Impacts of Noise from Marine Turbine on Bottlenose Dolphin (*Tursiops truncatus*)

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Abstract

There is a clear vision that the use of non-renewable energy to generate electricity has caused significant environmental degradation such as global climate change and rise of sea level. At the same time, the increasing global energy demand accelerates the consumption of global non-renewable energy resources and consequently leads to the "energy crisis". Therefore for the need of sustainable development, renewable energy such as wind, solar and hydro is required for solving the increasing energy demand and reducing the adverse impacts to the environment.

However, renewable energy development especially offshore renewable energy development (ORED) is completely new in human history. There are many side effects brought by the ORED, for example, release of contaminants to the sea, collision of marine species with marine structures, habitats exclusion, etc. Among various impacts, there is a growing concern about the noise impact to marine species especially marine mammals. Marine mammals mainly cetaceans replied on hearing and echolocation for finding preys, communicating with each other and self-orientation. But noise produced from the construction, operation and decommissioning activities of marine turbines could potentially influence the accuracy of the echolocation and hearing system of marine mammals. Furthermore, noise could also cause physical injury such as deafness.

The latest ORED in Europe is the upcoming underwater tidal turbine project in Alderney, Channel Islands. Alderney waters are rich in marine mammals, which the main residential marine mammal is bottlenose dolphin. Based on the desktop study of many existing literatures of noise and bottlenose dolphins, this paper is aiming to assess the noise impacts brought by the tidal turbines on bottlenose dolphins in Alderney area, and if possible to give suggestion on any future investigation for better monitoring and mitigation of the impacts.

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For everyone stated above and anyone that is not mentioned but helped me with my work, please accept my most sincere appreciation because this paper will not be created without your help.

Author’s Declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University’s Regulations and Code of Practice for Taught Postgraduate Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, this work is my own work. Work done in collaboration with, or with the assistance of others, is indicated as such. I have identified all material in this dissertation, which is not my own work through appropriate referencing and acknowledgement.

Any views expressed in the dissertation are those of the author and in no way represent those of the University of Bristol.

The dissertation has not been presented to any other University for examination either in the United Kingdom or overseas.

SIGNED:

DATE: 30 September 2011

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1. Introduction

1.1 Old Days and New Days

In nearly last two hundred years, non-renewable energy resources such as oil, coal and natural gas were extensively used for generating electricity. The burning of fossil fuels can generate green house gases, particles and other pollutants into the atmosphere and will impose impacts such as global warming, rise of sea level, etc. Although the issue of climate change is still under debate, the fact however is that there had been a global temperature rise of 3°C – 5°C and increase in climate variability (Houghton, 2001). Moreover, with significant growing of world's population and energy demand, non-renewable energy resources are becoming more and more precious and could only be used for finite years.

In contrast electricity generated from renewable energy such as solar, hydro, wind, tidal and geothermal heat is more sustainable and harmless to the environment (A.Gritsevskyi, IAEA, 2007). The major benefits of using renewable energy are that the energy resources are relatively perpetual and will not generate any green house gases. In order to achieve sustainable development, the need of alternative energy is essential and many countries are now shifting from using of non-renewable energy to renewable energy. Among various renewable energy options, marine energy is particularly important due to the various engineering options and vast sea areas. Countries with long coastlines normally have valuable marine renewable energy sources such as tides, water currents and waves (Gill, 2005). Offshore wind farm is currently recognised as the most developed and preferred method for gathering marine energy. At the same time, tidal and wave energy is also getting more and more interests.

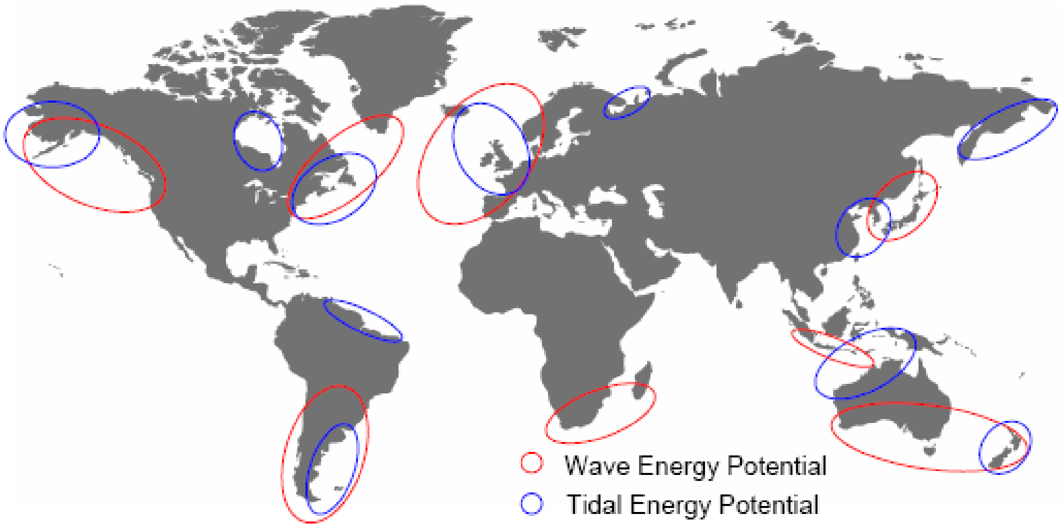

Figure 1: Wave and tidal energy potential of the world (Sarah J. Dolman1, 2009).

Tidal power is the use of the twice flood and ebb tides everyday. Recent studies found it is also possible to use tidal races if particular tidal turbines can be designed (Bahaj, 2003).

The benefits of all offshore renewable energy development (ORED) are remarkable. But on the other hand, ORED could also have some side effects to the ambient marine environment. The impacts could be acute and chronicle and are normally different according to the construction, operation and decommissioning activities of the project. Furthermore, since ORED is still relatively new, certainly not all of its impacts are fully identified and assessed especially for the tidal and wave energy projects. Therefore in order to achieve sustainable development without creating any new side effects, it is essential to identify any possible adverse impacts that could be caused by the ORED. Thereafter it is possible to evaluate the existing technologies and designs in order to avoid or mitigate these impacts.

1.2 Potential Impacts of ORED on Marine Mammals

ORED used to be restricted in shallow waters and the impacts on marine environment are therefore also limited. However, as deeper water development becomes legitimate, the range and depth of the offshore development are extended (Kempton, 2005). Along with this extension, one of the major impacts of ORED is the influence on marine species. More and more marine species would be affected including the ones normally live in deep water, for example, marine mammals.

"The danger of marine mammals being injured by tidal turbines have already been recognised following reports published in 2008 and 2009"

(McKenzie, 2011)

Marine mammals are highly intelligent species and are in the upper class of the food chain. They are extremely important in balancing regional biodiversity and modification of benthic habitat (Bowen, 1997). Some studies showed that ORED would mainly cause impacts on harbour porpoise, harbour seals and bottlenose dolphins (Carstensen, 2006) (Lusseau, 2005). The observed short-term impacts are mainly:

- Noise from the construction, operation and decommissioning activities could cause temporary or permanent shift of hearing sensitivity of marine mammals (Nedwell J.R., 2004).
- Increasing of turbidity of water could lead to decrease of the visual range of marine mammals.
- Increasing vessel activities could also increase underwater noise level and the probability of collision.

Moreover, there could be also some long-term impacts:

- Physical presence of the structures could block the foraging passage of marine mammals (ETSU, 2000).
- Increasing collision probability of the marine mammals with the structures.
- Continuous noise and vibration from operation of the turbines could cause fatiguing to the marine mammals.
- Electromagnetic impact emitted from the cable could impact on the food sources.

Besides these direct impacts, there are also many indirect impacts on marine mammals. For example, the impact on reduction of their food sources such as fish and crustaceans could also lead to reduce amount of residential marine mammals in the area. Furthermore, many impacts have not emerged yet and could be identified.

1.3 Needs of Research of Noise Impact on Marine Mammals

Among all impacts, marine noise to marine animals has been an emerging concern with the increasing development of marine renewable energy (WDCS, 2004). This is because marine mammals mainly live on object recognition, which is the ability of utilising sound to identify predators, preys, rivals and surrounding environment. This is especially important in environment with poor visibility conditions (Heidi E. Harley, 2008). However, noise could affect the accuracy of their ability on object recognition and could also lead to hearing damage and increasing stress (Dolman, 2004) (Sarah J. Dolman1, 2009). At the same time, our understanding of the noise impacts on marine mammals is inadequate. The study on underwater noise is still delayed comparing with the understanding of other impacts such as chemical pollution (WDCS, 2004). More useful data would only become available with the progress of ORED. In this case, the needs of research on noise impacts on marine mammals are urgent.

1.4 Tidal Turbine Project in Alderney

This entire study is based on the upcoming tidal turbine project in Alderney in Channel Islands, which the latest ORED in Europe. Alderney is very rich in marine energy resources. It is known as one of Europe's optimum sites for harvesting tidal power. Research estimated that the tidal power from Alderney area is capable of generating 1,000 – 3,000 MW energy. In order to utilise the abundant marine energy, Alderney Renewable Energy (ARE) was founded in 2004 and they proposed a complete renewable energy scheme for the island. By using two conventional 0.8 MW pumped storage hydroelectric power turbines (HEP), water will be pumped up to a reservoir in Fort Albert and discharged to a Reservoir located in lower altitude at Bibette Head. Since energy will be needed for lifting water up to the reservoir in Fort Albert, three tidal turbines will be installed underwater in the Race to generate the energy. This project could potentially help protect the island from rising oil prices, providing cheap and secure electricity and reducing carbon emission.

However, this is only a small picture of the entire blueprint. In phase 2 of the project, hundreds of additional turbines will be placed in the Alderney Race for larger energy generation and in phase 3, high voltage cables will be buried to interconnect France, Alderney and Britain (FAB) to allow exportation of additional energy produced from Alderney.

1.5 Major Residential Marine Mammal in Alderney: Bottlenose Dolphin

There are large amount and diverse range of marine mammals resident around Alderney waters because of the abundant food resources. These marine mammals live inshore and in the pelagic water for breeding, foraging and other activities. A UK based company named ENTEC carried out numerous boat surveys between 2006 and 2008 for recording the major marine mammals that would appear in The Race of Alderney. Between 14 March 2006 and 18 February 2007, 23 boat surveys were carried out and additional 21 surveys were undertaken between 27 March 2007 and 19 January 2008 (ARE, 2009). From April to December 2010, a marine mammals survey also carried out by Alderney Wildlife Trust (AWT) particularly in Longis Bay where the tidal turbines will be installed.

