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Ecologically-Sustainable Futures for Large-Scale Renewables and How to Get There.

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Abstract—**To arrive at a sustainable future we need offshore renewables to succeed, and to do so we need to work together. There have been ecological showstoppers in the past and there will be again in the future unless we can co-design devices, array layouts and site locations of multiple very large-scale developments such that cumulative ecological effects can be assessed and conflicts with ecological laws, local communities and fishing industries be minimized. In order to effectively spatially manage our marine habitats, weigh-up ecological trade-offs and avoid/adapt to the worst effects of climate change, we need all those involved to understand, at some degree of detail, how our marine ecosystems function such that impact mitigation efforts can start at the design stage of devices and developments. This paper outlines a straightforward way to convey the most important environmental issues that are concerning renewables developments, as well as in the context of climate change, and at the scales of individuals and ecosystems. It covers a range of suggestions for the design of data collection, analysis and modelling frameworks to deal with these concerns and finishes with suggestions for potential avenues for future collaboration between ecological and engineering sciences.**

Keywords—**Cumulative effects, Ecological Trade-offs, Modelling Frameworks, Strategic Environmental Assessments**

I. INTRODUCTION

Environmental concerns within renewable offshore industries are normally last on any list of priorities and generally seen as a tick box exercise that is unreasonably costly and unproductive outside of getting consent for the development. Hopefully by the end of reading this short paper you will be convinced that industries should be treating environmental concerns as they would any other issue of low Technology Readiness Level (TRL). I hope you will also be interested in investing earlier and with experts, in how to best mitigate ecological concerns to reduce overall cost and risk. In addition, I hope you will see the need for the collection of pre-deployment ecological data, and that on-going monitoring can be made much more inexpensive if it is embedded in the data collection for environmental power characteristics and device performance.

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Fourteen years ago I wrote a short paper called "A Renewable Engineer's Essential Guide to Marine Ecology" [1] and my central plea was that, for rapid progress to ensue, ecologists and engineers should work much closer together. The theme was to categorise the issues into direct and indirect effects and mainly to deal with the massive amount of unknowns we have about how our marine ecosystems function, especially in areas of high tidal and wave energy that are so difficult to sample. There has been some progress over these last 14 years despite low levels of strategic research funding in these areas, hence across reviews there has been and remains a consistently strong emphases on the need for more research [2],[3]. For the most comprehensive recent review of environmental effects of marine renewable energy, see [4]. As can be seen in the more advanced industry of offshore wind, only as the size of developments has reached the point (in the UK, Round 4 [5] and ScotWind [6]) that GWs per year are being planned, are investigations of the levels of cumulative environmental effects and ecological carrying capacity starting to be funded at appropriate levels to rapidly advance this field [7]. Constructive, cross-sector collaborative approaches will reduce the risk of ecological showstoppers as well as increasing robustness of environmental assessments.

II. THE 3DS OF ENVIRNOMENTAL IMPACT

Possible reasons that industry has been slow to appreciate the actual ecological issues may be that they are presented through what has been called a 'horrendogram' of laws [8]. The incredible array of regional, national and international legislation that overlaps with renewable developments can be very off-putting and impenetrable to those more interested in the engineering aspects and therefore only dealt with by the few specialists, usually ecologist and biologist dealing with the environmental effects. Therefore, to make the issues more straightforward for a wider audience I have condensed the focus of the environmental effects into what I call the 3Ds of direct environmental effects: Disturbance, Displacement and Death (see Fig. 1).

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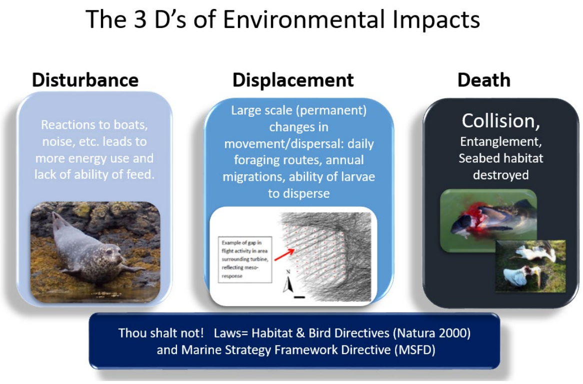

Fig. 1. The 3Ds of Environmental Impacts and the international policies that cover them.

