidence of a change in seal haulout behaviour, transit rates through the Narrows, time spent within the Narrows and time spent in the immediate vicinity of the device;
- Post-mortems of marine mammal carcasses have shown no link between mortality and the operating SeaGen turbine;
- Following analysis of T-POD data, detection positive minutes per day of porpoises were considerably lower within the Narrows during installation compared to the pre- and post-installation periods;
- No significant difference between porpoise detections during baseline and post-installation were observed in the inner Lough;
- Shore based observations of porpoises showed a decrease in their average relative abundance over time in the Narrows, which supports the T-POD findings;
- Shore based observation of seals showed no evidence of disturbance during installation phase, and there was no evidence of a change in underlying relative seal abundance in the area;
- Active sonar monitoring showed that both marine mammals and 'other' targets moved past the turbine in close proximity. However, due to the requirement for "precautionary turbine shutdowns" it was not possible to determine how marine mammals would interact with the turbine during operation.

As of 2011, the majority of other devices were in the prototype or test stages. Therefore, the remaining text focuses on the potential effects of tidal-stream developments on marine mammals.

INSTALLATION EFFECTS

PHYSICAL DISTURBANCE

The presence of installation vessels and equipment can disturb marine mammals, particularly hauled-out seals. This would be most significant for breeding seals hauled out at the coast and on intertidal banks, as it may lead to temporary abandonment of the young and could result in increased juvenile mortality. In addition, if moulting seals are scared into the water, they may lose condition as a result of additional energetic costs.

NOISE EMISSIONS

As with other anthropogenic activities in the marine environment, tidal-energy extraction is likely to result in an injection of acoustic energy into the water. In the construction phase, some aspects of introduced underwater noise will have direct parallels with the offshore wind industry, particularly when heavy lift vessels are used to deploy the devices. However the methods of site preparation and attachment are likely to differ and be more diverse, particularly as most tidal-energy sites are in areas of hard rather than soft substrate and there is a mixture in the mounting requirements of the turbines. In addition, where dynamically positioned ships are used, the energy and associated acoustic output needed to keep to their station is likely to be greater when these vessels need to keep station against the tidal-streams. Acoustic disturbance of marine mammals due to installation of devices and cable-laying can occur both within the water and in the air for seals using haulout sites. Should piling be the chosen method for installation of the foundation, in conjunction with other activities such as drilling, the impulsive noise input without applied mitigation measures may have a higher potential for injurious impacts (such as TTS or PTS) and wider displacement of animals. Though it should be noted in the case of installation of tidal energy devices, much smaller diameter piles are likely to be used compared to the offshore wind sector.

Exclusions for lengthy periods are particularly relevant in constrained areas (such as mouths of sea lochs and straits between water masses) as loud noise sources may prevent transit, effectively trapping individuals. Ships used for construction contribute to the ambient noise level in the area, especially those using lower frequencies. This poses the risk of masking biological significant signals of passive acoustic sensing in baleen whales, thus effectively shrinking the space of their acoustic soundscape.

REDUCED VISIBILITY

Increased turbidity leading to reduced visibility can occur during seabed installation, as fine particles travel further from the disturbed area, swept by tidal currents, which have the potential to effect foraging, social and predator/prey interactions. Grey and common seals have been identified as having a high sensitivity to reductions in visibility. However, tidal devices will be placed in high energy environments and it is likely that the relatively small amounts of sediment that are likely to be released into the water column during turbine and cable installation will be rapidly dispersed and accordingly have a negligible impact on background suspended sediment and turbidity levels. The introduction of devices and the associated increased hydrodynamic drag into areas with tidal-streams may however result in some relocation of previously stable (or dynamically stable) sediments at downstream sites. Such consequences have, so far, received little attention.

IMPACTS DUE TO CONTAMINATED SEDIMENT

Possible release of contaminants when dispersing sediment during cable and device installation could become problematic for marine species that are sensitive to contamination, i.e. marine mammals; though as noted above, as with fine particles, any release of contaminants may be rapidly dispersed and are unlikely to have accumulated in tidal-stream areas themselves.

COLLISION RISK WITH INSTALLING VESSELS AND CONSTRUCTING MACHINERY

Vessels are needed for installation of tidal devices and export cables. As both activities are likely to happen in an either stationary or slowly travelling mode, on first consideration collision risk during construction periods is likely to be lower than by commercial shipping activities. However, it should be remembered that these vessels may need to operate at full tidal flows and thus while stationary above the bottom may be moving at speed through the water (i.e. ≥ 3 $m.s^{-1}$). During 2009/2010, unusual seal mortalities were noted in the UK east coast and in Northern

Ireland; the carcasses having characteristic spiral injuries (Thompson *et al.* 2010a). The injuries are consistent with the seals being drawn through a ducted propeller such as a Kort nozzle or some types of Azimuth thrusters. Such systems are common to a wide range of ships including vessels likely to be associated with tidal-stream developments, for example tugs, self-propelled barges and rigs, various types of offshore support vessels and research boats.

OPERATION

COLLISIONS WITH MOVING PARTS

The information odontocetes derive from echolocation is limited by the update frequency of sound pulses. In addition, updates rates are limited by the travel time of the sound. Their active echolocation is continuously tuned to the objects of interest, e.g. while foraging. Thus although animals may be capable of detecting distance objects, they may be effectively blind to them when foraging on prey immediately in front of the devices. Factors which can contribute to the possibility of negative interactions with moving parts are for example detection failures, diving constraints, group effects, attraction, confusion, distraction and diseased/injured animals.

One mitigation option to lowering the risk of collision in the absence of a good understanding for potential impacts is the "precautionary turbine shutdown" approach. In Strangford Lough, work is progressing towards achieving full automation of the device shut down procedure, if marine mammals are within a certain distance to the operating SeaGen tidal turbine. Device shut down may be in the interests of the developer, to avoid damage to their turbines, however it prevents further assessment of the implications of interactions of wildlife with operational devices.

NOISE EMISSIONS

During operation, lower levels of noise are expected than during installation because the turbines are optimized to remove energy from the environment. They will however produce sound associated with the motion of the rotors against the water, internal gearing and so forth. Currently little is known about the actual and potential acoustic outputs of operating turbines both when first deployed and when they have had a period of operation; after wear and fouling. Coupled with this, information on the levels of ambient sound, relevant to marine mammals, in areas of strong tidal-streams is poorly known so that it is currently difficult to forecast over what range turbines will be audible to marine mammals. Initial modelling work has suggested that these ranges may be highly variable depending on the specifics of ambient sound and turbine noise levels (Carter 2008). However because both of these levels are likely to exceed the marine mammal hearing sensitivities, the precise hearing capabilities of species of risk are less important than is typically the case. The results of this study also showed that in some circumstances, such as quiet devices in noisy waterways, may be undetectable by animals until they are at very close ranges (e.g. <10 m, (Carter 2008).

GENERATION OF ELECTROMAGNETIC FIELDS

Cables may generate electromagnetic fields that could alter behaviour and migration pattern of species susceptible to those (e.g. sharks and rays) when in operation. Electricity cables produce small electric and magnetic fields, which have the potential to affect migration and prey detection in seals and cetaceans. Heat dissipation from transfer losses increase the temperature in the vicinity of power cables and may potentially affect the survival rate of bottom living species. There are various mitigations options to minimize these risks such as good construction of cables, i.e. using materials with very high conductivity and permeability values, using high voltage direct current and burying of the cables. There is, at present, no evidence that seals are sensitive to electromagnetic fields, although some large whale species appear to use variations in the geomagnetic field to navigate (Walker *et al.* 1992) and passive electroreceptors have recently been described for one odontocete species (Czech-Damal *et al.* 2012).

