Improving Understanding of Environmental Effects from Single MRE Devices to Arrays

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I. INTRODUCTION

Global expansion of marine renewable energy (MRE) technologies is needed to help address the effects of climate change [1], to ensure a sustainable transition from carbon-based energy sources, and to meet energy security needs using locally generated electricity. Although the amount of potentially harvestable tidal stream and wave energy from nearshore regions around the world is sufficient to meet current global electricity demand [2], the share of MRE in global electricity generation remains low at approximately 1 TWh yr^{-1}; falling well short of its potential and is due to the relatively small scale of device deployments to date (i.e., single devices and small demonstration-scale arrays). Expansion of MRE to large-scale commercial arrays (hereafter 'arrays') is needed to meaningfully address the effects of climate change, safeguard energy system transition, and provide energy security [3].

Several obstacles impede MRE expansion, including difficulties in obtaining regulatory approvals due to uncertainty around environmental effects resulting from a paucity of post-installation environmental monitoring data that confounds our ability to differentiate between unknown and realized effects of MRE development for marine ecosystems [4]. A long-established framework for assessing the effects of MRE development focuses on understanding 'stressor-receptor interactions' [5] (hereafter 'stressors'); seven of which have been identified as key concerns post-installation:

- Collision risk
- Underwater noise
- Electromagnetic fields
- Changes to habitats
- Displacement
- Risk of entanglement
- Changes in oceanographic systems

Our understanding of effects for these stressors continues to improve for single MRE devices, but remaining uncertainties complicate the task of predicting how marine ecosystems and their constituents will be impacted by arrays. Effects are unlikely to scale linearly with the number of devices, but are probably complex and nuanced, site specific, dependent on array configuration, cumulative (in some form), and have the potential for non-linear environmental responses. Establishing generalized concepts for how effects may 'scale up' provides a useful foundation for developing and testing hypotheses to improve our understanding of the potential environmental risks of MRE expansion. This paper establishes generalized concepts for these seven key stressors so that a robust scientific approach can be taken to improve our understanding of effects for arrays; information that is needed to facilitate the deployment of MRE technologies at scales that can make meaningful contributions in addressing the effects of climate change, assisting energy system transition, and ensuring energy security.

II. METHODS

A. *Defining 'large scale commercial array'*

Because no consistent definition exists about how many devices constitute a 'large-scale commercial array', we define this as 10 to 30 individual devices (i.e., wave energy converters, turbine rotors) that independently contribute to increasing the magnitude of effects for a given stressor.

B. *Framework for the scaling of environmental effects*

We developed and applied a structured approach for conceptualizing how effects may scale up for each stressor:

1. Describe the stressor,

2. Summarize existing knowledge about effects of the stressor for single MRE devices,
3. Define the nature of scaling-up using terminology adapted from the cumulative environmental effects literature (see below) to develop generalized concepts for how effects may manifest, and identify any caveats that could influence our understanding, and
4. Identify the research required (e.g., modeling, laboratory studies, field trials) to test these generalized concepts and improve our understanding of effects for arrays.

C. Environmental effects terminology for MRE arrays

Terminology does not exist to describe how effects may scale with an increasing number of devices, so we adapted terminology from the cumulative environmental effects literature for this purpose (i.e., [6], [7]). As the number of devices increases, the effects of a stressor may be characterized by comparatively simple additive or more complex non-linear (i.e., multiplicative) effects due to synergistic or antagonistic interactions. Here, we outline several scenarios to describe these effects:

- Scenario 1 – Dominance effects: For some stressors the effect may not scale with the number of devices; the effect from one device may overwhelm that of additional devices in an array (Fig. 1).
- Scenario 2 – Additive effects: These effects are equal to the algebraic sum of the effect of a stressor for each device (Fig. 1).