A. Disturbance

In increasing order of level of effect, I will start with disturbance. Disturbance can be described as human activities that cause animals to move away from the location they are currently using and/or behaviour they are currently performing. This can mean that the animal is prevented from feeding/resting/mating in a preferred area and may have to stop the behaviour or move to another area that is not its preferred location. Continual disturbance can add to distances travelled and therefore increase energy use of an animal's daily activities. The effects of using more energy/having less time to rest, or forage in areas with less food availability or the preferred prey species, can have a serious effect on the energy they have left for reproduction and therefore lead to a decline in the population numbers. In fact, it has been seen that, even in ecotourism events, too much disturbance leads to a high rate of miscarriage and / or infant mortality for dolphin species [9].

B. Displacement

The next level up is displacement; this is the permanent moving of an animal away from the area it wants to frequent, for either feeding, resting or reproduction. The offshore wind industry, with the use of radar and infra-red cameras, has put in the financial commitment to the correct size of project to finally put accurate, evidence-based numbers for avoidance rates of seabird [10] with the main results indicating that for most seabird species, 99.8% of individuals avoid going into the wind farm area. However, the flipside of that result is that those high percentages of animals are no longer using that area and this phenomena has already been witnessed for a range of seabird species [11], [12]. Evidence is also starting to gather for behavioural changes at tidal and wave sites but it is quite mixed depending on the species, with long term studies at SeaGen, Strangford Lough calling for more before data and standardised methodologies [13]. For marine mammals, where much more funding has been available for studies, it appears the noise of tidal turbines does have an effect on seals such that they will avoid areas where they can hear the turbine noise [14], [15]. However some studies have shown that seabird species are attracted to turbines even during operations due to the predictable wake that is created and may be bringing prey species to the surface, making them easier to catch [16],[17]. At established windfarms it has been clearly shown that seals will change their normal foraging areas as they find the foundations preferable places for foraging [18] which may be associated with the 'reef effect' of man-made structures providing new habitat. While this might be seen as a benefit rather than an impact, it can not only potentially lead to an increase in collision risk, but also lead to changes in communities (e.g. change of foraging grounds, increased competition within/between species). So, the jury is out on displacement effects for tidal and wave, however, it is clear from the work done to date that changes in behaviour are linked to changes in prey (fish) and the few groups conducting studies on characterising and predicting changes in fish behaviour have shown some large changes in fish distribution and behaviour around tidal turbine structures [19]-[21]. We do not yet have enough information to say how much of an effect all these changes will have on population levels as again, so little funding has gone into multi-trophic level type of studies which assess the predators, prey and habitat changes, simultaneously.

C. Death

The third level, death, is most often considered as collision risk from rapid moving parts of devices. It is quite clear and can be easily modelled to show that increased mortality can have significant effects on populations as the death of adults, especially for long-lived animals, will very rapidly lead to population declines. However, only recently have collision models stepped up to state-of-the-art simulation models [22]. Recently, there has also been the initiation of a modelling framework being developed to finally bring together all the direct effects of collision, displacement and disturbance [23].

D. Indirect Effects

However, work still needs to go further to understand the indirect effects [1] from the changes caused by the additions of structures and the extraction of very large levels of energy from the marine environment. Just the addition of structure is changing the level of mixing (stratification) in shallow seas and influencing the amount and timing of plankton production [24] which is an incredibly important ecological change that makes its way up the food chain and throughout the local ecosystem and should be an important part of marine spatial planning decision making [25]. These indirect changes to biodiversity are currently not considered by most marine environmental impact assessments, but these changes are predicted to become important when 10s to 100s of GW are being extracted. Major effects on biodiversity have been shown to matter for onshore wind [26] and ecologically significant changes in stratification are being predicted from very large scale tidal energy extraction [27] and have recently been detected at large offshore windfarms [28] and have implications for fisheries [29]. Therefore it is important that any aspects that can reduce or better yet, eliminate collision risk, displacement, disturbance and significant changes to local ecosystems should be considered in the design stage of all aspects of wave, tidal and wind deployments. Below I will outline the main ecological aspects of consideration at each stage of development.