According to the surveys, marine mammals including common dolphins and grey seals were recorded only in the north of Alderney, which is away from the tidal turbine location. Meanwhile, harbour porpoises were infrequently sighted. The sighting records however indicated that bottlenose dolphin is the major marine mammal resident in Alderney. They were frequently sighted during the survey periods that the encounter rate was about 0.1 individual per hour (ARE, 2009). The surveys also recorded seven pods (groups) of bottlenose dolphins ranging from 2 – 12 individuals frequently using the waters in Longis Bay area.

1.6 Needs of Research of Noise Impact on Bottlenose Dolphin

One of the major reasons for research on noise impact on bottlenose dolphin is legislation. Alderney is an independent British Crown Dependency and a constituent part of the Bailiwick of Guernsey. Although it is not part of the EU, the Alderney Renewable Energy Law was established in 2007, together with the birth of Alderney Commission for Renewable Energy (ACRE), is based on the EU regulations. Bottlenose dolphins are under protection of EU Habitats Directive 1992 (WDCS). Therefore it is essential to understand any impacts arise from the construction, operation and decommissioning activities on bottlenose dolphins in Alderney.

The illumination condition is very poor in deep water therefore dolphins are living on object recognition to recognise predators, preys, rivals and surrounding environment (Heidi E. Harley, 2008). Object recognition of bottlenose dolphins is accomplished by echolocation, which is the ability to produce acoustic sound called clicks. The clicks will be bounced back to dolphins after hitting an object and bottlenose dolphins could analyse the returning echoes to obtain information of the surroundings (DeRuiter, 2000). At the same time, in order to detect the clicks and ambient sound, bottlenose dolphins also possess highly developed hearing system. Combing the echolocation and hearing system, they could freely forage their preys, detect objects and communicate with each other (Heidi E. Harley, 2008). As described earlier, marine mammals like bottlenose dolphins are vital in balancing regional marine ecosystem. However, among various impacts, there is a growing concern that noise can give significant adverse impacts to the echolocation and hearing system of bottlenose dolphins and cause serious consequences (UN Secretary-General, 2007).

Various noises will be produced throughout the lifecycle of the marine turbines. For instance, huge noise will be produced by pile driving during construction, direct and indirect noise will come from the rotation of turbine blades during operation. Moreover, the explosion of structures while decommissioning could also cause noise. Recent studies showed that only foundation construction and cable laying activities would produce noise up to 260dB and 178dB respectively (Nedwell J. R., 2004). Noise at this level could cause temporary threshold shift (TTS) to bottlenose dolphins and reduce their hearing sensitivity. Furthermore, study from Whitlow et al. (2007) also showed that the detection range of bottlenose dolphins would be influenced by noise produced from their detecting targets. It is also clear that noise could lead to change of foraging and migratory behaviour, communicating and self-orientation precision of bottlenose dolphins. Loud noise will even result hearing damage and death (Weilgart, 2007).

Some companies and organisations such as CROWIE and WDCS already carried out many studies related to the noise impacts produced by offshore wind farm on marine mammals. However, there are not many studies particularly focus on the noise impacts from the underwater tidal turbines on bottlenose dolphins. Therefore based on the review of many existing literatures, this paper will first try to explain the properties of underwater sound and noise in section 2.1. Section 2.2 will introduce the bottlenose dolphin in marine mammal family and the details about its echolocation and hearing system. Followed by a case study, this paper will try to critically analyse an environmental statement produced by EMEC for a similar tidal turbine project in Sound of Islay, Scotland. Since no precise data is available at moment on any noise that could be produced from the tidal turbines in Alderney, the analysis of the noise impacts on hearing and echolocation system of bottlenose dolphins will be discussed using a source-pathway-receptor model. In particular, Section 4.3 will try to assess the impacts according to the magnitude of impacts and sensitivity of the receptor.

2. Literature Review

2.1 Underwater Sound and Noise

In order to assess the noise impacts on bottlenose dolphins, it is necessary to start the discussion with the understanding of sound and noise. Sound is a wave that can travel through different mediums such as liquid, solid and air and is normally produced by mechanical vibrations (Hildebrand, 2007). Since sound is a wave, the first physical property to explain is frequency (f). Frequency is described as the rate of oscillation of the sound wave per second and with unit of Hertz (Hz) (Hildebrand, 2007). 100 Hz means the sound wave oscillates 100 times when travelling from one place to another in 1 second. The travelled distance of 1 oscillation in 1 second is then called wavelength. Therefore the relationship between frequency and wavelength is:

velocity (c) = wavelength (λ) x frequency (f)

where c is the speed of sound. The sound speed in air is about 340ms^{-1} but when it travels in water, it is about four times faster (OGP, 2008).

The strength of sound at source is called sound power level (SWL), which is measured in decibels (dB). Decibel is a logarithm scale between two values and is used to compress quantities to a smaller scale for better comparison (Bellhouse, 2004). For example, log10 = 1 and log 1000 = 3 and the ratio of 1000:10 is now becoming 3:1. In practice, if one turbine produces 40dB of sound and the other one also produced 40 dB of sound, the total sound level is 43dB rather than 80dB (Rogers, 2006). This suggests that a 3dB increase in sound power level means doubling of sound strength at source.

Since the sound in the water is normally measured according to the pressure, another important definition to mention is the sound pressure level (SPL). Comparing with SWL, SPL is the measurement of the sound level at receptor and the unit is also decibel. It is expressed as:

Sound Pressure Level (dB) = 20 log (P/P_0)

where the P is the pressure and P_0 is the reference pressure. The P_0 in the water is known as 1μPa (Frank Thomsen, 2006).

It is essential to distinguish the definition between SWL and SPL where the former is the sound level at sound source and latter is the sound level at receptor. The relationship between SWL and SPL can be described using the formula below:

Sound Pressure Level (dB) = Sound Power level (dB) – 20 x Log(r) – 11 dB

In the formula, r is the distance (unit: metre) between sound source and the receptor. The sound Power Level is in dB re 10^{-12} watts (Bellhouse, 2004).

It is now much easier to understand noise after the understanding of sound. It has been widely recognised that any unwanted sound can be defined as noise. Therefore noise carries all the properties of sound. However, noise is a relative concept because "unwanted sound" is defined according to the perception of the receptor. For example, clicks produced by marine mammals maybe recognised as noise to other marine species. Therefore noise to marine mammals is the sound that can cause nuisance to them. However, it is still varied among different species of marine mammals. Vella et al. (2001) concluded the underwater noise into five levels according to the reaction of marine receptors (Vella, 2001):

- Detection level: the environmental noise that marine species detect in a normal underwater status.
- Avoidance level: the noise that causes marine species actively avoids the area.
- Temporary threshold shift level: the noise that causes temporary increase of the lowest sound that marine species can hear.
- Permanent threshold shift level: the noise that causes permanent increase of the lowest sound that marine species can hear.
- Physical damage level: the noise that causes damage of the hearing system of marine species.

However, not all noise will give adverse impacts to the receptors. There is a type of noise called white noise, which is a sound signal with constant loudness. In other words, the noise is fixed in sound level within a steady bandwidth (Yates, 2009). In contrast white noise will not cause nuisance to the receptors and could be used for masking other noises.

2.2 Marine Mammals

There are more than 120 species of marine mammals in the world. They can be divided into five groups, which are sirenian, cetacean, carnivore, desmostylia and pilose (Hoelzel, 2002). The major marine mammals in Alderney areas are cetaceans (ARE, 2009). Cetaceans can then be classified into two groups, which are odonotocetes (toothed whales) and mysticetes (baleen whales) according to their foraging methods (Hooker, 2009). However, as mysticetes like blue whales or killer whales were not sighted during the surveys between 2006 and 2008, they are not our primary concern in this paper and will not be discussed in details. The major residential odonotocetes are in Alderney waters are bottlenose dolphins throughout all year (ARE, 2009).

2.2.1 Bottlenose Dolphin

Bottlenose dolphin is one of the most famous odonotocetes in the world because they can be widely seen in aquariums or marine parks. They are widely distributed across tropical and temperate oceans (Dawson, 1993). Recent studies have found that there are two types of bottlenose dolphin: the Atlantic bottlenose dolphin (Tursiops *truncatus*) and the Indo-pacific bottlenose dolphin (Tursiops *aduncus*) (Akamatsu, 2005) where the latter is mainly living in the Indian Ocean (American Cetacean Society, 2004). The surveys carried out by NETEC did not indicate the type of dolphin in Alderney area but is more likely to be the Atlantic bottlenose dolphin. Bottlenose dolphins reply on object recognition by using their highly developed sound production system together with sensitive hearing ability to find prey and avoid predators, to identify partners and locate themselves (Songhai Li, 2011). In other words, they can both produce and received sounds underwater.

2.2.2 Sound Production and Echolocation

Although dolphins have good eyesight that can both work underwater and in-air, the illumination condition in deep water is normally too poor for them to focus (Herman, 1975). In this case, dolphins produce sound including clicks, whistles and pulses to achieve all kinds of activities underwater. There are two major types of sounds according to their properties: the long-duration narrow bandwidth sound and the short-duration broad bandwidth sound (Zamudio, 2005). Former is used for intraspecific communication which the frequency is about 1 – 20 kHz and the SPL is approximately 158 - 170 dB re 1μPa (Janik, 2000) (Scott M.D., 1999). The short-duration broad bandwidth sound is used for detection of surrounding environment and self-orientation and is also the sound used for echolocation.

Echolocation is defined as an ability to produce high frequency sound, which is also called click. In contrast, the sound produced for echolocation (click) is normally between 20 – 150 kHz (Figure 3 right) and the typical strength is 226 dB re 1μPa (S D Richards, 2007) (J.R. Nedwell, 2004). The detail of echolocation sound production has been studied for many years. The following sketch presented how bottlenose dolphins produce clicks and receive returning echoes from a biological point of view:

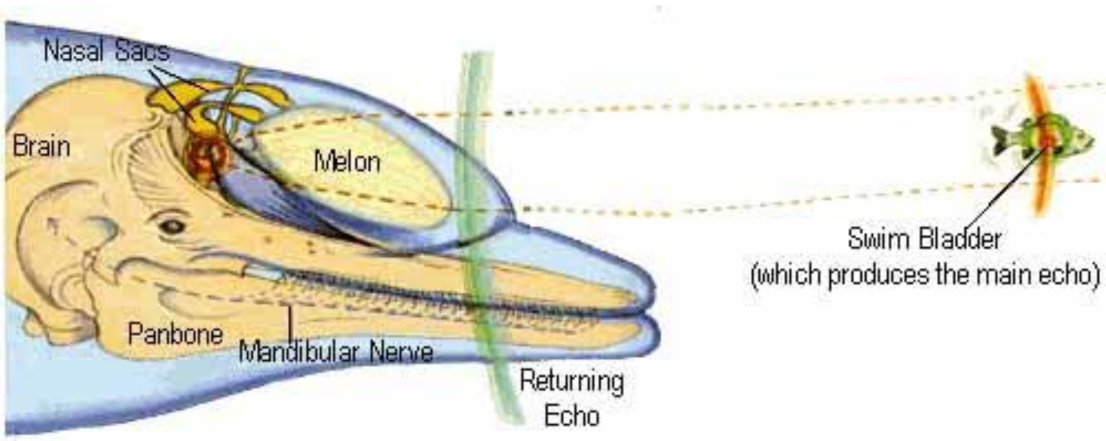

Figure 2: Echolocation process of bottlenose dolphin (Greenpeace Communications, 1990).

