Wave Energy and Underwater Noise: State of Art and Uncertainties

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***Abstract*- After several years of maturation of wave energy concepts and technologies some developers have finally reached a pre-mature phase. Over the course of this progress some concern has arisen regarding possible environmental impacts, however due to the limited number of devices tested in real sea conditions the few environmental studies available seldom resort to field data. Preliminary studies of wave energy converters (WECs) indicate that few and low environmental impacts are expected. However, with the forthcoming large scale deployment of WECs it will become possible to monitor the positive and negative environmental effects in more detail.**

Developers and promoters have demonstrated particular concern regarding the possible effects of underwater noise emitted by WECs. There are several references throughout the environmental studies on the potential impacts; however they tend to rely on literature reviews or comparisons to similar other offshore structures. Consequently there are several uncertainties related with this topic.

The acoustic signature of each device will be a product of the combination of the different sources of noise within each WEC.

Noise generation has a potential impact on marine fauna, for that reason it is necessary to identify the species present within the vicinity of the deployment area. In special cases sound can travel thousands of kilometres in water hence potentially affecting species which are far from the noise source.

The paper includes a brief review of existing environmental studies/documents of individual devices and projections of future wave farms regarding underwater noise as an environmental descriptor. It also addresses present uncertainties and knowledge gaps associated with this subject.

I. INTRODUCTION

1. Wave Energy State of Art

The growing concern for a sustainable energy development on a global scale, in association with the goals of the Kyoto Protocol emphasizes the need to push for renewable energy development.

Wave energy is an available energy resource with high potential to contribute to a renewable energy mix which can help curb current dependence on fossil fuels. Scientific research into wave energy began in the 1970s, prompted by the oil crisis, and since then a large number of devices have been developed. After more than three decades of being virtually restricted to academic research, the progress of wave energy has finally reached a pre-mature stage, emerging as a potential industry for the future. At this point there are technologies that have reached not only a demonstrative prototype phase but also pre-commercial projects of wave farms with the announced emergence of new projects all over the world in the forthcoming years.

At present, there are several technologies which are specific to the deployment site (onshore, nearshore, offshore) and conversion system. As opposed to other established renewable energy technologies, wave energy has yet to converge to one dominating design, as the 3-blade turbine in wind energy. However, as the devices are designed and tuned to operate at different deployment conditions, such as sea states and bathymetry, it is possible that more than one technology will prevail.

2. Wave Energy and Environmental Impact Studies

The increase of sea deployments of wave energy converters (WECs) raised concerns regarding possible environmental impacts. Due to the fact that WEC's are inserted in a sensitive, environment, it is especially important to evaluate the resulting ecological impacts of their implementation. The marine environment is an area of important biological diversity and there are few environmental studies available that refer to field data. Almost all current environmental studies have a strong component of literature review and resort, when possible, to comparisons with the offshore wind industry and other offshore activities.

In a general overview, the knowledge on the environmental impacts of offshore renewable energy is growing nonetheless significant knowledge gaps remain. Basic studies covering the main environmental topics were first implemented in 2001 [1]. Until now, these studies indicate that few and low environmental impacts are expected, however that remains to be proven. Nevertheless, the future large scale implementation of WECs offers the opportunity to monitor both positive and negative impacts. Still, it is important to remember that for a reasoned assessment it is essential characterize the reference scenario by performing baseline studies.

II. WAVE ENERGY AND UNDERWATER NOISE

The past decades have seen a growing concern in the scientific community regarding the effects of underwater noise on marine life in general and particularly on marine mammals. This apprehension is partially justified by the observation of several mass strandings of marine mammals after underwater acoustic military exercises took place in adjacent areas. There

1-4244-2523-5/09/$20.00 ©2009 IEEE

is evidence to suggest a possible correlation between these two events [2,3], namely documented strandings in the Mediterranean, Bahamas, Madeira and Islas Canarias [3]. Some marine species use sound as their primary sense, using it to communicate, socialize, feed and echolocate. As a result any change in underwater noise has the potential to disturb these species through physical, behaviour, perceptual, chronic and indirect effects. Consequently, the increase of anthropogenic activities in the ocean is a growing concern that needs to be addressed. Future large-scale implementation of WECs in the ocean may prove to be one additional source of underwater noise. Whilst it is not expected that each individual device will produce a high level of noise, the deployment of several devices in the same farm operating day and night may have an effect on the fauna.

There is scarce information on the sound levels produced by the different project phases of wave energy farms. Acoustical data on the sound produced during normal operations of wave energy technologies are not available.

III. Case Studies

Several documents and preliminary EIA's refer the importance to study the impact of underwater noise on marine life. To achieve this they tend to resort to preliminary assumptions based on general literature review, comparisons with studies of other offshore technologies, like offshore wind farms.

Observing some available EIA's, summarized on table I, we can see that almost all these case studies assumptions and conclusions are not based on field data. Only the Makah Bay, and Wave Dragon refer to values when analyzing the noise emitted. However, care is needed when dealing with values obtained through lab tests, where the oceanic environment is simulated but still differs in a lot of aspects, specifically the sound profile of the water column, and reverberation is an issue in a pool. Even if all the environmental conditions are equal to real conditions in the ocean, the transposition of the analysis of noise generated by a prototype device will not be adequate to represent a full scale device.