III. ENVIRNOMENTAL IMPACTS AT DIFFERENT DESIGN AND IMPLEMENTATION STAGES

It would be most helpful if all engineers involved in any aspects of the design of components, devices and deployments were at least aware of the importance of the 3Ds and ecological effects of energy extraction such that decisions can be made early in the process that could decrease impacts. In this next section I set out, with examples, how the direct 3Ds of environmental impact along with indirect local ecosystem changes can interact or are influenced by each of the elements of an offshore renewable development. See Figure 2 for the colour coding of the different stages of development for level of impact.

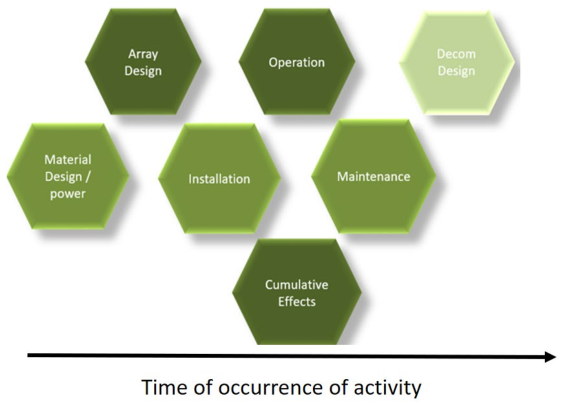

Fig. 2. The ecological impacts for each stage of development with the darker the colour representing higher levels of impact.

A. Material, Design and Power

In terms of choices of materials design, the first ecological aspect to appreciate is biofouling. Biofouling or as an industry spokesperson once said, subsea's 'dirty little secret' is so important to appreciate. Anything that goes in the sea will have something growing on it in rapid order. Therefore, calls from the ecological community are to consider knowing your enemy and then growing your enemy – seeding species you want to harvest later in the year, or in a few years [30]. In addition, there are many possibilities of multi-use of some sites with, for example, aquaculture, which have been comprehensively explored from engineering, economic and policy aspects [31]. In terms of considering materials to maximize power outputs, it is imperative that design engineers understand that because there are environmental laws that will not allow high percentages of deaths of protected species, all external rapid moving hard parts may hamper the ability to deploy in some areas (i.e. tidal turbine tip speeds of > 5.1 ms^{-1}, [32]). Also, when optimising power output, consideration of trade-offs between power and maintenance, knowing that the minimization of maintenance is perhaps the more environmentally friendly route (see section below on maintenance).

B. Array Design and Location

The design, size and location of arrays can have very significant ecological effects of displacement as discussed above; large offshore windfarm arrays may essentially block the movement of highly mobile animals such as seabirds, and large tidal arrays could block marine mammals and large fishes (basking sharks) from using daily routes to foraging areas and/or annual migration routes. For tidal arrays in particular the 'downstream' changes from both the introduction of structures and extraction of energy have significant impacts on the locations of shear, turbulence structures such as kolk boils [33] upwelling [16],[17]. Very large extractions of tidal energy (> 6 GW) have been shown to have further 'downstream' effects on stratification and mixing [27] with effects of up to 10% changes in physical and biological variables over hundreds of km of distance from the site of extraction [34]. These differences can change the location of tidal fronts and areas of high subsurface primary production which are very important areas for foraging for many marine species [35]. The size and type of spacing between devices and between developments is also very important as the fishing industry can be displaced by the location and design of large and multiple arrays which can lead to intense conflict [36],[37]. There also needs to be much more consideration of the potential ecological knock-on effects of fishing vessels being forced to make distributional changes and therefore increasing the intensity of fishing in less space. The assumption that the offshore renewable areas which displace fishing will become de-facto marine protected areas (MPAs) needs to be tested. Therefore in combination, I would suggest that array design and location are the most important aspect for environmental impacts and it is imperative that within the high level strategic environmental assessments (SEAs), [38] more consideration is given to the both the direct and indirect effects of arrays.