Bottlenose dolphins are able to generate the clicks from their nasal sacs and use melon to focus the click into beams for better propagation (Greenpeace Communications, 1990). Therefore when the sound hits an object, it will be bounced back to the dolphins (as echoes) and received by the Panbone. The Panbone could then pass the signal to allow them to determine the distance and shape of the object (Berta A., 1999). Dolphins normally produce the clicks in sequence. This means they will produce one click and receive the echo before they produce the second click. The interval between two clicks is usually the time needed for the sound to travel between the target and dolphin plus 19 – 45μs of signal-interpretation time (Figure 3 left) (Au, 1993).

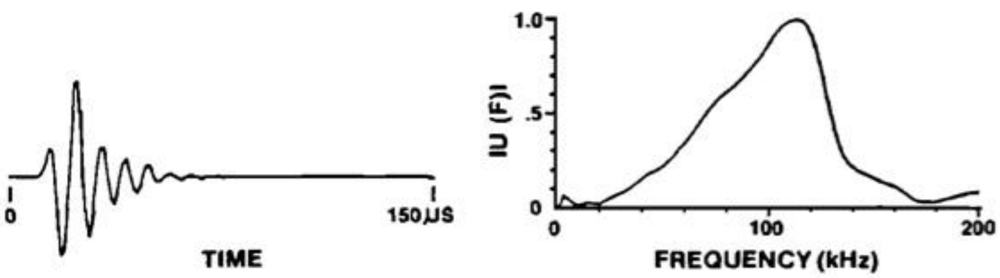

Figure 3: Bottlenose dolphin echolocation signal (Whitlow W. L. Au., 1987).

Au and Snyder et al. (1980) recorded the echoes bounced back from a water-filled cylinder and found that the actual echoes received by bottlenose dolphins are quite complex (Figure 4).

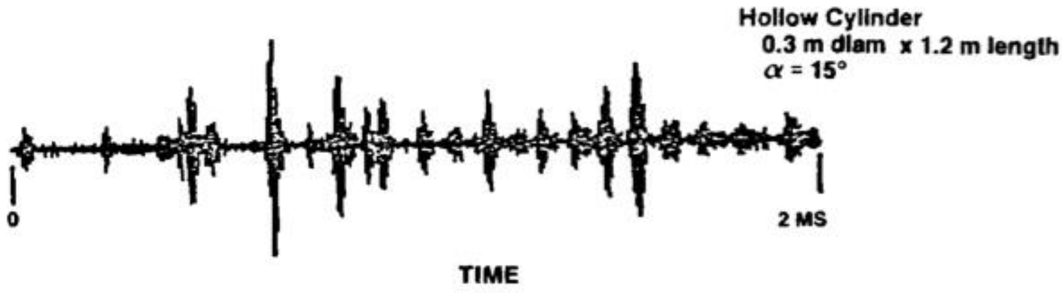

Figure 4: Received echoes of Bottlenose dolphin from a hollow cylinder (Au W. S., 1980).

The real situation underwater is even more complicated. Bottlenose dolphins will not only hear their own clicks when echolocating objects. The sound they receive will contain the returning clicks, natural noise like movement of water, noise from preys like fish and also the anthropogenic noise from marine activities. Au and Patrick et al. (1987) then did several experiments trying to identify how bottlenose dolphins distinguish echoes from self-generated clicks in noise. It is known that the ambient noise will reduce the efficiency of bottlenose dolphins. Therefore in the experiments, Au and Patrick et al. (1987) introduced a constant noise level of 64dB at frequencies between 80 – 120 kHz. They find out bottlenose dolphins are remain capable of recognising useful echoes among all incoming signals as they detect echoes according to the energy levels (Whitlow W. L. Au., 1987). The noise masked during the experiments is 5 – 11dB above background noise, however, this is not usually the case in real underwater world. Human activities have dramatically increased the strength and duration of marine noise and the actual underwater noise nowadays is much higher than just 5 – 11dB.

Houser et al. concluded the clicks produced by bottlenose dolphin into seven categories based on the frequency and magnitude of the sound. The research showed that most of the clicks are E type, which is the frequency greater than

70 kHz (D. S. Houser, 1999). However, the research did not suggest the relevant functions of each type of click and human's understanding of the echolocation system of bottlenose dolphin is still miserable. The limitations of using echolocation by bottlenose dolphins are not well studied. Information like distance and shape derived according to the returning sound is highly dependent on the outfit of the target but how they will influence the information is still not clear.

2.2.3 Hearing Mechanisms

The responses of bottlenose dolphins to any sound replies on the hearing system. Mammalian ears can be divided into three sections, which are the outer ear for collecting sound, middle ear for transforming the sound energy into mechanical energy and the inner ear to detect the mechanical energy for the brain to interpret the signals (Burgman, 2010). Likewise, bottlenose dolphin uses soft tissue and bone to conduct sounds to the middle ear through the lower jaw. The sound is then passed into the inner ears, which contain number of nerve cells and basilar membrane for further transmitting (Ketten D. , 1994). Ketten (1994) found that the stiffness and thickness of the basilar membrane is closely related to the hearing capability of the animals. In order to live underwater, the adaption made bottlenose dolphins have much stronger basilar membrane than terrestrial mammals and therefore possesses notably hearing capability. For example, humans can hear sound with frequency ranging from 0.02 – 20 kHz where the hearing range of bottlenose dolphin is from 1 – 150 kHz (Elert, 2003) (SeaWorld, 2002).

2.2.4 Threshold of Hearing

As introduced earlier in Section 2.1, sound consists of frequency and strength where strength is described as sound level. The minimum sound level that can be heard is called threshold of hearing or the sensitivity of hearing (Durrant J D, 1984). Bottlenose dolphins are very sensitive to sound but the hearing sensitivity could vary within the hearing range (Thompson R. H., 1975). The threshold of hearing is varied at different frequency where the frequency that hearing is most accurate is called peak frequency (Gelfand, 1990).

Many studies have been carried out on measuring the hearing threshold of bottlenose dolphins. Johnson carried one of the earliest and most detailed experiments in 1967. The results are as followed:

Frequency (Hz)	75	100	200	300	400	500	600	700	800	900
Level (dB)	132	131	113	104	100	98	105	91	94	98
Frequency (kHz)	1	2	3	4	5	6	7	8	9	10
Level (dB)	96	72	76	80	73	68	62	66	62	60
Frequency (kHz)	12	14	15	16	18	20	25	30	35	40
Level (dB)	53	43	50	52	50	51	47	52	44	49
Frequency (kHz)	45	50	55	60	65	70	75	80	85	90
Level (dB)	42	44	48	49	41	48	54	47	55	55
Frequency (kHz)	95	100	105	110	115	120	125	130	135	140
Level (dB)	51	59	53	54	50	59	62	62	65	70
Frequency (kHz)	145	150								
Level (dB)	96	136								

Table 1: Change of hearing threshold of bottlenose dolphin from low to high frequency of sound (Johnson, 1976).

The result of Table 1 was obtained by using the behavioural methods. Generally speaking, it is the method that detects the threshold level according to the animals' movement when different frequency was casted. There is another method called evoked auditory potential method, which is the direct measurement of the impulse in the dolphin's auditory nerves (J.R. Nedwell, 2004). By using the latter method, Popov et al. did another sets of experiments in 1990 and tested the hearing sensitivity of bottlenose dolphins again. The results are as follow:

Frequency (kHz)	5	10	20	40	60	80	100	120	130	140
Threshold Level (dB)	82	80	74	67	69	57	70	80	100	>120

Table 2: Threshold levels of bottlenose dolphin (Popov, 1990).

Although the frequencies of sound used is not as comprehensive as Johnson did in 1967, it showed the same trend that bottlenose dolphin has the highest hearing sensitivity when at sound frequency around 80 kHz.

Sometimes sound is radiated semi-spherically from the source, hence it is unpredictable which direction will the bottlenose dolphin face to when the noise arrives. Therefore Popov et al. (1990) also did some tests and found out that the hearing sensitivity of bottlenose dolphin is most sensitive at the head, where the sensitivity is averagely 35 dB lower at the back (Popov, 1990).

Moreover, the hearing sensitivity of bottlenose dolphins varies from male to female. Brill et al. (2001) tested two dolphins – a 14-year-old female and a 33-year-old male – with sound frequency from 10 kHz up to 150 kHz.

Male Bottlenose Dolphin:

Frequency (kHz)	10	20	30	60
Left panbone threshold level (dB)	92	79	92	154
Right panbone threshold level (dB)	107	112	122	135
Average threshold level (dB)	99.5	95.5	107	144.5

Table 3: Hearing threshold of male bottlenose dolphin (Brill, 2001).

Female Bottlenose Dolphin:

Frequency (kHz)	10	20	30	60
Threshold Level (Left panbone)	86	86	69	70
Threshold Level (Right panbone)	90	85	74	71
Average Threshold	88	85.5	71.5	70.5

Table 4: Hearing threshold of female bottlenose dolphin (Brill, 2001).

As we can see, the female dolphin showed peak sensitivity at 60 kHz where male dolphin is relatively less sensitive to sound at this frequency. This means the male and female dolphins may response differently to the noise generated by the marine turbines. But on the other hand, the result could be ambiguous. Although both dolphins are adults and have mature panbone for detecting sound, the difference in age of two dolphins may show different responses to the same sound. At the same time, because jawphones were fixed on the dolphin's panbones, the individual difference in adaption to the equipment could also cause difference in results.