TABLE I
Summary of Wave Energy Cases Studies in relation to Underwater noise

Case Study /Device	Classification	Methodology	Assumptions/Conclusion	References
A	Floating Device	Literature Review	• Predict that the installation of the device, particularly mooring operations, can contribute to underwater noise. • During operation, the internal motors of the device and wave interactions are suggested as possible noise sources although their effects are considered to be very low. • Temporary perturbations to whale migration patterns are considered.	Classified
B	Submerged Device	Literature Review	• Underwater noise from the maintenance ships will occur probably only once every two weeks • Low levels of vibration by mooring cables • Baseline noise measurements required before installation and comparison of data with the noise emitted by WEC and followed by comparisons with the audiogram of species that occur at the site.	Classified
WaveHub		Comparison with offshore wind farms	• Potential impacts on sensitive receptors (marine mammals and elasmobranches) caused by piling, operational WECs; o Piling: no effects on population levels because any noise disturbance will be short-term; o Operational WECs: not known, but is predicted to be unlikely to have a significant effect; however refer the importance of a monitoring plan to assess the effects on species in different phases of project	[5]
Kaneohe Bay (OPT)	Point Absorber		• Provides a review of the sensitivity of the biota in the area and conclude that only some species could be affected but there is no evidence that the frequency or amplitude of the sound from the buoys would cause harm to these species.	[6]
Makah Bay (Aquabuoy)	Point Absorber	Technical meeting	• Noise resulting from waves hitting the buoys is expected to have no significant impact on marine life; • Noise from project operation (hose pump, pressurized water, turbine) are expected to produce noise levels below the ambient noise (below 145dB); • Noise from construction would be localized, intermittent and short duration	[7]
WaveDragon	Overtopping	Literature Review and Measurement of the underwater noise from a single Kaplan turbine (lab tests)	• Predict that operational noise would result from the Kaplan hydro turbine, as well as from unknown levels and frequencies of sound from wave interactions with the body of the device, hydraulic pumps and the mooring system.	[8]
EMEC	Pilot Zone	Literature Review and Comparison with offshore wind farms	• Test devices and associated activities are likely to give rise to noise that may disturb and affect the behaviour of marine life. Although the exact cause and effect relationship can be difficult to determine. • Suggest that the amplitude of the noise must be quantified for the device as a whole or for different parts of device as appropriate.	[9]

On another hand the noise generated by a WEC will be the accumulation of different sources that will produce sound, like the mechanics within the WEC itself but also its interaction with the water.

The research done in offshore wind energy regarding noise emissions can help guide the work needed to do in wave energy, such as baseline studies, procedures, simulations and monitoring, but it will not address the fundamental differences of noise between wind and wave energy devices/farms.

In offshore wind energy devices noise is emitted into the water by: vibration of the structure until the bottom caused by blades/turbine movement (directly to water), noise transmission from air to water from blades/turbine, and cavitation around the structure. In contrast, WECs will produce most the noise under water and the project phases differ from wind farm projects, mainly the construction phase. The noise generated will be directly transmitted into the water column and, depending on the mooring system, to bottom sediments. Summarizing the project activities through the construction phase will be different and the sound path will be different as well.

All the case studies in table I mention the importance of understanding the effects of underwater noise on marine life, particularly marine mammals, and conclude that the assumptions taken in preliminary EIA is not sufficient to assess the true impact. Measurements, baseline data and monitoring plans have been indicated as very important to characterize the sound source and determine the impact.

IV. UNCERTAINTIES

As we can see through the previous analysis of case studies there are several uncertainties related with this topic:

- Acoustic signature of WECs;
- Sound generated by the interaction of WECs with the water;
- Sound Propagation in the ocean;
- Knowledge of marine species present in the area;
- Audiogram for those species;
- Effects/impacts of noise on marine animals;
- Impact of WEC's noise on other marine life.

1. WECs noise

The total noise generated by each WEC is produced from a variety of different sources and components related within the device itself and/or by environmental conditions.

The deployment of an array of WECs can have a cumulative effect, increasing the sound generated or in some special cases could result in the phenomena of sound annulation in some frequencies. In order to be able to predict this, the oceanographic conditions (temperature, salinity, bathymetry, sediments) need to be characterized in detail, as well as the acoustic signature of WEC. The noise emitted in different operational conditions due to the different sea states needs to be analysed, and the sound propagation from a single device and an array of devices needs to be modelled. However, the deployment of devices in an array can have different geometries, device number and layout, all factors which are expected to influence the acoustic properties of the farm

In a wave farm, it is unlikely that every wave will reach every device at the same time, as a result the sound will be produced at different phases. This, in turn, will be important to determine the synchronous or asynchronous noise generation by the wave farm. The synchronous or asynchronous generation of sound will be related with the direction and intensity of the wave, location of WEC.