C. Installation

Installation of devices has been a major focus of ecological impact due the loud noises generated from piling that can both cause disturbance and in very acute cases, death, by either immediate trauma or lingering death because the animal has become deaf/damaged sensory system and will not be able to catch prey. However, the many studies that have been performed via the offshore wind industry, the short story seems to be that many mobile animals move away during the time of pile driving but return soon after the noise has stopped, i.e. within 24 hours [39],[40]. Therefore the concern is to manage the number and location of regions that are experiencing pile driving at any one time so that they do not merge to produce massive regions. As noise travels so much farther underwater it has been shown that dolphins would have to modify their behaviour up to 50 km away from pile driving [41]. Also care has to be taken that noise is not continuous for long periods of time (weeks/months on end) or that the use of acoustic deterrent devices (ADD) do more harm than good [42]. Therefore designs that don’t require pile driving (i.e. gravity based devices, suction bucket techniques) are preferable for ecological reasons.

D. Operation

As with installation, the main issues with operations are displacement due to the production of noise, but now also death due to collision with moving parts and therefore has been considered a phase that can have very high ecological impact. However, different from installation, a much wider range of noises of different (especially lower) frequencies and the continuous nature of the noises that are produced, can have long term and permanent ecological effects (lack of ability to catch prey) on a range of species, especially fish [43]. These effects will then be felt up and down the entire food chain. During operation there is also the production of electromagnetic fields and mainly due to lack of sufficient field studies, the jury is still out as to whether the effects (behavioural changes, larval survival, etc.) are significant at population levels (see chapter in State of the art of Science Review [4]).

E. Maintenance

As maintenance requires the presence of humans, an increase in boat traffic to areas of offshore developments, where there may have been little traffic before, appears to have much more of an environmental effect than one would have assumed. A report with 10 years of data at the European Marine Energy Centre (EMEC) at both the tidal and wave testing sites, shows that disturbance due to vessel presence was the most significant factor for a decrease in animals numbers in the areas (i.e. disturbance / short term displacement) [44]. Therefore the fact that floating devices, which are detached and brought to shore for maintenance, and designed to greatly reduce the at-sea maintenance cost (time), may also greatly reduce disturbance to animals and will be a win-win approach.

F. Decommissioning

The impact of decommissioning is similar to installation issues of acute noises but generally not of the level of pile driving. However I have colour coded it as a light colour as I assume that we will have learnt lessons by the time many of the current devices need full removal.

G. Cumulative Effects, Working Together and Climate Change

Similar to calculations by engineering and oceanographic communities to assess the carrying capacity of a sensible level of energy extraction; assessing device interference and/or lack of additional energy which limits the size, location and numbers of arrays [45], so too is there an ecological carrying capacity to be able to sustain anthropogenic and natural pressures before population levels only fall, rather than oscillate up and down. The cumulative levels of the direct effects, the 3Ds, are extremely important to appreciate as larger devices, many more arrays and extraction of 10s to 100s of GW in finite locations will have large ecological impacts. The indirect effects are more likely to be non-linear, possibly non-intuitive effects and need to be modelled with ecosystem approaches in order to be appreciated (see section G.2 Climate Change). The indirect cumulative changes to ecosystems with large localized changes to mixing and stratification may actually turn out to be more important than the 3Ds, or at least more important than death, with displacement and indirect effects being the most important.

G.1 Working Together: Collecting the same data.

At this point it is useful to illustrate how mobile animals use the physical aspects of the seas. A lot of the same variables that the engineering community is interested in, in terms of understanding the resource: water column characterisation of speed and turbulence are the variables that seabirds, mammals and larger fish use to capture their smaller fish prey [46].

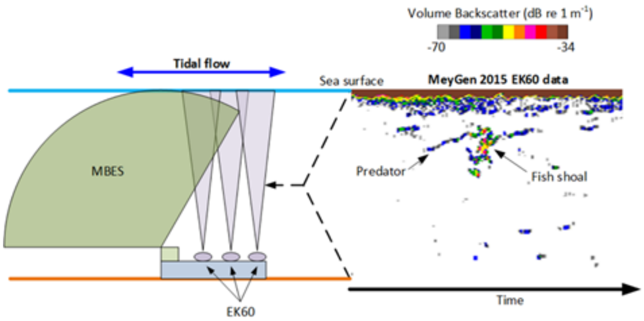

Fig. 3. Multi-sensor seabed platforms that combine multi-frequency echosounders and multibeam echosounders such as FLOWBEC allow measurement of animal presence and behaviour, including predator-prey foraging interactions as shown. Figure adapted from the techniques of [20],[21] using unpublished data from the MeyGen tidal stream site, Scotland.