Nedwell et al. (2004) concluded most of the past experiments and produced the following graph in order to compare the results:

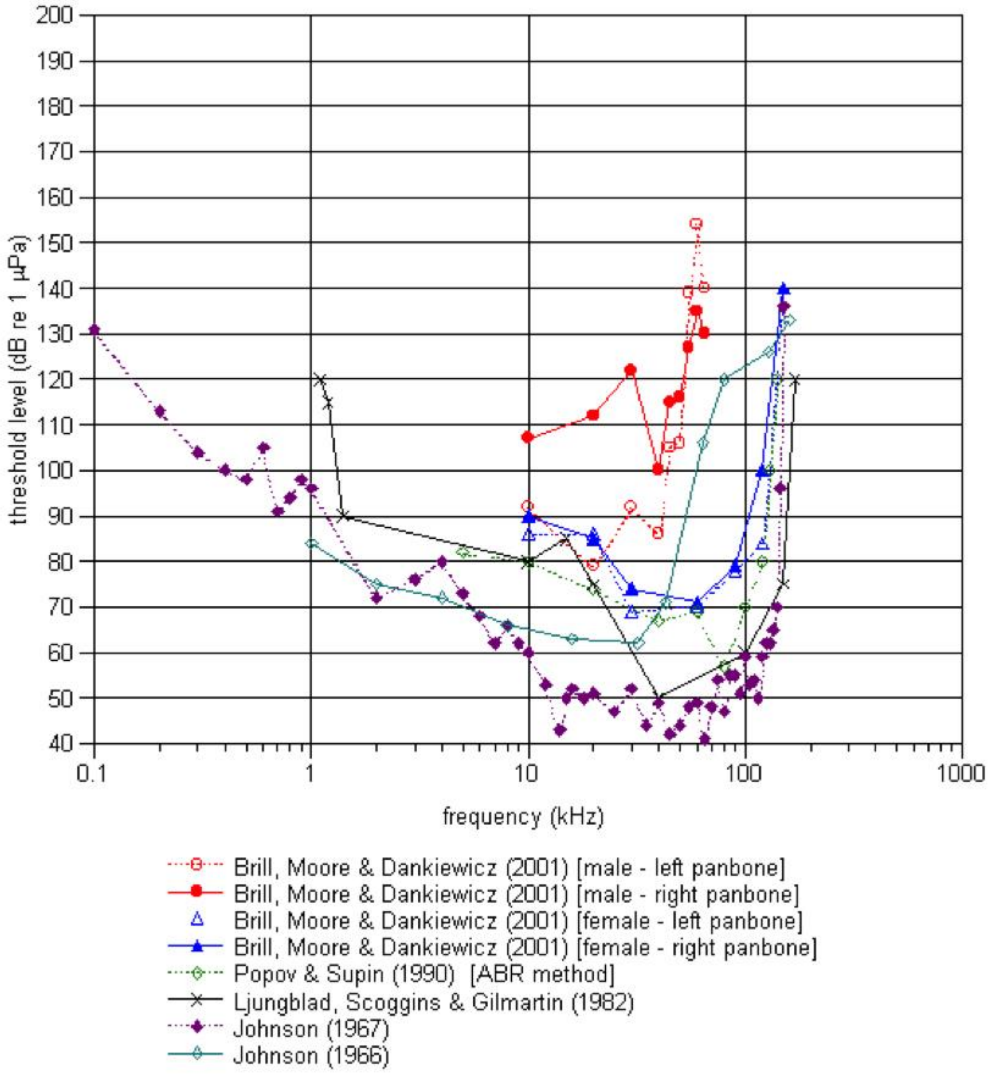

Figure 5: Compilation of Audiograms of bottlenose dolphins (J.R. Nedwell, 2004).

As concluded in Figure 5, it is clear that all the past studies of the audiograms of bottlenose dolphins gave a v-shaped curve where the optimum hearing ability is located in the middle. Therefore, the results can be summerised as:

Species	**Hearing Range (kHz)**	**Approximate Peak Frequency (kHz)**	**Hearing Threshold at Peak Frequency (dB re 1µPa)**	**Hearing Threshold at edge of hearing range (dB re 1µPa)**
Bottlenose dolphin	1 – 150	50 – 80*	40 – 50*	130 – 140

Table 5: Hearing range, peak frequency and hearing threshold of bottlenose dolphin *(Beatrice Environmental Statement, 2006)

When the sound at frequency between 50 – 80 kHz, bottlenose dolphins could hear sound down to 40 – 50dB. However, sound at frequency of 1 kHz or 150 kHz, bottlenose dolphins could only hear sound as loud as 130 – 140dB. Any sound above the upmost hearing range is called ultrasound and any sound below the lowest detectable frequency is called infrasound. However, both ultrasound and infrasound cannot be heard (Campell, 2011).

3. Case Study: Sound of Islay Demonstration Tidal Array

3.1 Introduction

After the understanding of the background information on sound and noise and also the echolocation and hearing ability of bottlenose dolphins, it is worth to mention a similar project as reference for our study here. This is because the environmental statement (ES) produced by the European Marine Energy Centre (EMEC) also included the impacts on marine mammals.

Scottish Power Renewables UK limited (SPR) is planning to install a tidal array within the Sound of Islay. By utilising the tidal flow and ebb, the development aims to install 10 of 1MW tidal turbines to achieve an average production of 26.3GWh energy annually. It is of course essential to assess the impacts on marine environment before the turbines are installed. The assessment methods used by EMEC were first identifying the relevant international and national legislations for marine mammals. Based on these legislations, they consulted with statutory bodies for scoping opinions. As one of the newest projects in the world, most of the information could only be collected through desk-based studies from data sources like Scottish Marine Renewables Strategic Environmental Assessment (SEA), Joint Nature Conservation Committee (JNCC) database and Hebridean Whale and Dolphin Trust (HWDT).

3.2 Learning from the Project

The research found out that all marine mammals in UK waters are of national or international importance and are marked as highly sensitive. EMEC outlined the sensitivity of the major marine mammals in Sound of Islay against different impacts where for bottlenose dolphin are:

Species	**Presence in Sound of Islay**	**Sensitivity**					
		Noise & Vibration	**Collision**	**Increased suspended sediments**	**Release of Contaminants**	**Barrier Effect**	**Habitat exclusion**
Bottlenose Dolphin	Likely	High	High	Medium	Low	Medium-high	Medium-high

Table 6: Sensitivity of bottlenose dolphin with respect to different impacts from the tidal turbine (EMEC, 2010).

EMEC's research once again approved the bottlenose dolphins are highly sensitive to noise and therefore it is necessary to assess how the noise will influence the activity of bottlenose dolphins.

The ES indicated that there are two types of noise underwater: naturally occurring noise and anthropogenic noise. In 2010, the Scottish Association for Marine Science (SAMS) undertook a survey measuring the natural noise level in the Sound of Islay. They measured the average natural noise level within the Sound of Islay is between 69 dB (slow ebb) and 116 dB (fast flood) at frequency of 20kHz and 5kHz respectively. This is because the natural noise level is closely related to the speed of tidal flow where increase of tidal flow leads to an dramatic increase of noise level and vice versa. Due to high tidal speed, the background noise of Sound of Islay is much higher than the open oceans.

The anthropogenic noise is more complicated but is mainly come from the construction, operation and decommissioning activities of the tidal turbines. The ES stated the maximum acoustic output of a single Hammerfest Strøm HS 10020 device would be 113dB. At the same time, the noise produced by tidal turbines is normally low in frequencies between 50 and 1000 Hz. Therefore, EMEC predicted that the operational noise of the turbine would be masked by the background noise and will not travel out of the sound due to the shielding effect. Moreover, the SAMS (2010) calculated that the noise from each turbine would travel around 20m to 400m before dropped down to noise level. At last, the ES anticipated that ten operational turbines within the Sound of Islay would have little change on current noise level.

3.3 Critiques on the Report

The ES produced by EMEC was very comprehensive and useful. But there could be some gaps of the research. According to the ES, the scoping method was mainly based on the feedback from statutory bodies but the opinions from stakeholders like fisherman, logistic companies are not stated in the report. Also the baseline description on the range of marine mammals is quite brief. For example, the research did not indicate any noise threshold levels of bottlenose dolphins. At the same time, the measurement of natural underwater noise is probably not accurate because it is very hard to completely isolate the area to avoid any anthropogenic noise disturbance.

The noise level produced by a single turbine was measured as 330KW, where in practice the output power will be 1MW. The ES stated the difference is marginal, but it is still unknown the actual noise level that would be produced from the turbine during operation. Lots of noise assessments were carried out by different organisations but the noise from the trenching of cables was omitted. Moreover, although noise will not propagate out of the Sound, the operational noise still exists. There is no guarantee that bottlenose dolphins will not travel into the bay. Therefore, the ES did not include how the dolphins will response when hearing the noise from the turbines.

At last, the 20m – 400m attenuation distance of noise mentioned in the ES is still theoretical which is only valid if the turbines are placed in the environment with lowest background noise level. But the attenuation distance is highly depends on the geomorphology of the Sound and the output power of the turbines.

4. Alderney Project: The Source-Pathway-Receptor Model

Based on the study of the Sound of Islay tidal project, it is clear that data are still quite limited for underwater renewable energy development and this is the same for the Alderney project. Therefore the source-pathway-receptor model will be used for analysing the noise impact from the Alderney project.

- Source: noise from construction, operation and decommissioning activities. Noise level is known as source level noise (SL). (Section 4.1)
- Pathway: water. Noise will be attenuated during the transmission underwater and the loss is known as transmission loss (TL). (Section 4.2)
- Receptor: bottlenose dolphin. (Section 4.3)

Since no precise data of SL is available at moment, no exact TL calculation is possible. However, the severity of any impacts is not just depends on the strength of the impacts but more significantly the reactions of the receptor, in this case, the bottlenose dolphins. Therefore, the source-pathway-receptor model will be focused on the noise impact on bottlenose dolphins. The following sections will first briefly identify the possible noise sources from the construction, operation and decommissioning of the marine turbines and how noise will be attenuated when travelling from one point to another. Section 4.3 will then focus on the noise impact on the echolocation and hearing system and behaviour of the bottlenose dolphins based on their sensitivity.

4.1 Potential Noise from Marine Turbines

There is already number of natural noise present underwater. For example, impact noise from the breaking of water and waves, turbulence noise from the tidal flow and also noise from any seismic activity. The frequency of natural noise appears to be 0.1 – 50 KHz (McCarthy, 2004). However, no specific data can be found for the background noise under the Race of Alderney.

Naturally existing noise is normally harmless to marine mammals but anthropogenic noise is different. Noise from the underwater activities is normally intense and long lasting. There are three stages of the lifecycle of marine turbines: construction, operation and decommissioning. Anthropogenic noise maybe produced from a variety of sources during these stages. The noise arises from the construction and decommissioning is normally short-term where the operational stage may result long-term impacts.

4.1.1 Potential Construction Noise

The level of the noise from the construction activities depends on the design of the turbines that will be used. For example, if the tidal turbines will be installed using traditional civil engineering method, piling will be needed for the stabilisation of the turbines. Therefore, the major construction noise is coming from the pile driving activity. However, current option for the Alderney project is likely to be the gravity base tidal turbine. By descending the turbine on the seabed under gravity, this method has the advantage of avoiding drilling, pilling or other activities, which could cause massive noise.