Each device will have an acoustic signature directly determined by its components. This signature will be a product of the combination of different sources of noise, which can be caused by mechanical components or other moving parts and might include other external factors.

The mechanical components can include:

- Turbines (hydro, Wells, Pelton, etc.)
- Generators
- Hydraulic components (rams; pumps; cylinders)
- Pressurized fluids (air; water; oil)

Other Causes:

- Cavitation
- Water and waves hitting the device
- Vibration of mooring cables

Characterizing the sound generated by each WEC component at different operational conditions, will allow an estimate of the sound emitted by a single WEC as a whole.

A model can be a helpful tool to analyse how the sound will propagate from a single device or an array of devices, synchronously or asynchronously.

To model the propagation of sound over distance background knowledge of the noise generated by a single device, the environmental conditions, including sea state and background noise is required. All this data is crucial to assess the attenuation of sound over distance, including absorption and transmission through sediments as well as boundary interactions.

Presently the WEAM project (Wave Energy Acoustic Monitoring) aims to develop a monitoring plan of underwater noise emitted by WECs, measurements of devices are expected and a model to analyse the sound propagation and its effects on marine mammals is being developed [10].

2. Marine Life

The marine species which has been best studied acoustically are the marine mammals, with documented case studies that correlate some behavioural or even physiological responses to noisy activities. Yet, there is some evidence that some fish, crustaceans and cephalopods have some acoustic sensitivity [11]. Some examples of noise effects on marine species can be seen on table 2.

TABLE II
EXAMPLE OF SOME NOISE EFFECTS REPORTED ON SOME MARINE SPECIES

Species	Causes	Effects	Critical / range values	References
Gray whales (*Eschrichtius robustus*)	Noise associated with offshore oil and gas development and vessel traffic	Changes in swim speed and direction to avoid the sound source, abrupt but temporary cessation of feeding, changes in callingrates and call structure, and changes in surface behavior	0.5 probability of avoidance when continuous noise levels exceeded about 120 dB re 1 μPa and when intermittent noise levels exceeded about 170 dB re 1 μPa	[12]
Harbor porpoise (*Phocoena phocoena*) and	-	-	Hearing ranges from below 1 kHz to around 140 kHz; Echolocation (sonar) is in a frequency range of 120-150 kHz	[13]
Harbor seal (*Phoca vitulina*)	-	-	Hearing ranges from less than 0.1 kHz to around 100 kHz Harbor seals communicate at frequencies ranging from 0.2 to 3.5 kHz	
Green turtles (Chelonia mydas) and loggerhead turtles (Caretta caretta)	Sounds of air guns used for marine seismic surveys	Above a noise level of 166 dB re 1 μPa rms the turtles noticeably increased their swimming activity, and above 175 dB re 1 μPa rms their behavior became more erratic, possible indicating that the turtles were in an agitated state		[14,15]
Caged squid (Sepioteuthis australis)	Sounds of air guns used for marine seismic surveys	Showed a strong startle response at a receiving level of 174 dB re 1 μPa rms. When sound levels were ramped up, the squid showed behavioral responses (e.g., rapid swimming) at sound levels as low as approximately 156 dB re 1 μPa rms, but did not display the startle response seen in the other tests.		[14,15]

Each marine mammal species has its specific auditive sensitivity related with the communication and echolocation functions. Through the audiogram specific of each species it is possible to attempt to calculate and define the influence areas for each one [16]. Reference [17] compiled audiogram for several species of marine mammals and fish. The previous knowledge and monitoring of species in areas adjacent to WEC deployment sites is crucial not only to characterize the species acoustically, through audiograms, but also to monitor its behaviour. It is important to note that marine mammals usually exhibit different behaviour depending on the location and season. This variability should be taken into account at the time of the monitoring plan design. However, a level of uncertainty will still remain because it is difficult to prove whether or not a given behavioural change or physiological damage is caused by a nocive emitted noise). Monitoring is still the better approach to correlate events.

V. CONCLUSIONS

Almost all existing preliminary EIAs mention that it is essential to assess the impact of underwater noise generated by WECs, however there is almost no data available, and their conclusions are based on literature reviews, measurements of some components, but not on a full scale device in real sea conditions.

Development of a monitoring plan is crucial. It is an essential tool to analyse sound generation through the different seasons and operational conditions. Models can help to analyse the sound propagation over space. The combination of this knowledge with that of the acoustic
sensitivity of the species enables an assessment of influence zones.

A possible approach to evaluate the impact of underwater noise of WECs on marine life could focus on:

- Measure the frequency and duration of noise generated by WECs, under different sea states and ocean conditions;
- Monitor and model the sound field, from a single device and an array, including several farm configurations (device number, density, geometry), to predict noise propagation
- Characterize and monitor the marine species;
- Calculate the influence zones and assess the possible effects.

Summarizing the three main steps are:

- Characterize the acoustic receptor, the marine species, determining their acoustic sensitivity;
- Characterize the acoustic channel through the and physical properties of the ocean;
- Characterize the acoustic properties of the wave energy converters.

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