Using active acoustics that fisheries science has been improving for the last 30+ years, one can enable not only to see fish school presence, but also behaviour of the predators of the fish schools as well. Adding multi beam sonar allows detailed information about the school behaviour [21]. Using upward facing multi-sensor seabed platforms that combine multi-frequency echosounders and multibeam echosounders we can identify regions and types of habitat that are the most important for foraging animals and therefore allow a very mechanistic understanding of where and how animals capture their prey (see Fig. 3). Seabed platform methods could also be used to help inform site expansion options, both in terms of resource and environmental impact.

G.2 Climate Change

If we can understand predator-prey interactions and the linkages to physical aspects of the environment at the very fine scale of individuals, we should also be able to take these understandings up to the much larger ecosystem level [47]. But to make accurate predictions we also need to take into account the dynamic changes in relationships within ecosystems being brought about by climate change effects [48] and be able to separate the effects of climate change from large-scale renewable energy extraction [45],[49]. This differentiation is important for several reasons, with the first being able to identify regions where the addition of structures and energy extraction could possibly counteract the effects of climate change or at least be neutral, not negative for overall ecosystem functioning. For example, very large tidal energy extraction can shift 'downstream' tidal front locations into shallower water [45], closer to the shore and the colony locations of seabirds and mammals providing shorter daily commutes to foraging grounds. Also the increase in mixing around windfarm foundations [28] may be able to counteract the increases in stratification that are predicted with climate change [45].

The second reason it is important to separate out the effects of climate change on ecosystem changes is to be able to assess the amount that offshore renewables are dampening the effects of climate change (see Fig 4). What current EIAs do is try to assess impacts of renewables against a supposedly stationary baseline, however only negative impacts of renewables can be considered [38]. The positive aspects of renewables, in their reduction in CO_2 production by replacing fossil fuels, needs to be brought into equation. In fact when looked at in terms of ecosystem services, more impacts of renewables are positive rather than negative [50]. Therefore the current system of EIA and cumulative impact needs to change in order to make proper assessments of positive vs negative trade-offs of locations and sizes of renewable developments [51]. This will also require the difficult issues of local (protected animals only living at a set location) vs global (overall reduction of CO_2) to be discussed and weighed up. Properly assessed trade-off approaches would improve the integrity of marine spatial planning decisions as to which regions would be best served with large-scale renewable developments and others that possibly should be avoided.

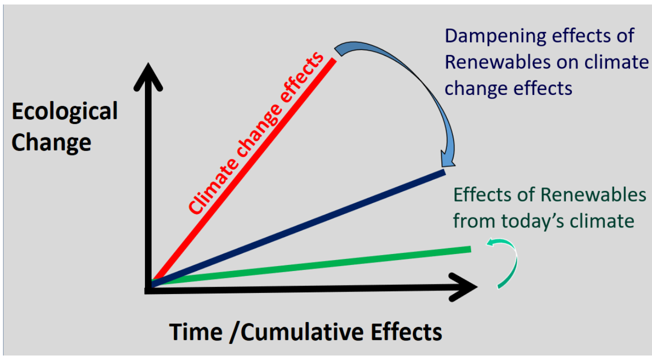

Fig. 4. The ecological effects of climate change (represented in red) are increasing rapidly with time. The level of ecological change that EIAs are assessing is represented with the green line and arrow. The positive impacts of renewable energy production in dampening the effects of climate change (shown with blue line and arrow).

IV. Conclusions

Hopefully after reading this short article you will have in mind the direct 3Ds and indirect environmental impacts at all stages of design and can consider the collection of ecological data as a must-do much earlier, and collaboratively. If you are interested to know more detail about ecological issues please see the State of the Science Review [4]. Also know that the ecological science community has a common goal with the offshore renewable engineering community: to see the levels of climate change decreased. Climate change is the worst enemy and must be beaten, but some areas of our seas are more ecologically important than others and there is an urgent need to consider the connectivity of impacts throughout the ecosystem such that we can construct a truly sustainable renewable energy system for the future.

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