From the case study of Sound of Islay, we knew that by sinking the tidal turbines down to the target location under gravity, it could reduce the noise generated by construction compare with traditional pile driving method. But similarly, there is no exact measurement of the noise level of this method.

No matter which method will be chosen as the final design, cable will be installed to connect the turbines and the structures at Fort Albert. Therefore, noise will be produced from the trenching of the cables. Taking the North Hoyle Wind Farm project as reference, the cable trenching noise level at source is approximately 178 dB measured at depth of 1 metre.

There were not many vessels using the Longis Bay in the past, therefore increasing of vessel activities is another major noise source during construction. There is currently no exact data on the noise that will be produced by the additional vessel activities. Sara et al. (2007) concluded that for Sound of Islay, noise produced by ferries is between 160 – 170dB at frequency less than 6 kHz. However, other studies indicated that the noise from the vessel activities is recognised as white noise, but how the bottlenose dolphins will react to the white noise remain unclear.

4.1.2 Potential Operational Noise

Same as construction noise, the noise generated from the turbine operation depends on the final design of the turbine. What we know for now is that the noise from the turbines is usually broadband noise, which means the frequency of the noise is not specific and covers the entire audible spectrum (Bellhouse, 2004). For example for the Sound of Islay project, the

Hammerfest HS1000 tidal turbine produces low frequency noise between 0.05 – 1 kHz. If the turbine from Openhydro would be chosen as the final design, the turning speed of the blades is will be slow (about 1.5 – 2 rpm) and is believed to produce noise at low frequency as well. Although it is not possible to identify the exact strength of the noise from the turbine operation, the ES from EMEC suggested that the noise would be masked by the ambient noise.

Compare with the direct noise produced from the operation of the turbines, indirect noise could be larger. During operation, routine maintenance is needed which means increasing of vessel activities. However, the strength and duration of the noise is depends on the procedure and frequency of the maintenance work.

4.1.3 Decommissioning Noise

The lifespan of the turbines are expected to be 20 – 25 years. At the end of the period, the turbines will either be refurbished or replaced. Hence noise will be produced through these processes. As mentioned in the ES of Sound of Islay, the decommissioning of the turbines are expected to give similar noise impact as the construction noise but in a shorter duration. However, since there is currently no information about the decommissioning of the underwater tidal turbine at all, no precise data can be included at moment.

4.2 Noise Propagation and Attenuation Underwater

Sound is the most efficient energy form that can travel in water comparing with light or heat (Songhai Li, 2011). Since noise is sound, it is able to travel a long distance in high speed from one point to another and this is called noise propagation. However, as noise is a form of energy, the energy will be dissipated into other energy forms along the path of propagation and this is called noise attenuation or transmission loss (Kinsler, 1982). There are three major factors that could lead to transmission loss:

Geometrical Spreading

The noise wave emitted from the source only contains certain amount of energy (OSPAR, 2009). Noise from source will propagate spherically and the energy will decline at the rate proportional with the inverse of distance (OGP, 2008).

Transmission and Reflection

When noise transmitted from the source and arrive at the seabed, it will be reflected. The reflected noise will then have higher amplitude but is recognised as different in properties, for example, lower in frequency. However, low frequency noise can travel longer distance in the strata of the seabed than in water (OGP, 2008). Most of the noise from the turbine operation is known as low in frequency and will travel further along the seabed.

Absorption

During propagation, the noise energy will be converted into heat and, as a result, the measured sound pressure level decreases with increasing distance from the sound source. The energy loss via absorption is significant for high frequency noise, however, is negligible for frequency less than 1000 Hz (OSPAR, 2009). As concluded from the Sound of Islay project, the operational noise from the turbines is usually low frequency noise (50 – 1000 Hz) and therefore the absorption attenuation factor needs no concern here.

The noise generated by the turbine can be calculated with the formula mentioned in Section 2.1. For example, if the marine turbine generates the noise at 200 dB and the sound level in 1000 metres will theoretically be:

$$SPL = 200 - 10 \times \log 1000 - 11 = 159 \text{ dB}$$

Normally the propagation of sound is spherical. However, tidal turbines are located on the seabed and the propagation of sound is hemispherical. Therefore, the SPL will be then 3dB higher than the spherical radiation, which is 163dB (Bellhouse, 2004).

Noise will not just come from the underwater activities but also from the surface of the water, which is mainly the vessel traffic. Noise would also be attenuated when travelling from surface to deeper water. As mentioned earlier, most of the noise from vessel is low in frequency. Therefore, Richardson et al. (1995) picked the frequencies of 250 Hz and 2000 Hz and concluded how the noise level will behave when travel from the noise source at water surface:

Distance to source (m)	Ship noise (dB re 1μPa)	
	Noise at 250 Hz	Noise at 2000 Hz
1	160	150
10	145	133
50	135	122
100	130	117
1000	115	100
10,000	99	80

Table 7: Noise level of ship at difference distance to source (Frank Thomsen, 2006).

Table 7 firstly indicated that low frequency noise tends to travel longer than high frequency noise. Secondly, noise will not be auditable by bottlenose dolphins at frequency of 250 Hz, which is out of the hearing range. However, noise can be detected at 2000 Hz when dolphins are within 1 km of the vessels (see Table 1 for hearing threshold reference).

In conclusion, the actual propagation of sound in the water is quite complex. The speed and distance of travel is highly depends on the surrounding environment. For example, every 1% increases of the salinity of water lead to an increase of sound speed by 1.5m/s where 1°C drops of the water temperature result a decrease of sound speed by 4m/s (Wartzok, 1999). For the Island of Islay project, due to geomorphology reason the noise will be trapped in the Sound and therefore not be able to travel out. But this is not the case for the Alderney project. But the calculation of how far that the noise could travel needs specific measured data from the vessel and turbines.

4.3 Noise Impacts on Bottlenose Dolphin

The noise would mainly give impact on the behaviour, hearing and echolocation of bottlenose dolphins. Southhall et al. (2007) proposed a graphical presentation of the degree of the noise impacts as:

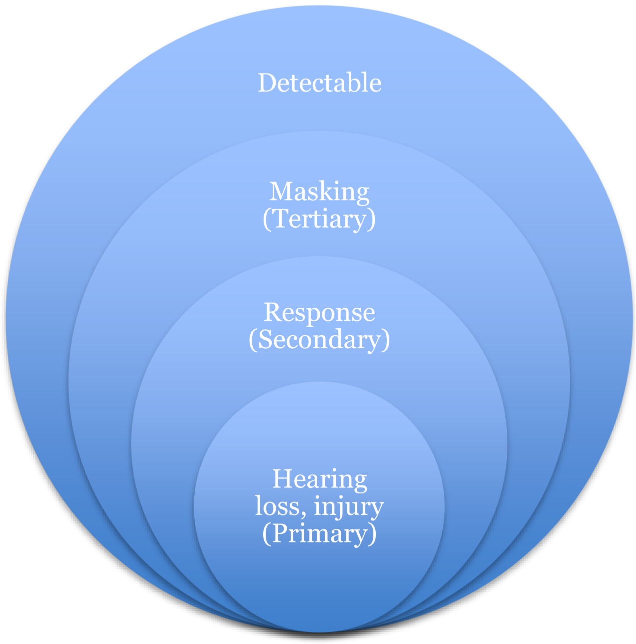

Figure 6: Hierarchy of the noise impacts on marine mammals (Southall, 2007).

If considering noise as the source factor, the severity of impacts is predominantly depends on the strength, exposure duration and frequency of the noise. If considering bottlenose dolphin as the receptor factor, the severity of the impacts is mainly related to the sensitivity of the receptor. However, both aspects are indispensible for assessing the impact. Therefore in this section, the assessment of noise impact on bottlenose dolphins will be based on the following matrix:

Impact Level (Noise)	Sensitivity of Receptor (Bottlenose dolphin)			
	High	Medium	Low	Negligible
Primary (High)	Major	Major	Moderate	No effect
Secondary (Medium)	Major	Moderate	Minor	No effect
Tertiary (Low)	Moderate	Minor	Negligible	No effect
Negligible	Minor	No effect	No effect	No effect

Table 8: The matrix of the significance of the effect and the sensitivity of the receptor.

The red column in Table 8 indicates the severity of the impacts with respect to different noise levels where the sensitivity of bottlenose dolphin is described to be high. Primary impact is described as acute fatal injury to the dolphin due to immediate powerful noise occurrence (J. Nedwell, 2003). For example, noise produced from any underwater explosion during the construction stage. Secondary impact is normally the effect such as PTS and TTS where tertiary impact is the change of behaviour and masking effect on the bottlenose dolphins.

4.3.1 Impacts on the Echolocation System of Bottlenose dolphins

Taking Figure 6 as reference, the lightest nuisance that caused by noise is the masking effect on bottlenose dolphins. Noise masking is known as the noise level in the environment covers the wanted sound. In this case, if the noise from the tidal turbines exceeds the sound level of bottlenose dolphins' clicks, it could possibly mask the echoes of the clicks. However, this is probably not possible for noise from underwater turbines. As discussed earlier, most of the noise from the vessel or the turbine related activities are low in frequency where the clicks produced by bottlenose dolphins are high frequency. Dolphins are able to recognise the different frequencies of incoming sound (Whitlow W. L. Au., 1987). Moreover, whether the masking will always take effect is still under debate. Madsen et al. (2006) argued the noise from construction activities are unlikely to cause significant masking effect on marine mammals. This is mainly because most of the noises are broadband noise. Therefore since the masking noise is normally continuous pure tone, the power is defined as “not strong enough” to cause the masking effect (Madsen, 2006).

However, noise from the target could influence the **detection range** of echolocation. Whitlow et al. (2007) carried out some experiments to estimate how far dolphins could detect their preys in different ambient acoustic condition.