CONTAMINANTS

Parts of the different types of tidal devices are likely to need antifouling. Methods of achieving this for many devices have not yet stipulated though antifouling paints will undoubtedly be used. Although organotins are now banned for these, copper is still in use. Further potential sources of contaminants are leaching of toxic compounds from sacrificial anodes, or leakage of hydraulic fluids e.g. due to storm damage, device malfunction or collision with vessels such as transiting ships. The latter could even lead to significant leaks of cargoes or fuel carried by the vessel involved.

HABITAT EXCLUSION

It is unknown how animals will respond to operating devices. As with other anthropogenic activities, responses are likely to be species- and context-specific *i.e.* could depend on factors such as age or reproductive state, behaviour and previous exposure (Scottish Marine Renewables SEA 2007). While some may be attracted, it is likely that neophobic species will show avoidance reactions to the novel, moving structures. Such avoidance may result in displacement and even long-term habitat exclusion (Wilson *et al.* 2007).

ENTRAPMENT

Operating devices, especially arrays, could from a barrier for migration routes and transit patterns of marine mammals, which again is of particular relevance in constrained areas; where noise and the physical presence of moving structures may prevent transit, leading to entrapment of individuals.

WATER COLUMN CHANGES

To species that are sensitive to changes in tidal flows a decrease in water flow resulting from extraction of tidal energy could be a relevant impact. Seals have been shown to use their vibrissae to sense small-scale hydrodynamic vibrations and flow vortices in the water column. It is likely that that they use this sense to track the wake of prey organisms swimming through the water column.

WAVE ENERGY CONVERTERS

Wave energy converters, in the broadest possible sense, work by absorbing kinetic energy from the water column. There are a wide variety of wave energy converters in development, for use in a range of marine environments (including at least partially onshore, in shallow coastal waters as well as deeper waters further offshore). These vary both in their basic energy extraction concepts and in their specifics, including water depth requirements, water column position, extent of surface piercing, methods of seabed mooring/attachment, deployment techniques, extent and velocity of exposed moving parts, size and seabed footprints, noise emissions, lubricants used and maintenance/decommissioning requirements (Scottish Marine Renewables SEA 2007). Although some environmental interactions, such as removal of the wave energy itself, cable runs, maintenance boat access, anchoring and fisheries exclusions are likely to be generic, it is anticipated that, given the variability between device types, the majority of issues relevant to marine mammals will vary depending on the particulars of the individual devices. WECs can be aggregated into several broad design categories (based on the descriptions by ECN 2012; EMEC 2012): surface attenuators, point absorbers, oscillating wave surge converters, oscillating water column devices, overtopping devices, submerged pressure differential devices, and others (see ICES WGMME 2012).

Most of the devices are still in an advanced prototype stage although some are currently operational at a small scale. Individual devices have a generating capacity of between 10-750 kW; the ultimate goal is to create arrays of devices capable of generating energy at the 20-50MW-scale. The operational lifetime of individual devices is generally expected to be on the order of 10-20 years. Individual device designs vary greatly in terms of dimensions and inertial mass. For instance, most point absorbers are broadly similar in size and shape to large navigational buoys, whereas the Pelamis™ surface attenuator device has a length of 180 m in its current configuration.

Many devices (especially the surface attenuators and point absorbers) have some kind of surface expression as a critical operational element. These devices remain in place by means of a mooring system consisting of a range of elements such as anchors, cables and chain clumps, and are expected to be deployed some distance offshore. Other devices (such as the oscillating wave surge converters and several of the oscillating water column devices) need to be constructed in the surf zone or the intertidal zone for maximum results, and may require pile driving, pile drilling or gravity-based systems to ensure firm attachment to the substrate. Exact installation and/or mooring methods are likely to vary widely based on specific device requirements, environmental characteristics and infrastructure availability. At the moment, most devices are designed for deployment in inshore coastal environments, although several (*e.g.*, the Pelamis™) could potentially be deployed widely across continental shelf areas far offshore.

The moving parts of some devices (*e.g.*, Pelamis™ and Oyster™) are directly exposed to the outside environment, but in many other devices the parts that take off the kinetic energy (such as a turbine) are either contained within the device (*e.g.*, WaveDragon™) or built on-shore separate from the device itself, with the energy obtained by the WEC being used to pump seawater through a more traditional hydro plant (*e.g.*, CETO™). Elongated devices such as the Pelamis™ WEC or the Anaconda™ are expected to be somewhat responsive to changes in wave (and, to a lesser extent, wind) direction, while point absorbers are unlikely to be deflected. Other devices (*e.g.*, Oyster™, Limpet™) are essentially immobile and attached to the underlying substrate.

As wave energy converters are at a relatively early stage of development when compared to other renewable energy technologies, reflected in the lack of knowledge of effects that these devices might have on the marine environment in general, there is a lack of information available for environmental consenting. In order to satisfy national and international requirements (e.g. the European Commission Habitats Directive), monitoring schemes for WECs, and all renewable devices, need to gather baseline information before construction begins, as well as continued impact monitoring during the construction, operation and decommissioning phases of the deployment. Broadly, monitoring must take place at spatial and temporal scales that are appropriate to assess impacts upon marine mammals at the population level, although, as noted earlier, this rarely happens. It is, therefore, essential that full advantage is taken of test deployments and early arrays to gather information on the actual interactions between devices and wildlife.

POTENTIAL EFFECTS OF WAVE ENERGY DEVELOPMENTS ON MARINE MAMMALS

Marine mammal species can potentially be impacted during installation, operation and decommissioning of wave energy devices in a number of ways. Similar to the tidal-stream energy devices, most of the effects described below are considered probable, but are speculative and require verification with any new device being built. A number of effects are similar to those described for the tidal-stream sector.

It is vitally important to realise that any effects suggested here are likely to be species-specific and will also be influenced by particular features of the development site. For this reason, extrapolation of any likely risk assessments from experiences with one species or area to a completely new species or area should only be undertaken after careful consideration.

INSTALLATION

PHYSICAL DISTURBANCE

There is a risk that marine mammals could be disturbed by the presence of installation vessels and equipment, particularly those that require deployment on or close to the shoreline. This is a particular risk for seals that are hauled out in these areas during their breeding period, as this could lead to temporary abandonment of young and potential subsequent increases in juvenile mortality. Moulting seals that are scared into the water may face increased energetic costs. In some cases where land-based infrastructure needs to be constructed in the vicinity of seal haul-out sites, there is a similar risk of disturbance as outlined above. Cetaceans in coastal and offshore waters may also be disturbed by installation activities as well as the continued presence of the WECs themselves. Neophobic individuals (or species) may be more likely to avoid devices at greater range, whereas other animals might actively choose to investigate devices more closely.

UNDERWATER SOUND

As with other anthropogenic activities in the marine environment, wave energy extraction is likely to result in an injection of acoustic energy into the water. These negative impacts can include disturbance and habitat exclusion at considerable distances, as well as (at increasingly close range) masking of biologically relevant acoustic input from other sources, TTS (temporary loss of hearing due to high sound levels) or even PTS (permanent physical hearing damage as a result of high sound levels).

During site preparation, acoustic methods are commonly employed. Depending on the method used (*e.g.*, side scan sonar vs. seismic point surveys), several potential effects on the marine environment need to be considered. In the construction phase, some aspects of introduced underwater noise will have direct parallels with the offshore wind and tidal sectors particularly when heavy lift vessels are used to deploy the devices and associated moorings and subsea cables (Qinetiq Ltd. 2007, Scottish Marine Renewables SEA 2007). Acoustic disturbance of marine mammals due to installation of devices and cable-laying can occur both in water and in air (particularly for seals using haul-out sites). If the construction of infrastructure involves use of blasting, pile driving or drilling, the sound input without applied mitigation measures has a higher potential for impairment or even injurious impacts and wider displacement of animals - this may also be relevant for onshore installations near the waterline.

Only a very small number of WECs currently under development require the use of pile driving (Wave Star A/S 2011) or pile drilling (Aquamarine Power Ltd. 2012), with the rest relying on anchors or gravity-based structures for stability. The acoustic impacts of pile drilling are less well known (Nedwell and Howell 2004) than pile driving, and several devices that use wave energy to drive seawater to a conventional onshore hydro-electric plant will require directional drilling through the substrate from shore in order to install the flow lines (*e.g.*, the Oyster™; APL 2012). Therefore, sound emissions from this drilling activity also need to be considered.