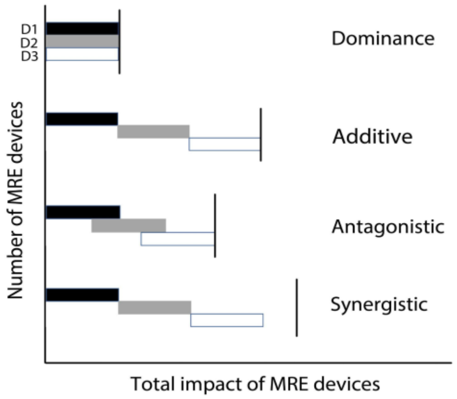

Fig. 1. Conceptual schematic for how environmental effects of a stressor may scale with an increasing number of MRE devices; derived from the cumulative environmental effects literature [6], [7]. Color bars represent the number of MRE devices (i.e., D1, D2, D3), and solid vertical lines represent the cumulative environmental effect of the array.

- Scenario 3 – Antagonistic effects: Here, the effect is equal to the sum of the effects of each additional device, but adjusted by some proportion that describes a diminished effect as the number of devices increases (Fig. 1).
- Scenario 4 – Synergistic effects: This may also result from a scalar on the effects of a device or from multiplicative interactions, but here the effect of the array exceeds the sum of effects from individual devices (Fig. 1).

III. RESULTS

Throughout this section, it is important to recognize that the scaling of effects will be influenced by environmental heterogeneity, the characteristics of the environment that devices are deployed in, and the spatial arrangement of the array, among several other factors.

A. Collision risk

Collision risk describes the likelihood that animals might be harmed by coming into contact with moving parts of devices [8] and is considered the greatest risk of turbine operations [4]. A recent synthesis of international research for collision risk around single devices revealed no observations of collisions for marine mammals or seabirds [9], and interactions with fish have not resulted in obvious harm. Mounting evidence suggests that when marine animals can detect turbines, they may exhibit avoidance or evasion behavior to prevent being struck [8], [10]. Although uncertainties about collisions with single devices remain, results to date suggest that collision risk for arrays may be additive or synergistic if devices are installed ‘in parallel’ [8] across a migratory corridor with no alternative access to important resources (e.g., foraging grounds, spawning habitat); necessitating the need for animals to navigate through the array and elevating their risk of collision (Table 1). However, antagonistic effects may arise if an array is configured ‘in series’ [8] so that much of the migratory corridor remains unobstructed; providing animals with ample space to navigate around the array (Table 1). Other relevant factors include the specific technology (e.g., floating *vs.* bottom-mounted device), physical habitat characteristics, the species under consideration and their capacity to exhibit avoidance and evasion. In the absence of arrays for *in situ* assessment, modeling approaches provide insight about how effects may scale up. Species distribution models can predict the likelihood of overlap with MRE devices [11] and can help quantify encounter rate. Incorporating avoidance or evasion behavior into this framework using an Agent-Based Model [12], Eulerian-Lagrangian-Agent Method, or fault tree analysis may help reveal how effects of collisions scale up.

B. Underwater noise

Marine animals use sound for various biological functions (e.g., communication, navigation, foraging, etc.), and underwater noise generated during device installation may disrupt behavior, induce stress, and if sufficiently high in intensity (i.e., pile driving) may result in physical injury [4]. However, operational noise from single devices is generally of low intensity and has not been associated with physical injury [13], but may elicit behavioural responses [14]. Although little is known about the particle motion component of underwater noise, sound propagating as a pressure wave is expected to scale in an additive manner (Table 1); the area over which sound will be elevated from baseline levels is expected to scale with array size. However, this will be influenced by environmental conditions, array geometry and technology type. Acoustic propagation models may help elucidate how effects of underwater noise scale up, but this requires *in situ* measurements of acoustic outputs from different technologies following established international standards [15], and the inclusion of relevant environmental variables in models to be effective.