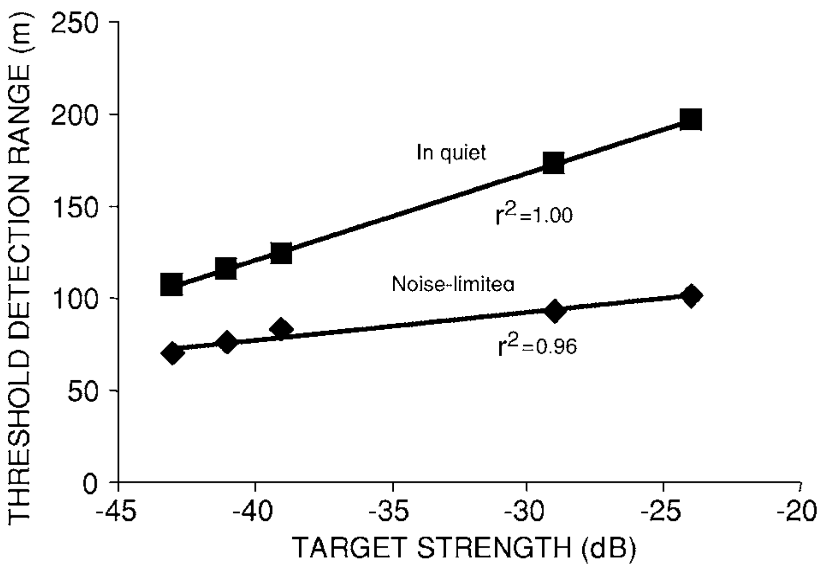

Figure 7: Echolocation detection threshold of bottlenose dolphin against the sound strength from the target (Whitlow W. L. Au, 2007).

From the result (Figure 7) obtained by Whitlow et al. (2007), we can clearly see that the lowest threshold detection range in the quite environment is larger than the highest threshold detection range in the noise-limited environment. This means noise from the source could significantly decrease the detecting range of the echolocation. Although the test subject of Whitlow's experiment was fish, which only produce small amount of noise, the theory is the same and can be applied here. Noise produced from the turbine could potentially decrease the detection range of bottlenose dolphins when they taking the turbine as detecting target.

If the impact happens, the impact level is low and the sensitivity of bottlenose dolphin is high. Therefore the impact is described to be **minor**. However, for phase 1 of the project, the likely of happening is **unlikely** and the magnitude of impact is **negligible**.

4.3.2 Impacts on the Behaviour of Bottlenose Dolphins

The severer noise impact on bottlenose dolphins is their responsiveness, namely, the behaviour of the dolphins. The major phenomenon of the behavioural disturbance is **avoidance**, which is swimming away from the noise source area) (Richardson, 1995) (Würsig, 2002). The consequences of avoidance behaviour are normally not acute but chronicle. For example, change of foraging habit and shift of regional population (MMC, 2007). Nedwell et al. (2004) concluded the threshold for avoidance of bottlenose dolphins as:

Species	Threshold of avoidance
Bottlenose dolphin	90 dB re 1μPa

Table 9: The noise threshold of bottlenose dolphin for behavioural disturbance (Nedwell J. R., 2004).

The noise threshold stated above is in broadband frequency, which matches with the noise produced from the tidal turbines. The radius of the avoidance zone is depends on the strength of the noise (SL) produced by turbines and transmission loss (TL). Taking the Beatrice wind farm demonstrator site as reference, the avoidance radius for bottlenose dolphin is approximately 2 km when the noise level is 225 dB (Beatrice Environmental Statement, 2006).

However, the noise impact on the responsiveness of bottlenose dolphins could be temporary. Many literatures showed that when animals exposed to the same type of noise repeatedly, they might habituate to that particular noise over time (MMC, 2007). Bottlenose dolphins may show initial avoidance of the area but will swim back to the area when "get used to" the loudness of the noise or when the noise is stopped (Tougaard, 2003). But it is still unknown for bottlenose dolphin the threshold of duration and strength of the noise for them to familiar with.

In practice, it is hard to quantify the behavioural disturbance caused by noise because there are many factors that could lead to change in behaviour of bottlenose dolphins such as age, sex, season, and social status (Southall, 2007) (Richardson, 1995). For example, seasonal migration of bottlenose dolphins would show an avoidance phenomenon from the turbine area but is not caused by noise.

If the impact happens, the impact level is low and the sensitivity of bottlenose dolphin is high. Therefore the impact is described to be **moderate**. However, for phase 1 of the project, the likely of happening is **unlikely** and the magnitude of impact is **negligible**.

4.3.3 Impacts on the Hearing System of Bottlenose Dolphins

It has been widely recognised that bottlenose dolphins possess highly developed hearing system and is extremely sensitive to sound. Therefore, the severest noise impact on bottlenose dolphins is their hearing system. Noise could cause reduce of hearing sensitivity, and this is called **threshold shift**. There are two types of threshold shift: **temporary threshold shift (TTS)** and **permanent threshold shift (PTS)** (Ketten D. R., 1998). TTS is the short-term change of hearing ability and can be fully recovered after time. In contrast, PTS is referred to permanent change of hearing ability such as deafness (T. Aran Mooney, 2009).

The occurrence of threshold shift is closely related to the strength, frequency and exposure duration of noise. By using an 18-year-old male Atlantic bottlenose dolphin, T. Aran et al. (2009) completed lots of experiments in order to predict the pattern of TTS of bottlenose dolphins with regard to the noise exposure duration and frequency.

TTS and Sound Exposure Duration

Figure 8 showed the relationship between the duration of bottlenose dolphins and the likelihood of TTS:

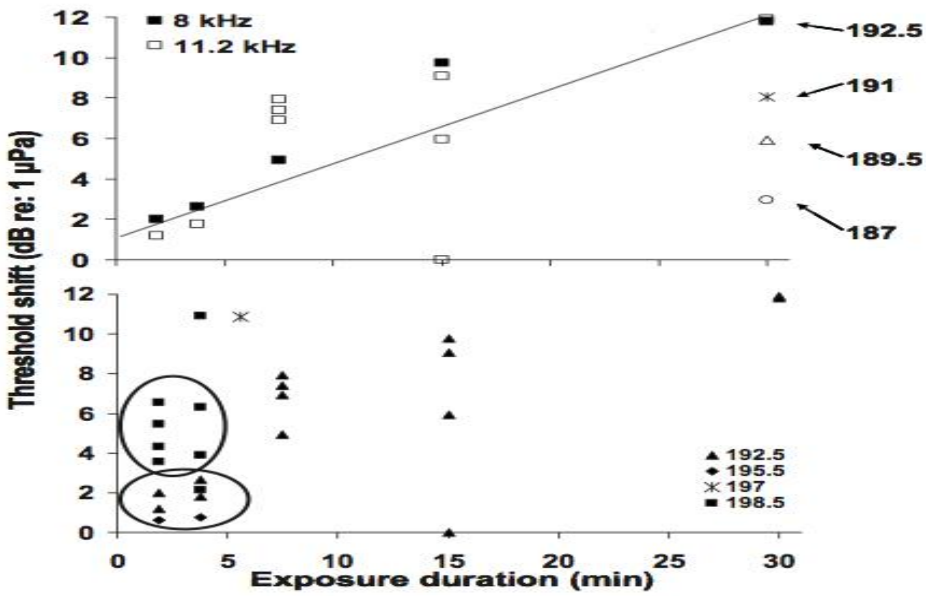

Figure 8: The correlation of sound exposure duration against threshold shift (T. Aran Mooney, 2009).

The upper figure showed a clear linear relation that increasing of noise exposure duration will leads to an increase of threshold shift at frequencies of 8 kHz and 11.2 kHz when sound level was kept at 192.5dB. The lower figure was obtained when the sound frequency was kept constant, but the sound exposure level was changed. It demonstrated that at shorter duration, higher sound level is required to activate the TTS. Meanwhile, the TTS is unlikely to happen with increase of exposure duration. This is probably because the dolphin has habituated to the noise as discussed in the previous section.

TTS and Sound Frequency

T. Aran Mooney et al. (2009) also found that threshold shift did not occur too frequent at high frequency (16 and 22.5 kHz) where mid-tone noise at 5.6, 8 and 11.2 kHz tends to trigger the threshold shift more significantly. Results are presented in Figure 9:

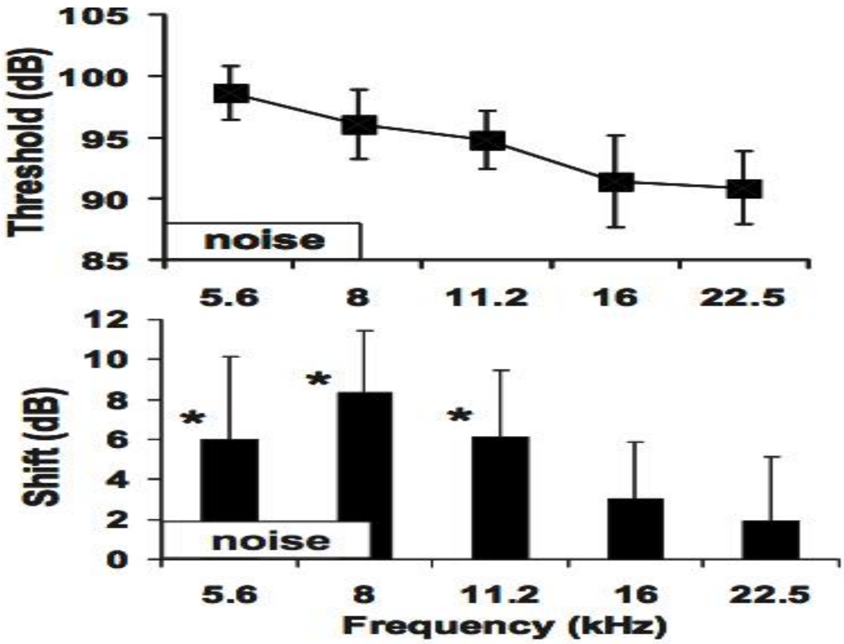

Figure 9: (Upper) Average hearing threshold of bottlenose dolphin when exposing under frequencies from 5.6 – 22.5 kHz. (Lower) Average numbers of TTS at each five frequencies tested (T. Aran Mooney, 2009).

The threshold shift does not happen all the time. The occurrence is 43% at 5.6 KHz, 71% at 8 KHz, 29% at 16 KHz and 14% at 22.5 kHz (T. Aran Mooney, 2009).

The recovery time from temporary threshold shift from the experiments performed by T. Aran Mooney et al. was about 80 minutes. This means within the period, bottlenose dolphins is “blind” to surrounding environment and could lead to increase risk of collision with turbine structures.

The noise exposure level needs to be about 90 – 120 dB higher than the hearing threshold of the bottlenose dolphin for TTS to occur and the occurrence is also related to the sound frequency, exposure duration and distance to the noise source. The frequencies involved in T. Aran Mooney's experiments (2009) were mainly high frequencies ranging from 5.6 KHz to 22.5 KHz. They did not suggest how the hearing threshold will change when dolphins receive low frequency sound, which is more likely to happen underwater. However, due to the hearing threshold of bottlenose dolphins are quite high at low frequency, the TTS is unlikely to happen unless the noise level is extremely high. This is again not very possible to happen because dolphins will try to avoid the area if the noise is described as "loud enough" to activate TTS. But on the other hand, all the studies undertook by T. Aran Mooney et al. (2009) was trying to predict the TTS of the bottlenose dolphins and therefore noise warm up were carried out before the start of each set of experiments. But underwater noise is sometimes sudden such as the noise from explosion during decommissioning stage of the turbines. This could directly lead to PTS (deafness) without the phase of TTS (Ketten D. R., 1998).