As noted earlier, ships used for construction will also contribute to the ambient sound level in the area; and possibly pose the risk of masking. This effect may be significant if ships used during deployment emit higher sound levels than ships normally occurring in the area and/or if deployment occurs in areas that had heretofore seen very low levels of shipping activity (Scottish Marine Renewables SEA 2007).

COLLISION RISKS

Vessels are needed for installation of tidal devices, their moorings and electric cables. Vessels involved in WEC installation need to be able to manoeuvre accurately at small spatial scales, which, as noted earlier, is typically achieved by using ducted propellers such as Kort nozzles or some types of Azimuth thrusters. Although ships equipped with these propellers are not new (see tidal-stream device section), there has been an increase in the amount of operational time such ships spend in shallow inshore waters, partially driven by expansion of the marine renewable energy sectors.

REDUCED VISIBILITY

Increased turbidity leading to reduced visibility can occur during seabed installation of devices, cables and/or mooring components, with fine particles traveling even further from the disturbed area. It is conceivable that sudden, unexpected increases in turbidity may impact marine mammal foraging, social and predator/prey interactions. However, many marine mammals spend considerable amounts of time in turbid waters. Furthermore, WECs are likely to be deployed in comparatively energetic locations where large amounts of fine sediments are unlikely to accumulate, and any increases in turbidity as a result of re-suspended sediments are unlikely to persist for any length of time (although this will need to be assessed for specific developments on a case-by-case basis).

IMPACTS DUE TO CONTAMINATED SEDIMENTS

As described previously (see tidal-stream device section), it is likely that wave action will ensure rapid displacement of any contaminated sediment that might be re-suspended, minimising risks to marine mammals.

GRID CONNECTIONS

As with some other renewable energy devices, many of the most suitable sites for wave energy generation are in comparatively remote locations without suitable cable infrastructure connecting the devices to the national power grids (*e.g.*, (Scottish Marine Renewables SEA 2007)). This requires a potentially substantial investment in terms of additional interconnector cables, substations etc. Some of this infrastructure will be land-based but other elements will have to be deployed under water. This will require the presence of additional installing vessels and construction machinery outwith areas where devices are to actually be installed, and thereby increase the size of the footprint of the industry.

OPERATION

COLLISION

Marine mammals can be at risk of collision with the various different categories of WECs in various ways. For those devices meant for deeper water that have a surface expression *e.g.*, surface attenuators and point absorbers, animals may potentially collide with the device itself while breathing, feeding, resting or travelling near the surface (Wilson *et al*. 2007). Collision risk is considered to be greater when a greater proportion of the device is below the surface (Boehlert *et al*. 2008). Devices may be less detectable under conditions of poor visibility (turbid waters), or reduced manoeuvring options such as in surge conditions or during storms. Animals could also potentially collide in mid-water with those devices that do not have a surface expression (*e.g.* the submerged pressure differential devices) as well as with interconnector cables or elements of the mooring system. It is worth noting that the mooring system of some devices can be quite extensive, relative to the size of the device itself (*e.g.*, (Pelamis Wave Power Ltd. 2012)).

Marine mammals have the capacity to avoid and evade WECs, but only if they are able to detect the objects, perceive them as a threat and then take appropriate action at long (avoid, *i.e.* swim around) or short range (evade, *i.e.* dodge or swerve; Wilson *et al*. 2007). The ability of animals to detect devices depends on species-specific sensory capabilities, local visibility and level of sound output by the device relative to ambient noise levels. Neophobic individuals (or species) may be more likely to avoid devices at greater range, whereas other animals might actively choose to investigate devices more closely. There is presently no information on avoidance or evasive behaviour of marine mammals relative to wave energy converter devices, given the small scale of deployments to date. Detection distances are likely to be strongly influenced by ambient environmental conditions. Considering that WECs are moored to the seabed in sites that do not experience extreme tidal currents, it is likely that under normal circumstances animals should be able to detect the devices in time to avoid them, but that this may be affected by particular environmental conditions.

Finally, marine mammals are at risk of collision with vessels involved in device maintenance in the same way as described above under the installation phase.

SOUND EMISSIONS

The characteristics of sound emitted by WECs are likely to vary considerably between devices and also depend on the surrounding acoustic environment. To date, theoretical sound output of one surface attenuator-type WEC (the Pelamis™ device) has been independently reviewed (Qinetiq Ltd. 2007, Scottish Marine Renewables SEA 2007). Since no direct measurements of Pelamis™ sound output were available, the review considered radiated sound data from similar machinery on board oceangoing ships. This comparison suggested that the machinery within a single Pelamis™ device (particularly the hydraulics) could generate sounds of 350Hz at an intensity of up to ~140dB re 1 μPa at 1m. The review made a number of assumptions but suggests that "based on the limited data available, it is not expected that a wave energy device of this type (Pelamis™) would present any potential for causing PTS", and that "the risk of an animal experiencing TTS from a single 1 MW device of this type is insignificant" (Qinetiq Ltd. 2007). Results of array simulations furthermore suggest that "there is unlikely to be a significant PTS impact for commercial arrays of wave devices like Pelamis" (Qinetiq Ltd. 2007). Risks of TTS appear similarly unlikely given the expected sound outputs. Behavioural reactions and masking are likely to occur over a limited range around WECs, but it is important that detailed impact assessments be carried out on a case-by-case basis for each individual project. Further in-situ work on assessing sound outputs from different devices under a range of environmental conditions is a necessary next step in assessing risks of widespread WEC deployment. During the operational phase, further sound is likely to be generated by vessels if devices are to be inspected at sea, or towed to port for servicing or repair.

ELECTROMAGNETIC FIELDS (EMF)

See section on tidal-stream devices

CONTAMINANTS

Parts of some WECs may need the application of antifouling products to retain functionality, although it has been suggested that biofouling is not likely to be a major issue for WECs (*e.g.*, (Langhamer *et al.* 2009, Aquamarine Power Ltd. 2012, Pelamis Wave Power Ltd. 2012). Methods of achieving this have not yet been stipulated for many devices although antifouling paints are likely to be used. Further potential sources of contaminants are similar to those outlined for the tidal-stream sector. Because many WECs are intended to be moored in the open sea, they may be sought out by cetaceans for use as rubbing posts in a manner similar to ships or other structures, in which case direct skin-anti-fouling contact might possibly occur (Ritter 2009, Williams *et al.* 2009). Further details on the types of chemicals present on the outer surfaces of WECs and their associated infrastructure would improve the ability to assess the relative contaminant risks posed by these devices.

HABITAT EXCLUSION

Effects will be possibly similar to those outlined for tidal-stream devices. Large arrays of WECs could potentially result in the loss of significant areas of habitat if animals do not perceive the gaps between the devices as passable based on the visual or acoustic signature of the array. Based on discussions with developers, typical array sizes are likely to be on the order of several km^2 for wave devices (7 –100 devices; (Scottish Marine Renewables SEA 2007)).

DOWNSTREAM WAVE ENERGY REDUCTION

When wave fronts interact with WECs, there is likely to be at least a limited reduction in wave height downstream as a result of kinetic energy uptake by the WEC. To a certain extent diffraction of wave energy around the WEC will compensate for energy loss at the WEC, but some degree of downstream wave height reduction is still likely. Artificially reducing wave energy in nearshore waters may therefore impact geomorphological processes vital for maintenance of coastal environments, such as rates of erosion, sediment transport and deposition (Millar *et al.* 2007).