C. *Electromagnetic fields*

Electromagnetic fields (EMFs) are naturally present in the ocean but may be modified by EMFs generated by subsea power cables and could influence the behavior and physiology of EMF sensitive species. Although there is consensus that EMFs in power cables from single (or a few) devices pose a low risk to animals [16], cables that transmit the combined energy from an array may have higher EMF and may affect animals. These effects are likely to be additive if power cables are 10s of metres apart so they do not interact, but dominance or antagonistic effects may arise if inter-array cables overlap at 180°, causing magnetic fields from separate cables to cancel each other out (Table 1). The development of robust sensors for systematic measurement of EMFs where devices connect to shore are required to understand how effects scale up [17], and would be supported by controlled laboratory- and field-based studies to elucidate behavioural responses to EMFs.

D. *Habitat changes*

MRE devices and supporting infrastructure will interact with benthic and pelagic habitats, and may lead to habitat alteration, loss, or creation, and could affect animal behavior or ecosystem function [18]. Rapid recovery of benthic habitat after disturbance from single device installation has been shown [19], as well as increased biomass, abundance and species richness for marine animals around habitat created by gravity-based foundations [20]. For arrays, the scaling of effects for changes like alterations to sedimentation patterns due to seabed scour, seafloor area loss due to installation of gravity foundations, or artificial reef effects and biofouling biomass increases due to new habitat creation, is expected to be additive; each device producing relatively similar levels of effects. However, this is a complex stressor with the potential for differing effects at varying spatiotemporal scales. Indeed, the scaling of seabed scour may depend on array configuration and sediment type and could be antagonistic. Similarly, the location of a device within an array may influence the level of effect on local food webs, leading to antagonistic or synergistic effects (Table 1). Understanding how effects of habitat changes scale up requires consistent collection of robust baseline data prior to device deployment that will provide empirical data for the development of habitat suitability and ecosystem-wide models that are useful for simulating the effects of arrays.

E. *Displacement*

The presence or operation of devices may cause marine animals to depart (or not enter) their preferred or critical habitats, or to move into areas that are new to them (i.e., via avoidance, exclusion, or attraction). This stressor has not been thoroughly investigated around single devices because it likely to only become observable once arrays are installed and may be triggered by underwater noise, EMF, changes to habitat, device movement, or hydrodynamic changes. The threshold number of devices required for displacement may be device- and environment-specific, with no single threshold broadly applicable across species or device types. Although we may come to understand how effects for some of the triggering stressors will scale up, there is nothing to indicate how the effects of displacement will change for arrays; they may be additive or synergistic (Table 1). Information about how effects of displacement scale up could be gleaned from agent-based models to demonstrate changes in animal movement in the vicinity of simulated arrays. Validation of model predictions using empirical data (e.g., acoustic telemetry, observation data) will be needed once arrays are installed.

F. *Entanglement*

Floating and mid-water devices are attached to the seabed using mooring lines that allow them to maintain their position in the water column or on the sea surface. In an array, cables often transport power from multiple devices to a single power export cable on the seabed. There is potential for large marine animals (e.g., cetaceans and sharks) to become entangled or entrapped in this infrastructure, although the consequences remain largely unknown. However, these lines and cables do not have sufficient slack to form a loop (there are no loose ends that pose such a risk), and the risk from single devices is considered low. Although the risk may increase with arrays, this has not been shown for surrogate industries [21], and we hypothesize that effects will increase with the number and length of lines/cables in an additive or antagonistic way (Table 1). An absence of empirical data hinders our understanding about how the effects of entanglement might scale up. How much room species need to safely navigate through lines and cables is not known and is likely species and site dependent. Agent based models that simulate animal movement around an array could be used to estimate the probability of an animal’s path intersecting with lines and cables, and could be validated with empirical data (e.g., acoustic tags, observations) following array installation.