If the impact happens, the impact level is medium to high and the sensitivity of bottlenose dolphin is high. Therefore the impact is described to be **major**. However, for phase 1 of the project, the likely of happening is **unlikely** and the magnitude of impact is **negligible**.

5. Discussions

All the statements and results of this paper are based on the desktop studies of many past and present literatures. These literatures are normally based on certain assumptions or applied only in particular location. Therefore there are limitations of these studies already. At the same time, for the upcoming Alderney tidal project, due to lack of practical data and confidentiality of many research results from stakeholder companies, there are also additional restrictions of this research.

- Current studies about the hearing system of dolphins are still limited. Some studies were based on certain assumptions, for example, Songhai Li et al. (2011) used certain age of the dolphin (24 years) for the experiment and the dolphin used for trial was also well trained. Since it is hard to do experiment on untrained dolphins, therefore, it is still unclear that how the echolocation will differ from trained dolphins and wild dolphins and hence the result is probably not completely applicable to the Alderney dolphins.
- Most of the dolphins used for the experiments on testing the hearing sensitivity have being kept in captivity for years, for example, the 8 year old dolphin used in Johnson's experiments had been in captivity for nearly 2 years (Johnson, 1976). It is unknown that how the hearing ability is varied from the captive dolphins and free-range dolphins.
- At present, although there are many desk studies and experiments on the echolocation system of the bottlenose dolphins, but the clear conclusions is still inadequate. Little is known about how the dolphin utilise its echolocation system (Heidi E. Harley, 2008). This can be approved by the imperfection of the sonar system used in Submarine. Therefore how

exactly dolphins processing echolocation signal with noise blend in remains miserable.

- The echolocation system of bottlenose dolphin is related its physiological maturation. Cetacean acoustic system becomes mature over time. But the surveys did not indicate the age of the dolphins and therefore not be able to predict the variance.
- There are two major methods for obtaining the audiogram of the hearing sensitivity of bottlenose dolphins, which are behavioural method and evoked auditory potential methods. There is currently no comment on which method is better and hence it is unknown how the results will vary by using different methods.
- The surveys undertook on marine mammals can be inaccurate. This is mainly because marine mammals are highly mobile species and show irregular seasonal migratory activities according to the distribution of preys. Therefore for the surveys performed by ENTEC and AWT, the frequency and duration of the surveys maybe not match with the activity pattern of the marine mammals. Meanwhile, the visual survey might be difficult to carry out in winter due to poor weather conditions.

6. Future Investigation Suggestion

This study is just a preliminary research about the noise impact on bottlenose dolphin for the phase 1 of the Alderney tidal turbine project. More turbines will be installed underwater in project phase 2 in order to harvest more marine energy and in phase 3 the excess energy will be exported to Britain and France. Therefore, it is impossible and unreasonable to predict the noise impacts on bottlenose dolphins at this stage. However, further investigation of the actual underwater situation is absolutely necessary.

Collecting practical noise level data

For a better assessment of the noise impact on bottlenose dolphins, the precise noise data is crucial. By using the underwater **hydrophone**, it is easily to obtain the exact background noise level, and noise level at source including any sound from the construction, operation and decommissioning stages of the marine turbines.

Monitoring of bottlenose dolphins

The sighting records are limited in both duration and number of surveys. Therefore, long term monitoring of bottlenose dolphins' activities in the target areas is compulsory. As discussed earlier, the traditional visual boat survey method (the method used by ENTEC) has many limitations like limited coverage, unpredictable weather conditions, etc. One of the latest monitoring methods is the use of **T-Pod**. T-Pod is a unit that consists of a hydrophone, an analogue processor and a digital timing system. It can record and filter the acoustic sound produced by bottlenose dolphins and transfer the data to computer for analysis afterwards. The T-Pod method can give a dramatic increase of efficiency and accuracy of the results comparing with traditional boat survey method. The major advantage is that it can record the underwater behaviour of bottlenose dolphins (Alford, 2006). Therefore, it is possible to quantify the noise impact on bottlenose dolphins. In addition, using of cameras on the turbine to monitor the behaviour of bottlenose dolphins when they get close to the turbines could also be helpful.

If enough sighting records can be made in the future, it is possible to plot a GIS map of the distribution of the bottlenose dolphins and estimate the probability of their appearance in different areas around Alderney. This could help with the noise impact assessment when thousands of turbines are installed underwater.

Studies on bottlenose dolphin related species

Bottlenose dolphins are highly mobile species but their movements are mainly related to food distribution and abundance (Thompson H. B., 2006). Their seasonal migratory is also according to the redistribution of preys (Alford, 2006). As predators, they consume primarily fish and crustaceans (Santos, 2001). Therefore the study on fish and crustaceans is important for studying the movement and migratory of bottlenose dolphins. The reason it that if we understand the distribution of fish and crustaceans, it is then possible to predict the foraging passage of the bottlenose dolphins to see if they are within the noise zone.

7. Conclusion

The hearing centre in the brain named inferior colliculus of bottlenose dolphins is about 40 times bigger than in humans, which gives the dolphins extremely developed sound processing system for collecting and interpreting different types of underwater sound(Branstetter, 2006) (Glezer, 2004). Therefore as discussed in Section 2.2, bottlenose dolphins will be able to distinguish whether the returning sound is noise or are the echoes of their own clicks according to the sound energy level and frequency.

The masking effect will not necessarily affect the accuracy of the echolocation of bottlenose dolphin. This is because in order to obtain better information from the echoes, bottlenose dolphins are able to increase the amplitudes of the echoes by increasing the intensity of the clicks when they get close to the target (Houser, 2005). To the contrary, if the turbine could produce sound at "proper" level during operation, it could help bottlenose dolphins to detect the target and avoid collision.

The noise threshold of bottlenose dolphins can be generally classified into three stages. When the noise level is at 90 dB, they will try to avoid the area.

Species	Avoidance	Harassment	Injury
Bottlenose dolphin	90 dB*	160 dB	180 dB

Table 10: Noise threshold levels of bottlenose dolphin. * (Nedwell J. R., 1998)

Although bottlenose dolphins can bear noise up to 160dB, they will get injured when noise level goes up to around 180dB (P .E. Mark Bastasch, 2008).

However, the noise produced from the construction and operation activities of the tidal turbine are discussed as low frequency. At the same time, noise from the vessel activities is also low in frequency. Therefore, because the hearing threshold of bottlenose dolphins is high when the sound is at low frequency, they probably could hardly hear the noise.

The noise impact level including masking, responsiveness and TTS on bottlenose dolphins described in Section 4.3 are minor, moderate and major respectively. However, the severity is only valid when the impact occurs, where the occurrence is unlikely for the Alderney underwater turbine project Therefore, the magnitude of the impacts is described to be **negligible**. Based on the magnitude of the noise impact and the sensitivity of the bottlenose dolphin, Table 11 showed the suggested assessment result of noise impact on bottlenose dolphin for the upcoming tidal turbine project in Alderney:

Impact	Construction			Operation			Decommissioning		
	Magnitude of Impact	Sensitivity of Bottlenose Dolphin	Significance of Impact	Magnitude of Impact	Sensitivity of Bottlenose Dolphin	Significance of Impact	Magnitude of Impact	Sensitivity of Bottlenose Dolphin	Significance of Impact
Noise	Negligible	High	Minor	Negligible	High	Minor	Negligible	High	Minor

Table 11: The proposed assessment of the noise impact on bottlenose dolphin during the lifecycle of tidal turbine.

However, this does not mean the turbine noise will not give any impacts on the bottlenose dolphins. As discussed in Section 4.3, the masking effect could reduce the range of echolocation and hence decrease the range of activity of bottlenose dolphin. Furthermore, loud noise can lead to temporary or permanent threshold shift, which is a major nuisance to bottlenose dolphins.

The three turbines to be installed in the Race is only phase 1 of the whole project that to provide renewable energy to Alderney. Since massive energy can be produced from the Alderney waters, phase 2 and phase 3 of this project is to sink more turbines down the Race and eventually export clean electricity to Britain and France. As described earlier, a 3dB increase means doubling of sound level and a 20dB difference is approximately 6 – 7 times increase in sound level. The multiply of noise level is not likely in the first phase of the Alderney project, but could happen when thousand of turbines are installed and working at the same time in the future. The occurrence of impacts brought by three turbines might be negligible but the consequences of thousands of turbines are unpredictable. However, the impacts are believed to be substantial.

The final design of the turbine is the key because it determines many other activities like vessel size for turbine deployment, frequency of maintenance, etc. and therefore give different noise production mechanism. Moreover, with enormous amount of turbines working at the same time, it could cause seismic activity such as shift of seabed. Research found that the seabed at south bank of Alderney is consists of soft sand and is in high dynamic status (Simon P. Neill, 2011). There vibrational force from the turbine operation could possibly lead to move of the sand bank and cause huge seismic noise, which would give additional noise level and cause nuisance on bottlenose dolphins.

At last, not all impact accompanies with the underwater turbine development are adverse. Research showed that fish tends to aggregate around structures placed underwater (Vella G. , 2003). If same phenomenon will happen for tidal turbine structures, this could help to create new habitats and increase biodiversity. Therefore in conclusion, to avoid or mitigate the adverse impacts caused by the marine turbines project and enlarge the benefits brought by the project is the best solution to all offshore renewable energy development.