Marine mammals could potentially be indirectly affected by these changes in a number of ways. Some animals might seek out calmer waters leeward of a WEC array for shelter, *e.g.*, during storms, as has been suggested for harbour porpoises among aquaculture sites in Atlantic Canada (Haarr *et al.* 2009). Calmer waters may mean that formerly-exposed rocky shores become more attractive as additional haulout sites for seals. Conversely, as wave action is one of the main drivers for longshore currents that carry sediments from which new beaches are rebuilt (Dean and Dalrymple 2002), widespread extraction of wave energy might result in a decline in replenishment of beaches and sandbars downstream of device arrays, potentially threatening existing seal haul-out sites. However, it is likely that the largest waves will continue to bypass WECs without being significantly reduced, suggesting that their impact as an ecological driver will remain largely unchanged (Pelc and Fujita 2002).

PHYSICAL RESTRAINT

Following a collision with power cables or mooring elements, marine mammals may be subsequently at risk of entanglement (Boehlert *et al.* 2008). The entanglement risk posed by cables is dependent on their thickness (with thin cables providing a greater risk), their tension (with slack cables being more dangerous than taut ones), position in the water column (horizontal cables being considered more dangerous than vertical ones) and the materials chosen for their outer casing (smooth cables being less likely to entangle than rough ones). Entanglement risk involving cables is most likely to be a problem for larger cetaceans, particularly foraging baleen whales, but is not considered to be a major risk.

As a secondary effect entanglement may also be caused by lost fishing nets ("ghost nets") that may have become attached to sections of the WECs, and may thus impact small cetaceans and pinnipeds as well. WECs are not envisaged to have any effect on ghost net numbers, but may aggregate them if the nets become entangled by devices, cables or other infrastructure. If WEC array sites indeed act as Fish Aggregating Devices or otherwise lead to increased abundance of commercially targeted species (see Ecological Effects section below), it is conceivable that fishing activities seeking to exploit these species might become concentrated near these sites with increased entanglement risk to marine mammals. Alternatively, a shift of fishing effort out of an area due to WEC deployment may lead to changes in marine mammal bycatch in a wider area, in terms of absolute numbers and/or distribution.

There is a risk that seals or small cetaceans might enter the chamber of shore-based oscillating water column devices, and be unable to find their way out again, although this has not so far been observed in the Limpet™ device operating on Islay since 2000 (Voith Hydro WaveGen Ltd. 2011); D. Moysey, Marine Civil Engineer, Voith Hydro, pers. comm., 2012).

INJURY THROUGH MOVING PARTS

Some of the WECs operate by means of moving parts that are exposed to the environment, such as articulation of segments of surface attenuators (Pelamis Wave Power Ltd 2012), the flaps of oscillating wave surge converters (*e.g.*, the Oyster™; APL 2012) and even the turbines involved in power take-off in overtopping devices such as WaveDragon™ (WaveDragon ApS 2012); the latter being mainly a concern for seals that might enter the overtopping basin). If animals are unable to detect these moving parts in time to avoid them, there is the potential for injury by being struck by, or crushed between, these parts. These risks would presumably be exacerbated under conditions of poor detectability and/or when device movements are likely to be faster than average, *e.g.*, during storms (Wilson *et al.* 2007).

ECOLOGICAL EFFECTS

Widespread deployment of WECs in inshore and offshore waters, as currently proposed for some areas, has the potential to impact marine mammals in a range of indirect ways, by changing the local environment. As with tidal-stream devices, WECs with a surface expression (*e.g.*, the Pelamis™) could become attractive as haul-out sites for seals (Boehlert *et al.* 2008, Nelson *et al.* 2008). This might allow for a local expansion of foraging ranges for individual animals further offshore, although it might also put animals at greater risk of collision or injury if devices contain moving parts exposed to the outside environment.

All WECs, particularly those intended for deployment in deeper, offshore waters, are likely to alter their immediate environment. Many of the mooring systems currently under consideration are designed to operate on sediment rather than exposed bedrock, and offshore WECs are most likely to be deployed over areas of sediment. The introduction of hard substrate into this type of environment (the WEC device itself, but also associated mooring and cable elements) will lead to the appearance of communities associated with hard substrate, while the sedimentary communities within the immediate mooring footprint may be damaged or destroyed (Langhamer and Wilhelmsson 2009, Langhamer *et al.* 2009, Langhamer 2010) for a consideration of natural variability). To date the evidence suggests that some species associated with hard substrates might become more abundant in the immediate vicinity of WECs and their moorings, both through colonising the devices and moorings themselves and through generating increasing amounts of hard shelly debris in the sediment surrounding the WEC, facilitating further settlement of hard-substrate species. These processes could result in locally elevated levels of prey biomass (particular benthic fish species) that may attract marine mammals, in a manner similar to other hard structures (Todd *et al.* 1999). Furthermore, many different fish species are attracted to floating objects, a phenomenon that has long been exploited by fishermen worldwide through the use of Fish Attracting Devices (FADs) (Fonteneau *et al.* 2000, Castro *et al.* 2002). WECs floating at the surface may thereby inadvertently act as FADs leading to an increase in fish abundance, potentially resulting in locally elevated levels of prey biomass that may attract marine mammals (*e.g.*, (Brehmer *et al.* 2012) as well as other piscivorous species, although this may subsequently also attract top predators such as sharks or killer whales. The closure to fishing of areas immediately surrounding WECs may also contribute to changes to local productivity and biodiversity, with possible knock-on effects for marine mammals (Inger *et al.* 2009). Attraction of marine mammals to devices may put them at greater risk of collision or entanglement in cables.

DECOMMISSIONING

Decommissioning of WECs is likely to involve structure/device removal, waste and debris clearance and disposal, seabed restoration and subsequent maintenance, monitoring and management of the site (Scottish Marine Renewables SEA 2007). Many of the activities involved with these steps are similar to those encountered in device installation, and as a result many of the associated risks to marine mammals (*e.g.*, collision with maintenance vessels, noise, seabed disturbance, and disturbance of animals) are also broadly similar. Removal of elements of the mooring system and other submerged hardware may pose the greatest impact risk, particularly if structures such as piles need to be physically removed from the seabed.

Current device deployment plans suggest a device operational lifetime of 10-20 years, after which the device operator is likely to be required to remove the device and all associated infrastructure according to specified decommissioning standards (UNCLOS 1982, Scottish Marine Renewables SEA 2007, DECC 2011). In the UK guidelines, it is recognised that under certain circumstances (including when "the installation or structure will serve a new use, such as enhancement of a living resource, or serves a purpose beyond that of renewable energy generation, and would not be detrimental to other aims such as conservation") complete removal of devices may not be the best solution (Scottish Marine Renewables SEA 2007, DECC 2011). The importance of WEC-related infrastructure for marine mammals needs to be periodically reviewed to ensure that eventual removal of this infrastructure will not have detrimental effects on particular marine mammal populations.

RECOMMENDATIONS

Looking at the forecasts for the development of renewable energy deployments in the wider OSPAR/ICES/European marine environment, together with the predicted spatial scale of any impacts, it is important to develop consistent approaches (at least on a regional sea basis) to providing basic information about the ecological features within a region, especially those that are protected and/or are known to be especially sensitive to pressures resulting from construction and operation of renewable energy devices.

Because current marine mammal monitoring is not designed to address impacts of renewable energy extraction, it is almost certain that additional measurements of population trends of abundant and sensitive species needs to be carried out; both small-scaled for the actual construction site (and also to assess changes in behaviour) as well as larger-scaled to gain an overview of the regional sea area and mitigation pattern. Coordination of monitoring of adjacent developments is required, ideally leading to joint action, e.g. distributional surveys which cover the spatial distribution of marine mammal populations. In general, impacts of wet renewable energy (especially tidal-stream devices) during normal operations will probably be more significant than those related to installation. Mitigation will become more relevant once the actual impacts are better known and will need to consider additional effects such as the collision with (underwater) moving parts of the wet renewable devices or operational noise.

The following are recommendations made by the ICES WGMME on management, monitoring and mitigation.

MANAGEMENT

PRECAUTIONARY MANAGEMENT FRAMEWORK

Development of an appropriate precautionary management framework is recommended for marine renewable energy technologies.