G. *Changes to oceanographic systems*

Tides, wave, currents, and water circulation control the marine environment by determining the concentration of dissolved gases and nutrients, transporting sediment, and

TABLE 1
SUMMARY OF GENERALIZED CONCEPTS FOR HOW EFFECTS OF STRESSORS MAY SCALE UP WITH THE DEPLOYMENT OF ARRAYS

Stressor	Environmental effects				
	Dominance	Additive	Antagonistic	Synergistic	Notes
Collision risk		✓	✓	✓	-Dependent on array layout, configuration, MRE device type, site location, and species' ability to detect device and avoid/evade collisions
Underwater noise		✓			-Area over which sound will be elevated will increase with array size; elevation in received levels will increase non-linearly
Electromagnetic fields	✓	✓	✓		-Increases linearly with additional electrical current; effects may be influenced by spatial arrangement of subsea cables
Habitat changes		✓	✓	✓	-Complex effects that may vary across spatiotemporal scales, with array geometry, and equivalency of effects for individual devices within an array
Displacement		✓		✓	-Effects observed at some threshold number of devices; no single threshold applicable across species or MRE device
Entanglement		✓	✓		-Risk increases with number of devices, but dependent on scale and configuration of mooring lines/cables, depth at MRE site and animal behavior/movement
Changes to oceanographic systems		✓	✓	✓	-Effects observed at some threshold number of devices; dependent on MRE device type, array configuration, and MRE site hydrodynamics

supporting habitats and water quality that maintain marine organism health and ecosystem function. Extraction of energy by MRE devices may alter these processes at varying spatial scales and could impact animal distributions [11], predator-prey interactions [22], and sedimentation patterns and coastal erosion [23]. The effects of energy extraction by single devices on circulation patterns and wave heights are too small to be measured against the natural variability inherent in dynamic marine environments. Changes are only likely to be observable at some threshold number of devices, but this is dependent on MRE technology, array configuration, and site-specific hydrodynamics. We anticipate that effects of this stressor maybe additive, increasing with the size of the array, or perhaps antagonistic or synergistic (Table 1). To understand how the effects of this stressor may scale up, improvements to numerical and physical models must be made with particular focus on accurate site characterization, site bathymetry and hydrodynamics, and the use of simulations that include realistic devices and their operation. These models will need to be validated once arrays are installed using standard oceanographic measurements (e.g., temperature, salinity, conductivity, etc.) with a focus on quantifying variability and uncertainty.

IV. DISCUSSION & RECOMMENDATIONS

Adapting terminology from the cumulative environmental effects literature and using knowledge about effects for single devices and small demonstration-scale arrays enabled us to develop generalized concepts for how the magnitude of effects for arrays may be expected to scale up for key stressors. These generalized concepts provide a basis for developing testable hypotheses so that a robust scientific approach can be used to increase our understanding of effects of arrays; thereby improving our ability to delineate between unknown and realized risks of MRE development, identify critical knowledge gaps, and facilitate expansion of the MRE sector.

A variety of factors (e.g., environmental heterogeneity, physical habitat characteristics, array configuration, etc.) will influence how effects for different stressors scale up. Beyond the potential for non-linear effects, it is important to consider that ecosystem components do not exist in isolation, and interactions between stressors may results in magnified effects at larger spatiotemporal scales as the MRE sector expands.

Although the generalities of effects for some stressors (e.g., underwater noise, EMF) may be transferrable across some MRE sites, how the magnitude of effects scale up may not be, and could manifest differently depending on the location. Thus, the effects observed for an array in one location are not necessarily indicative of effects for an array in a different area and will need to be investigated using standardized methods.

We have identified the need for modeling and simulation studies for several stressors to advance our understanding of effects for arrays. Those studies should consider realistic array configurations that will be limited by the physical constraints of the environment (e.g., geography, bathymetry, hydrodynamics, etc.) *vs.* hypothetical configurations that are commonly used [24].

The greatest impediment to resolving environmental effects of MRE development remains the lack of empirical data collected around devices after installation; a deficiency that will only become more acute with MRE expansion. A system is needed to ensure post-installation monitoring data is collected in a standardized manner to inform environmental risks, and this must be the purview of a wider public interest. MRE test centres are ideal locations for establishing robust environmental monitoring programs, but they require stable and continuous funding to conduct the required work. Moreover, uncertainty associated with environmental risks of MRE development could be managed with the application of adaptive management principles [25]. By applying these principles to the collection of data around devices, the greater community of researchers, developers, regulators, and stakeholders will be able to move forward confidently, periodically assessing the results of monitoring data and adapting to the outcomes.

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