Bibliography

J.R. Nedwell, B. E. (2004). *Fish and Marine Mammal Audiograms: A summary of available information .* Subacoustech.
UN Secretary-General. (2007). *Report on Oceans and the Law of the Sea.* UN.
Zamudio, R. (2005). *TPOD detection and acoustic behaviour of bottlenose dolphins in Cardigan Bay SAC: a comparison between visual and TPOD surveys.* M.Sc thesis University of Wales, Bangor.
Würsig, B. a. (2002). *Effects of Noise in Encyclopedia of Marine Mammals.* Academic Press.
Wartzok, D. a. (1999). *Marine mammal sensory systems.* Smithsonian Institution Press .
Weilgart, L. S. (2007). *A Brief Review of Known Effects of Noise on Marine Mammals .* Dalhousie University, Canada.
WDCS. *Introduction to British whales and dolphins.* Whale and Dolphin Conservation Society.
WDCS. (2004). *Oceans of Noise.* Whale and Dolphin Conservation Society.
Whitlow W. L. Au, K. J.-B. (2007). *Modeling the detection range of fish by echolocating bottlenose dolphins and harbor porpoises .*
Whitlow W. L. Au., P. W. (1987). *Detection of Complex Echoes in Noise by an Bottlenose Dolphin.*
Yates, R. (2009). *Mean of a White-Noise Process.*
Vella, G. R. (2001). *Assessment of the effects of noise and vibration from offshore windfarms on marine wildlife .*
Vella, G. (2003). *The Environmental Implications of Offshore Wind Generation .*
Victoria Transport Policy Institute. (2009). *Transportation Cost and Benefit Analysis II - Noise Costs.*
Au, W. S. (1980). *Long-Rang Tearget Detection in Open Waters by an Echolocating Atlantic Bottlenose Dolphin (Tursiops truncatus).*
Au, W. (1993). *The Sonar of Dolphins.*
A.Gritsevskyi, IAEA. (2007). *Renewable vs. non-renewable energy sources, forms and technologies.*
Akamatsu, M. T. (2005). *Geographic variations in the whistles among three Indo-Pacific bottlenose dolphin Tursiops aduncus populations in Japan.* Fisheries Science.
Alderney Wildlife Trust. (2010). *Seabird and Marine Mammal Survey in Longis Bay and Associated Areas.*
Alford, L. (2006). *The occurrence and foraging activity of bottlenose dolphins and harbour porpoises in Cardigan Bay SAC, Wales.*
American Cetacean Society. (2004). *American Cetacean Society Fact Sheet: Bottlenose Dolphin.*
ARE. (2009). *Environmental Statment.* Alderney Renewable Energy.
Burgman, J. (2010). *An Analysis of the Potential Acoustic Effects of Cape Wind's Offshore Wind Farm on Marine Mammal Populations.*
Bahaj, A. S. (2003). *Fundamentals applicable to the utilisation of marine current turbines for energy production.*
Beatrice Environmental Statement. (2006). *Section 9: POTENTIAL IMPACTS OF UNDERWATER NOISE AND VIBRATION .*

Bellhouse, G. (2004). *LOW FREQUENCY NOISE AND INFRASOUND FROM WIND TURBINE GENERATORS: A LITERATURE REVIEW .* Energy Efficiency and Conservation Authorit.
Berta A., a. S. (1999). *Sound production for communication, echolocation, and prey capture .* New York: Academic Press.
Bowen, W. (1997). *Role of Marine Mammals in Aquatic Ecosystems.*
Branstetter, B. &. (2006). *Sound localization by cetaceans.* International Journal of Comparative Psy- chology .
Brill, R. M. (2001). *Assessment of dolphin (Tursiops truncates) auditory sensitivity and hearing loss using jawphones .*
Campell, D. (2011). *Aspects of Human Hearing.* University of Paisley.
Carstensen, J. H. (2006). *Impacts of offshore wind farm construction on harbour porpoises: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs) .*
Elert, G. (2003). *Frequency Range of Human Hearing.* The Physics Factbook.
EMEC. (2010). *Sound of Islay Demonstration Tidal Array Environmental Statment.*
ETSU. (2000). *An assessment of the environmental effects of offshore wind farms.* Department of Trade and Industry .
Durrant J D, L. J. (1984). *Bases of Hearing Sciences.* United States of America: Williams & Wilkins.
D. S. Houser, D. A. (1999). *Classification of dolphin echolocation clicks by energy and frequency distributions .*
Dawson, J. A. (1993). *The abundance and distribution of bottlenose dolphins in Doubtful Sound, New Zealand.*
DeRuiter, S. L. (2000). *Echolocation-based foraging by harbor porpoises and sperm whales, including effects of noise and acoustic propagation .* MASSACHUSETTS INSTITUTE OF TECHNOLOGY .
Dolman, S. S. (2004). *Marine windfarms and Cetaceans.*
Frank Thomsen, K. L. (2006). *Effects of offshore wind farm noise on marine mammals and fish .* COWRIE.
Gaskin D.E., Y. S. (1993). *Harbour porpoise, Phocoena phocoena (L.), in the coastal waters of northern Japan .* Fishery Bulletin.
Gelfand, S. A. (1990). *Hearing: An introduction to psychological and physiological acoustics.* New York and Basel: Marcel Dekker, Inc.
Gill, A. B. (2005). *Offshore renewable energy: ecological implications of generating electricity in the coastal zone .* Journal of Applied Ecology.
Glezer, I. H. (2004). *Echolocation in Bats and Dolphins.* University of Chicago Press.
GREC. (2010). *Regional Environmental Assessment of Marine Energy.* Guernsey Renewable Energy Comission.
Greenpeace Communications. (1990). *The Greenpeace Book of Dolphins.*
IUCN. (2008). *IUCN Red List of Threatened Species.* IUCN.
ICNIRP. (1994). *Guidelines For Limiting Exposure To Time-Varing Electric, Magnetic, And Electromagnetic Fields.* ICNIRP Guidelines.
Heidi E. Harley, C. M. (2008). *Echoic Object Recognition by the Bottlenose Dolphin.* Comparative Congnition and Behaviour Reviews.
Herman, L. M. (1975). *Bottlenosed dolphin: Double-slit pupil yields equivalent aerial and underwater diurnal acuity.* Science.

Hildebrand, J. (2007). *Sources of Anthropogenic Sound in the Marine Environment.* University of California San Diego.
Houghton, J. D. (2001). *Climate Change 2001.* Cambridge University Press .
Houser, D. M. (2005). *Echolocation characteristics of free-swimming bottlenose dolphins during object detection and identification.* Journal of the Acoustical Society of America .
Hoelzel, A. (2002). *Marine Mammal Biology: an evolutionary approach.* Oxford: Blackwell Publishing.
Hooker, S. K. (2009). *Encyclopedia of Marine Mammals (2nd Ed.).* Academic Press.
J. Nedwell, J. L. (2003). *Assessment of sub-sea acoustic noise and vibration from offshore wind turbines and its impact on marine wildlife; initial measurements of underwater noise during construction of offshore windfarms, and comparison with background noise .* COWRIE.
Janik, V. (2000). *Source levels and the estimated active space of bottlenose dolphin (Tursiops truncatus) whistles in the Moray Firth, Scotland .* Journal of Comparative Physiology.
Johnson, C. (1976). *Sound detection thresholds in marine mammals.*
Kastelein, R. (2002). *Audiogram of a harbor porpoise (Phocoena phocoena) measured with narrow-band frequency-modulated signals .* Journal of the Acoustic Society of America.
Kempton, W. F. (2005). *The Offshore Wind Power Debate: Views from Cape Cod .*
Ketten, D. (1994). *Functional analyses of whale ears: Adaptations for underwater hearing.*
Ketten, D. R. (1998). *MARINE MAMMAL AUDITORY SYSTEMS: A SUMMARY OF AUDIOMETRIC AND ANATOMICAL DATA AND ITS IMPLICATIONS FOR UNDERWATER ACOUSTIC IMPACTS .*
Kinsler, L. E. (1982). *Fundamentals of acoustics.*
Lusseau, D. B. (2005). *Sensitive area for marine mammals.*
Nedwell J.R., H. D. (2004). *A review of offshore windfarm related noise sources: Subacoustech report to COWRIE.*
Nedwell, J. R. (2004). *Assessment of Sub-Sea Acoustic Noise and Vibration from Offshore Wind Turbines and its Impact on Marine Wildlife; Initial Measurements of Underwater Noise during Construction of Offshore Windfarms, and Comparison with Background Noise.* COWRIE.
Nedwell, J. R. (1998). *Guiding fish with sound, the acoustics of fish behavioural barrier design .* 128th Annual Meeting of the American Fisheries Society Conference .
Madsen, P. W. (2006). *Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs .*
McCarthy, E. (2004). *International Regulation of Underwater Sound.* Boston: Kluwer Academic Publishers .
McKenzie, S. (2011). *Whale and dolphin turbine injury risk to be studied.* BBC.
MMC. (2007). *Marine Mammals and Noise - A Report to Congress from the Marine Mammal Commission .*
OGP. (2008). *Fundamentals of underwater sound .* International Association of Oil and Gas Producers.
OSPAR. (2009). *Overview of the impacts of anthropogenic underwater sound in the marine environment .* OSPAR Commission.

P .E. Mark Bastasch, M. F.-D. (2008). *Oregon LNG Terminal and Oregon Pipeline Project— Underwater Noise Propagation, Monitoring, and Mitigation .* TECHNICAL MEMORANDUM.
Popov, V. &. (1990). *Electrophysiological studies of hearing in some cetaceans and a manatee.* Plenum Press, N.Y.
S D Richards, E. J. (2007). *Underwater Noise Study Supporting Scottish Executive Strategic Environmental Assessment for Marine Renewables .* QinetiQ Proprietary.
Santos M.B. Pierce G.J., L. J. (2003). *Variability in the diet of harbour porpoises (Phocoena phocoena) in Scottish waters .*
Santos, M. P. (2001). *Stomach contents of bottlenose dolphins (Tursiops truncatus) in Scottish waters .* Journal of the Marine Biological Association of the United Kingdom.
Sarah J. Dolman1, M. G. (2009). *Marine Renewable Energy and Cetaceans.* Whale and Dolphin Conservation Society (WDCS).
Scott M.D., W. R. (1999). *Bottlenose dolphin Tursiops truncatus.* Academic Press.
SeaWorld. (2002). *Senses.*
Simon P. Neill, J. R. (2011). *Impact of tidal stream turbines on sand bank dynamics.*
Southall, B. B. (2007). *Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations.* Aquatic Animals.
Songhai Li, P. E. (2011). *Dolphin hearing during echolocation: evoked potential responses in an Atlantic bottlenose dolphin (Tursiops truncatus) .* The Journal of Experimental Biology 214, 2027-2035.
Richardson, W. G. (1995). *Marine Mammals and Noise.* Academic Press.
Rogers, A. L. (2006). *Wind Turbine Noise, Infrasound and Noise Perception .* University of Massachusetts.
Turl, C. (1993). *Low-frequency sound detection by a bottlenose dolphin.*
T. Aran Mooney, P. E. (2009). *Predicting temporary threshold shifts in a bottlenose dolphin (Tursiops truncatus): The effects of noise level and duration .* Acoustical Society of America .
Thompson, H. B. (2006). *Quantitative analysis of bottlenose dolphin movement patterns and their relationship with foraging .* Journal of Animal Ecology 2006 75, 456 - 465.
Thompson, R. H. (1975). *Underwater frequency discrimination in the bottlenosed dolphin 1- 140 kHz) and human (1-8 kHz).* Journal of the Acoustical Society of America.
Tougaard, J. C. (2003). *Short term effects of the construction of wind turbines on harbour porpoises at Horns Reef .*