Probably the most important consideration concerns the effects of wind and wet renewable energy devices at population and/or management unit level. The renewables industry is developing rapidly and regulators need to make decisions on granting consent for licensing in the near future. As this industry expands from a few sites to a large number of sites over larger areas of sea, it will become increasingly more important to be able to predict population effects in order to meet management objectives such as Favourable Conservation Status under the Habitats Directive and Good Environmental Status under the European Commission Marine Strategy Framework Directive. A good management framework requires a sufficient level of basic understanding of animal-device interactions, and include a precautionary “survey, deploy and monitor strategy” for assessing these interactions; it would also benefit from ongoing data collection (monitoring) at appropriate scales to allow the incorporation of a feedback mechanism and to enable determination of whether management actions are allowing objectives to be met.

DECISIONS BASED ON APPROPRIATE POPULATION AND/OR MANAGEMENT UNIT

Multinational studies and management decisions on wind and wet renewables should be encouraged, and based on appropriate populations and/or management units for the relevant marine mammal species, irrespective of national borders.

Consent for development, and assessment of impacts are matters for individual governments. Many marine mammals are wide ranging and occur in populations that regularly move and mix across national boundaries. This means that assessments of impacts cannot be carried out entirely within territorial boundaries, and that consents given by one government can affect the acceptability of potential developments within a neighbouring jurisdiction. Some recognition of this is essential in decision-making. In some cases coordination can occur within existing frameworks, as for example the Trilateral Wadden Sea Agreement and ASCOBANS. In other cases new fora for coordination must be created. Increased cooperation between EU Member States will be required by the European Marine Strategy Framework Directive through the application of an ecosystem-based approach to the management of human activities.

STRATEGIC SPATIAL AND TEMPORAL PLANNING

A strategic approach to identifying sites of low marine mammal risk for early stage deployments should be carried out before consenting to renewable device or array developments in more sensitive sites.

Because of the scarcity at present of operational wet renewable devices, subject to robust monitoring schemes, our understanding of the nature and significance of any impacts they might have upon marine mammals is speculative. In order to furnish such data with minimal environmental risk, a strategic approach to device or array deployment is strongly recommended. Thus, development should focus initially on resource areas and periods of lesser importance for marine mammals (and other environmental interests), and discouraged in areas of relatively greater importance (e.g. Natura 2000 sites). This will enable data to be gathered and interpreted that is necessary to inform and guide consenting decisions in areas of higher sensitivity.

DEVICE AND ARRAY DIVERSITY IN THE WET RENEWABLE SECTORS

In recognition that animal-device interactions are likely to be both species- and device- (or device-type) specific, extreme care should be taken when extrapolating conclusions about environmental impacts between species and renewable energy device types.

There are currently a large number of different device types being simultaneously progressed by the wet renewable energy sectors. Ranging both in their manner of energy extraction to their specifics of size, extent and velocity of exposed moving parts, and their location, particularly placement in the water column and preferred current speeds. This design variety is at a range of different stages of development from conceptual or scale models to a small number of full-scale test-rigs deployed at sea. Because the most significant lessons on likely interactions with marine mammals are to be learned with full size devices in operation it will be tempting to extrapolate from the environmental monitoring carried out on these to the other device types. However until the parameters that shape any impacts (or absence of impacts) are known then extreme caution should be applied when extrapolating results from one device trial to another, one species to another or one habitat to another. Cumulative effects may also occur due to interactions between devices/arrays and other marine resource users, which also require further study.

Extreme care should be taken when scaling-up environmental lessons learned from studies of single devices up to arrays as the nature of any impact relationships (linear or otherwise) between one and many devices is currently unknown. In light of this, a stepwise approach should be taken for array development.

There are likely to be differences in the way marine mammals respond to individual devices, as opposed to when multiple devices are deployed in arrays over larger areas. As with the offshore wind installations, the ultimate goal of the wet renewable sectors are to place multiple full-scale devices in array configurations that optimize energy capture. It is currently unknown how marine mammals encountering wet renewable devices in arrays are likely to behave. It may be that they respond to each one in isolation or that there are emergent properties generated by the stimuli coming from multiple devices which elicit alternative responses. In the absence of robust information on the impact of single devices it is of course even more difficult to quantify the impact of arrays. Further work is necessary to compare and contrast (first through modelling) the likely effects of different array configurations on marine mammals, in relation to a range of environmental parameters (*e.g.*, bathymetry, current direction, distance from shore etc.). Attention needs be focused on studying the likely effects of different array configurations on marine mammals, including sound output and potential barrier effects.

ALLOWABLE TAKES

Appropriate metrics should be developed to regulate any population level deleterious effects of marine renewable energy developments. To achieve this, target population size should be explicitly chosen and all appropriate data should be used to assess allowable impacts.

At present, Potential Biological Removal (PBR) estimates for populations of marine mammals at both local and regional scales are being widely used to set limits on 'takes'. However, this is not necessarily the most effective or sensitive method. The target of conservation management should be to achieve and maintain suitable population sizes and structures, and take limits are a tool to achieve this. PBR provides a relatively simple automated process but its target population size is implicit and generally unknown. An additional criticism of the PBR methodology is that it does not use all available data. Where time-series data are available they can provide additional information to refine the take limits, consistent with predefined population targets; e.g. the Catch Limit Algorithm approach (see (ICES WGMME 2009)).

DATA SHARING

With regard to marine renewable energy developments, establishment of means for efficient dissemination of results of common interest and means of making previous EIA reports and previously collected baseline data available for subsequent studies and assessments.

The risks and potential impacts of many offshore developments are similar. It is obviously inefficient that EIAs are carried out entirely independent from each other because this will result in the duplication of effort and repetition of the same mistakes. The Aarhus Convention of the EU (ECE/CEP/43: http://ec.europa.eu/environment/eia/full-legal-text/aarhus_en.pdf) along with the Convention on Biodiversity (http://www.cbd.int/doc/legal/cbd-un-en.pdf) recognize this. The latter set up a Clearing House Mechanism to promote the sharing of information. There are currently two limitations to using this approach: awareness of the existence of data and the availability of publically owned data. While the release of commercially sensitive data has to be subject to delay, this needs to be balanced against the benefits of its use in evaluating other applications and thus also data collected by private companies should be made available. Shifting the balance towards more rapid dissemination could reduce the amount of new information, and experimental studies, required and, improve the assessment of new projects.

A shared international common database could be set up that would allow wider dissemination of relevant datasets while ensuring confidential and anonymous treatment of commercially sensitive information.

Lack of reliable information is a major constraint on our ability to predict the likely effects of marine renewable energy developments and on our ability to design and estimate the efficacy of mitigation strategies. For most developments there are strict and well defined EIA requirements and the issuing of permits and consents is usually contingent upon some form of baseline data collection and/or some level of pre- and post-deployment monitoring. For commercial reasons the data collected by developers for most developments typically remain unavailable to the wider research community. In order to make better use of these datasets, a shared international common database could be set up that would allow wider dissemination of relevant datasets while ensuring confidential and anonymous treatment of commercially sensitive information. This would require standardisation of data, including metrics for reporting on individual test parameters but also study design, *i.e.* pre- and post-deployment monitoring as well as defining the requirements for reference sites. The Joint Cetacean Protocol (JCP), which was set up to aggregate and integrate information on cetacean distribution, abundance and population trends for the European North Atlantic using data from academic, government and commercial sources (to data, mainly offshore wind farm operators) working within their waters, provides an example of successful collaboration of the kind suggested here (see (Paxton *et al.* 2011, JNCC 2012).

SURVEILLANCE AND MONITORING STRATEGIES

Monitoring in connection to renewable energy sites can be divided into two phases: baseline data collected prior to construction (often as part of the EIA process) and impact data collected during construction and operation of the renewable energy devices.

In order to satisfy national and international requirements (*e.g.*, the Habitats Directive), monitoring schemes need to gather baseline information before construction begins, as well as continued impact monitoring during the construction, operation and decommissioning phases of the deployment. Broadly, monitoring must take place at spatial and temporal scales that are appropriate to assess impacts upon marine mammals at the population level. The following broad questions (based on Macleod et al. (2011) are suggested examples of issues that monitoring programmes need to address:

- Do marine mammals occur in the area of interest?
- What is the spatial and temporal distribution and abundance of marine mammals in the area?
- What are the marine mammals using the area for? (*e.g.*, foraging, breeding)
- What is the sensitivity of marine mammals to different stressors linked to the construction, operation and decommissioning of renewable devices?
- Is detected change limited to the development footprint or over a wider area?
- Does the impact change with time or distance?
- Could any change at the population level be attributed to the development's construction, operation or decommissioning?
- Could any impact affect the conservation status of the population under (inter)national legislation?

BASELINE MONITORING

The aim of baseline monitoring can be twofold. First and foremost it is to establish abundance patterns of marine mammals in the proposed construction area and thus provide important information for the decision process of the EIA. Second the baseline monitoring should collect baseline data for later impact studies, given that such are undertaken. Some countries (e.g. Germany) always require baseline data to be collected during the EIA, whereas most other countries only require collection of new data if other relevant data are not available. With regard to baseline monitoring, the WGMME advises the following:

A cooperative monitoring approach for marine renewable energy developments is taken, which combines small scale monitoring efforts with large scale cross-boundary marine mammal surveys in order to provide information at a spatial and temporal scale relevant to marine mammals. This approach should incorporate further development of common measurement standards for both noise and marine mammal abundance.

Marine mammals are typically wide ranging and consequently are likely to spend only a proportion of their time within the footprints of any particular demonstrator or commercial-scale renewable energy array. Thus to view any impacts within a population level context, a nested monitoring approach, in which small scale monitoring efforts at renewable energy sites are developed in such a way as to allow integration with regularly repeated large-scale cross-boundary marine mammal surveys. This would provide information at a spatial and temporal scale relevant to marine mammals while allowing the assessment of individual development sites.

To enhance the power of the results all such monitoring efforts should be coordinated between adjacent developments and between countries sharing transboundary populations. Survey methodology should be standardized as much as possible, using surveying methods appropriate for the areas and species of interest, and results should be analysed as a whole (as exemplified by Ireland and the UK's JCP programme). Surveys with ships and airplanes are already covered to a large degree by de facto standards through the very widespread use of distance sampling methods and analysis by means of the associated software (Buckland *et al.* 2001). In contrast to this are stationary visual surveys (from land or fixed platforms) where no standards are available. Some work has been conducted in the field of common standards for using passive acoustic monitors (T-PODs and C-PODs) (Teilmann *et al.* 2001, Teilmann *et al.* 2002, Anon 2009), but there is clearly a need for more work in this direction. Currently there is only one instrument available for high-frequency species (the C-POD), but competing designs are beginning to appear, which increases the need for intercalibration and common standards. In addition, for low-frequency species as well as noise in the range up to 20 kHz, a range of dataloggers are available.

Current methods used to quantify marine mammal distribution, activity and abundance should be adapted or improved so that they can be appropriately applied to studies in and around fast moving water.

Methods to determine the distribution and abundance of marine mammals have been developed over many years and for a variety of applications (Hammond 2010). Further adaptation is currently underway to allow these methods to serve the needs of assessments associated with offshore wind and other renewable energy sites (SMRU Ltd 2010). Several key features of tidal-stream energy sites are shared with these other energy technologies; particularly their location in frequently rough waters and the discrete nature of the developments in relation to the more expansive ranges of the animals using them. However tidal sites are fundamentally different from others in one key feature: the water mass containing the animals of interest is itself mobile relative to the footprint of the development site. Local tidal speeds targeted by the industry typically range from 9 to 15 km.hr-1. This runs the risk of violating some of the assumptions of traditional survey techniques such as boat based visual surveys, towed or fixed passive acoustic monitoring or when performing stationary observations from coastal vantage points.

Geographical location of renewable energy sites should consider the distribution of marine mammals throughout the year, time of day and under typical weather and hydrographical conditions.

For most species of marine mammals the information available on distribution comes from limited sources and there is thus in several cases a strong bias in the information towards times of the year and weather conditions where for example surveys can be conducted. One example is SCANS-II survey which assessed the abundance of harbour porpoises throughout the North Sea. The results of this survey regarding the distribution of porpoises reflect a single moment in time (summer 2005), and they do not provide for information about migration, and for instance on the distribution of porpoises during winter. Also, important shifts in the distribution of marine mammals have occurred throughout recent years, and therefore regular monitoring activities should be undertaken with appropriate methods. Evidently, one single method cannot cover all species, so the most appropriate method must be used for each of the species in question.

As the development of renewable energy sites extends further offshore and into new waters, monitoring should be extended to include all commonly occurring marine mammal species and marine mammal species of particular concern.

Most impact studies and assessments so far (for offshore wind developments) have focused on harbour porpoises and harbour seals. These are the most 'accessible' species: they are the most common species in the coastal waters where wind farms are currently being constructed, methods to study them have been well developed, and captive animals are accessible. However, as renewable energy sites are planned further offshore and extend into new waters, such as the English Channel, the northern North Sea and the Baltic Proper, other species become increasingly important and should be included in assessments and impact studies. For the North Sea this includes species such as the white-beaked dolphin, common dolphin, minke whale and killer whale, while for the Baltic Proper the ringed seal becomes relevant. Offshore wind farm developments on the east coast of the US and Canada will possibly interact with other species, most importantly right whales and belugas.

IMPACT MONITORING

Impact monitoring deals with determining actual effects of construction activities and/or habitat loss connected to the operating renewable energy sites. In addition it also includes quantifying the source of the impact, if this is known. The most prominent example of the latter would be measurements of underwater noise from construction activities and operating devices.

UNDERWATER NOISE

Significant evidence has been collected on the effects of underwater noise due to pile driving, and there is little doubt that this activity can have significant negative effects on marine mammals. Comparatively less is known about the levels and possible impact of underwater noise in general during the construction and operational phases, and as such these also should receive attention.

Next to the recommendations related to the direct effects of underwater noise on marine mammals, there are possibly indirect effects, through effects on the main prey species of marine mammals.

An increase in efforts to characterize sources of underwater noise related to the construction, operation and maintenance of renewable energy sites is required. As part of this, common standards for measurement and characterization of underwater noise should be developed.

Given the many factors influencing the underwater noise emissions and transmission, monitoring of underwater noise should be undertaken whenever there are reasons to believe that results from research at other renewable energy sites cannot be extrapolated. It should be emphasized that at present, there is limited knowledge of the general patterns of noise generation from offshore wind turbines, meaning that emitted noise characteristics cannot be predicted. Transmission loss models for the relevant areas should be developed and used to map the predicted noise impact, based on actual noise measurements.

Underwater noise is now described in different ways, which makes it difficult to compare data. Standards should be chosen in a way to facilitate the monitoring of the effects. Standards for expressing noise have been proposed by Southall *et al*. (2007) and de Jong *et al*. (2010). Southall *et al*. (2007) put the main focus on measures relevant to effects, whereas de Jong *et al*. (2010) put the focus on the physical description of noise. A common best practice of measuring, analysing and presenting underwater noise should be adopted, including methods to quantify the particle motion part of the sound field in addition to the pressure field which is normally the only component measured[2].

[2] Many species of fish, in particular species without swim bladders are mainly sensitive to the particle motion part of the sound field, whereas marine mammals hear only the pressure part. Particle motion is thus primarily of interest concerning impact on fish but the possibility that marine mammals can perceive intense low frequency particle motion should not be excluded.

To understand the perception range available to marine mammals in the vicinity of operating wet renewable energy devices, the sound output of operating devices is quantified along with the surrounding ambient underwater sound of the sites.

During operation of wet renewable devices, lower levels of noise output are expected compared with the construction phases. However the motion of the rotors, internal gearing and so forth will introduce acoustic energy to the water. It is currently unknown over what range this will be audible to marine mammals manoeuvring in close proximity. Coupled with this, information on the levels of ambient sound, relevant to marine mammals, in areas of strong tidal-streams is poorly known. It is currently unknown over what ranges operating turbines will be audible to marine mammals to aid them in avoiding collisions.

Develop methods to assess cumulative effects on marine mammals of the underwater noise level caused by the simultaneous construction and operation at nearby sites.

Currently a lot of data are lacking, which prevents us from assessing the impact of the construction and operation of renewable energy sites on marine mammals, both on individual animals and on populations. Effects should be assessed on a short-term and long-term level, and during the construction and operation phases of the projects. Evaluation of cumulative effects should not be limited to the marine renewables industry but must include all other anthropogenic impacts in the area (such as other construction work, shipping, fishing, and oil and gas activities). Noise mapping (see Section 4.3.1.3.) could act as a tool to account for cumulative impacts of the construction and operation activities of marine renewables as well as other influencing noise sources.

Step up research on the behaviour of marine mammals as a consequence of increased underwater noise levels, in particular on how changes ultimately affect population parameters.

Impact studies have demonstrated behavioural reactions of harbour porpoises towards pile driving noise. Although it is clear that the impact area can be extensive and extends out to at least 20 km from the piling site, the implications of this reaction for the fitness of the affected animals is unknown. It remains important to address this question and establish for example which consequences the reaction has on metabolic intake and ultimately on population parameters such as fecundity and survival. While the individual response of the animals can be measured, the impact should be assessed at the population level; the response of the animals should therefore be translated into a meaning of the effect on the (local) population. Cumulative effects on populations of marine mammals, due to the simultaneous construction and operation of different renewable energy sites, should likewise be assessed.

Increase efforts to characterize fundamental properties of the auditory system of marine mammals and the way noise affects physiology and behaviour.

Assessment of the impact requires fundamental knowledge of the way marine mammals perceive and use sound. For a few species, such as bottlenose dolphins and harbour seals a great deal is known, for others such as harbour porpoises the knowledge is more limited, and for still other species such as grey seal, ringed seal, common and white-beaked dolphins and baleen whales next to nothing is known about hearing physiology. As there can be large and unexpected differences between even closely related species, it is important to have information about parameters such as hearing range, critical bandwidths and TTS-susceptibility. Common for all species is that a fundamental assumption underlying the recommendations of Southall *et al*. (2007), the loudness function, has only been described in a single mammalian species: humans. Extrapolation by means of robust models of the auditory function should be used to assess the impact on species for which limited information is available and for which it is unlikely that such information can be obtained in the near future.

Even though most odontocetes and to some degree seals have comparatively poor hearing at very low frequencies, it is also important to investigate to which degree intense low-frequency sound affects these species.

ANIMAL-DEVICE INTERACTIONS

Independent research should be carried out into the nature of close-range interactions between marine mammals and wet renewables and the potential population consequences of these.

Interactions between wet-renewables and marine animals remain poorly understood. The principal environmental concerns derive from the potential for physical injury to animals through direct contact with the device's moving structures. In addition other potential effects include habitat exclusion, barrier effects to passage, and noise-related injury.

The diversity in technical design, size and developmental stage of wet renewables is immense and the industry is evolving quickly. Animal-wet renewable interactions are likely to be species-, site- and device- (or device-type-) specific, and therefore care needs to be taken when extrapolating conclusions about environmental impacts between species, sites and device types. Such extrapolation might eventually become justifiable once more insight into the stressor-response functions between all parameters is achieved. Many potential impacts described above are, however, likely to be relatively rare events. However, if scaled up to large numbers of devices, such rare events could still have a considerable impact. Under these circumstances, further in-depth investigation of such issues with a small number of device types could significantly advance our understanding of the risks posed by wet renewables more generally. It is important to reiterate that the conduct of impact monitoring by site developers needs to be a condition upon any consent given for a demonstration device or array, taking into account what might be considered appropriate monitoring levels given environmental conditions and statistical data requirements in order to draw firm conclusions.

ELECTROMAGNETIC FIELDS

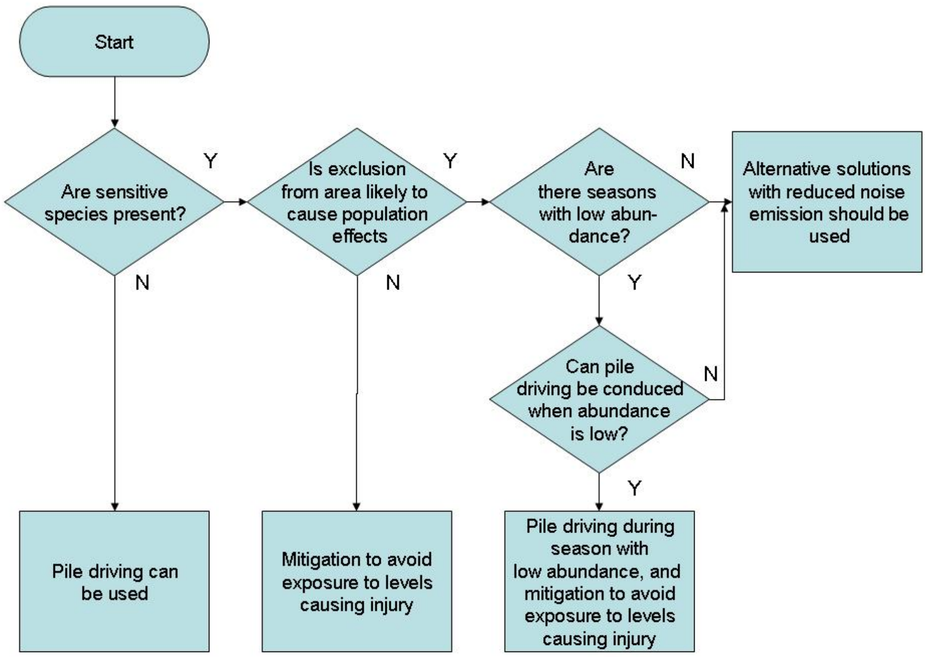
The sensitivity of marine mammals to environmental perturbations from electromagnetic fields, possibly generated by cables, should be investigated and the potential displacement implications considered.

Large marine generators and the high voltage alternating and direct current cables that transmit power between devices and the land have the potential to interact with aquatic animals that are sensitive to electric and magnetic fields. Although this is known to affect some fish species there is currently little understanding of its potential to affect marine mammals; although recent experimental studies of the effects of electric fields on pinnipeds indicates that they may be unexpectedly sensitive to, and show avoidance of, relatively low intensity electric field.

MITIGATION

If a temporary exclusion from the renewable energy site and adjacent areas impacted can be shown to be unlikely for the population in the relevant management area, then it may be appropriate to mitigate at the level of physical injury (TTS, PTS and non-auditory effects). This means that mitigation measures should ensure only that (ideally) no individuals are exposed to sound levels causing physical injury. If on the contrary, there is insufficient information available or direct concern that temporary habitat loss may affect the population, then mitigation must take place at the level of behavioural disturbance. This implies that the habitat loss should be minimized to a degree considered within acceptable levels.

The following diagram illustrates how a decision process could be organized for offshore wind farm developments:



COMMON GUIDELINES FOR MITIGATION

With regard to marine mammals, to work towards common accepted tolerance limits for acute noise exposure and the development of common guidelines for mitigation in relation to pile driving and other adverse activities.

The information regarding acute effects of underwater noise on marine mammals has increased considerably in recent years (reviewed among others by (Southall *et al.* 2007, OSPAR 2009a, b))and has reached a level where it makes sense to start discussing the establishment of scientifically based tolerance limits. Such a development also falls along the lines of the requirements of the European Marine Strategy Framework Directive, which among other requires indicators for Good

Environmental Status regarding underwater noise. Work in this area is being, or has already been undertaken within different organizations, such as the US Marine Mammal Commission. In line with recommendations of Southall *et al*. (2007), such exposure criteria should consider both unweighted and frequency weighted sound pressures as well as cumulated sound energy, both within single sounds and across multiple exposures. Exposure criteria should, as far as possible, be developed on a species by species basis.

Connected to the establishment of common tolerance limits, is the development of common guidelines for best practice and mitigation measures to be used to minimize the risk that marine mammals are exposed to sound levels exceeding the exposure criteria.

ACOUSTIC DETERRENT DEVICES

To undertake studies to develop better marine mammal acoustic deterrent devices, including realistic trials in the field to demonstrate their effectiveness.

One method for mitigating the risk of hearing damage from pile driving is to move vulnerable animals out of the danger zone by broadcasting aversive sounds, i.e. sounds which cause animals to move away without adding significantly to the animals' acoustic dose. If a method based on aversive signals could be developed and shown to be effective, it could have a number of advantages. As marine mammals are so difficult to detect at sea and mitigation zones are substantial, aversive signal mitigation could be more effective than current methods which relies on detecting animals within the impact zone followed by a temporary shut-down of piling. The use of deterrent devices would also allow construction to continue in poor weather conditions and at night and they should be very cost-effective. SMRU Ltd (2007) explored the potential advantages and problems of such a system and reviewed terrestrial examples where sound is used to move animals. Overall their conclusions were encouraging. They cited many examples of marine mammals moving considerable distances in response to sound. The authors mention two important caveats however. The first is that, to avoid habituation, whatever aversive signal might eventually be deployed, it should be quite different from other signals that animals might be routinely exposed to. For this reason existing acoustic deterrent devices such as fisheries pingers and "seal scarers" should not be used. By using a unique signal, which is coupled to something unpleasant (the pile driving noise that will follow) the risk of habituation is strongly reduced, as the animals are not reinforced for habituating to the signal as is the case with for example seals to seal scarers. Here the seal scarer is intended to deter animals from something they want to obtain (fish in fishing gear or in a fish farm).The other important caveat of deterrent devices is that these methods can only be relied upon once a substantial body of data has been collected to prove that they are effective on all the species of concern. These should be based on field trials in realistic field conditions, including on foraging grounds.

REAL-TIME DETECTION OF MARINE MAMMALS

Attention should be given to improve efficient means of real-time detection of marine mammals during pile driving.

Visual observers and passive acoustic monitoring have been suggested as a mitigation measure during pile driving. Operators are asked to shut down the operation if marine mammals are observed inside a designated safety zone. The efficiency of such a procedure depends critically on the ability to detect the presence of marine mammals with sufficient reliability (low rate of misses, low rate of false alarms) within the entire relevant impact area (zone of injury), which could extend out to distances of several kilometres from the construction site (Gordon *et al*., 2009).

ALTERNATIVE METHODS FOR INSTALLIATION

Measures should be taken to prevent marine mammals from being exposed to high levels of underwater noise. This includes limiting the radiated energy during pile driving and the development of alternative methods for installation.

The most efficient way to reduce impact from widespread and extensive pile driving is to develop alternative methods for installing foundations with reduced noise emission during installation. The best approach to reducing impact from construction of renewable energy devices is to avoid pile driving altogether, such as through developing alternative methods for pile driving or the use of alternative types of foundation. In the case of offshore wind farms this includes, but is not limited to use of gravitational foundations or suction piles, installation by water jet or by drilling, and in deeper waters use of floating platforms tethered to the seabed. Secondary solutions involve limiting the energy radiated from the pile driving into the water for example by using bubble curtains or pile sleeves (if feasible and if efficient).

SUMMARY OF THE MAIN DATA GAPS

Data gaps that are identified in this review should be addressed. These include interactions with the devices, noise outputs under a range of environmental conditions, and synergistic effects of arrays versus individual devices.

Significant data gaps presently limit greater understanding of potential impacts of marine renewable energy devices on marine mammals. These include basic knowledge of marine mammals and how they behave around devices, emissions from different devices (*e.g.*, noise, EM fields) and their effects on marine mammals under different environmental conditions, and cumulative effects of multiple devices in arrays. These data gaps need to be addressed to help reduce the impacts of the marine renewables industry on marine mammals. Some of these gaps will need to be addressed by individual site developers, while others are best tackled by academic institutions or regulatory agencies. A collaborative approach between different stakeholders may be appropriate.

Many data gaps remain in our knowledge of basic biological features of many marine mammal species (e.g., spatiotemporal distribution, population size and structure, foraging and breeding areas) as well as any effects of marine renewable devices on these species. Filling these data gaps is likely to be the responsibility of academic institutions and national regulators, rather than individual developers. These include:

- Abundance, seasonal distribution, migration patterns, population structure and development and habitat use for all marine mammal species in the areas of interest.

- Information on diet and foraging ecology for all marine mammal species in the areas of interest.

Underwater noise can be generated by a variety of sources in conjunction with the site preparation, construction, operation, and decommissioning of energy devices. Their potential effects on marine mammals can be diverse and an assessment can be complex (NRC 2005, Southall *et al.* 2007, Boehlert *et al.* 2008, Ellison *et al.* 2011). Underwater sound plays a primary role for marine mammals. However, the acoustic sensitivity of many marine mammal species remains poorly studied or completely unknown. Therefore the analysis of impacts needs to be relevant for the species found near these devices and needs to be related to the specific sounds emitted by each particular type of device. It has to be stressed that the range of sounds generated by these devices remains as yet largely un-described.

The sounds emitted during the construction, operation and decommissioning of the systems will have to be assessed separately. Depending on the method used to install the devices intense noise can be generated and emitted into the marine environment, with particular construction methods such as blasting or pile driving of particular concern. Dedicated studies need to be conducted to document the acoustic characteristics of sound emitted during site preparation, construction, operation, and decommissioning of single devices. This should also take into account the sounds emitted by the ships used during installation and cable laying as well as the potential cumulative sound field of an array of devices.

Currently the key data gaps within, particularly, the wet renewables sectors in terms of sound emissions are:

- Acoustic measurements need to be conducted for the various techniques used during installation of the devices.

- The acoustic signature (level and spectrum as well as their temporal variation) of single devices and multiple systems in an array needs to be monitored. These measurements need to be conducted both inside and outside of the array. This is especially important to address the generation of synchronous or asynchronous noise by an array.

- Ambient (background noise) needs to be monitored in a wide variety of environmental conditions, with particular focus on higher sea states.

- Measurements need to be gathered under different sea states conditions to differentiate background noise from the device noise, and to understand how noise generation changes under different environmental conditions (e.g., by means of seafloor-mounted passive acoustic recorders).

- Sounds emitted by the ships employed during the installation/decommissioning process or for maintenance need to be measured under different environmental conditions.

Most of these data gaps could be filled by site developers as part of the regulatory licensing process. Ambient noise monitoring is also likely to be initiated as part of wider environmental monitoring efforts under the EC Marine Strategy Framework Directive (Tasker *et al.* 2010).

There are also several data gaps concerning both acoustic and aspects of animal-device interactions:

- Auditory studies need to be undertaken to test the acoustic sensitivity and acoustic tolerance of those marine mammal species that are at risk but where data are currently unavailable to assess ranges of auditory perception. This is particularly important when construction of the renewable energy devices involves the emission of intense sound into the underwater environment.

- Auditory studies are needed to investigate the potential for masking of communication and/ or other biologically significant sounds by means of sounds emitted by renewable energy devices.

- Behavioural studies including controlled exposure studies on free-ranging animals could be conducted.

- Assessment of the nature of close-range interactions between marine mammals and, operating wet renewable devices and, vessels using ducted propellers.

These particular data gaps are likely to be more appropriately addressed at a broader level by academic or regulatory bodies.

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