Future policy implications of tidal energy array interactions

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Abstract

Tidal stream energy technology has progressed to a point where commercial exploitation of this sustainable resource is practical, but tidal physics dictates interactions between tidal farms that raise political, legal and managerial challenges that are yet to be met. Fully optimising the design of a turbine array requires its developer to know about other farms that will be built nearby in the future. Consequently future developments, even those in adjacent channels, have the potential to impact on project efficiency.

Here we review the relevant physics, consider the implications for marine policy, and discuss potential solutions. Possible management paths range from minimal regulation to prioritise a free market, to strongly interventionist approaches that prioritise efficient resource use. An attractive exemplar of the latter is unitization, an approach to resource allocation widely used in the oil and gas industry. We argue that an interventionist approach is necessary if the greatest possible energy yield is to be produced for a given level of environmental impact.

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1. Introduction

The tidal stream energy resource available to the UK is estimated to be between 12 and 32 TWh/yr [1–3]. While large, this is only a small proportion of the 2017 UK electricity demand of 336 TWh [4]. Similar circumstances apply in other countries [5–7]. Tidal stream energy is thus a scarce resource, and as such our use of it should be carefully optimised.

Emerging understanding of the physics involved suggests that future governance will need to allow for holistic rather than piecemeal regional planning. Exploiting this resource efficiently, whilst minimising the environmental impact, will require close interaction between science and policy. Establishing an appropriate planning and policy framework for marine energy is important not only for tidal power, but as part of the wider "blue growth" agenda and because of the precedent that it will set regarding the governance of access to marine resources.

To date, consenting for tidal stream energy (henceforth simply "tidal energy") has mainly considered single sites in isolation, and has focused mostly on direct environmental concerns such as collisions with sea life. This approach is appropriate for present small-scale developments, where the physical effects of turbines will largely be confined to their immediate vicinity. However, if tidal energy is to make a significant contribution at regional or national scales, it will be necessary for future projects to become large enough that they will affect the overall dynamics of their channels[*]. This will cause significant inter-array interactions and far-field changes to the flow.

These implications are of environmental importance because changes to the flow will have biological and ecological effects: direct impacts will be felt on benthic habitats, and on any species that propagate by free floating of larvae [9]. Diving birds and pelagic predator/prey relationships may be affected through alterations to sediment transport, mixing, and other physical processes [10–12].

At the same time, the Levelized Cost of Electricity (LCOE) from marine energy technology – a project's discounted lifetime costs divided by its lifetime energy output – is especially sensitive to changes in energy yield, and hence in revenue, which could be caused by interactions between arrays. This is due to a combination of high fixed costs and a very low marginal cost of generation.

In this analysis we briefly describe the relevant technical findings and their implications, and then we discuss possible management approaches with reference to legal considerations and to partially analogous situations in other industries.

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[*] Vennell et al. [8] offered a rule of thumb that "large arrays" in this context are "ones where the area swept by the turbines occupies more than 2–5% of a channel's cross-sectional area".

2. Technical findings & implications

2.1. Electrical output and environmental impact are only loosely connected

The purpose of a tidal farm is to remove kinetic energy from the flow and convert it, minus some unavoidable losses, to electricity. Removing this energy has the effect of slowing the flow through the farm, causing a partial obstruction. Let us consider a large tidal energy farm which occupies part of a channel, marked "A" in Figure 1.

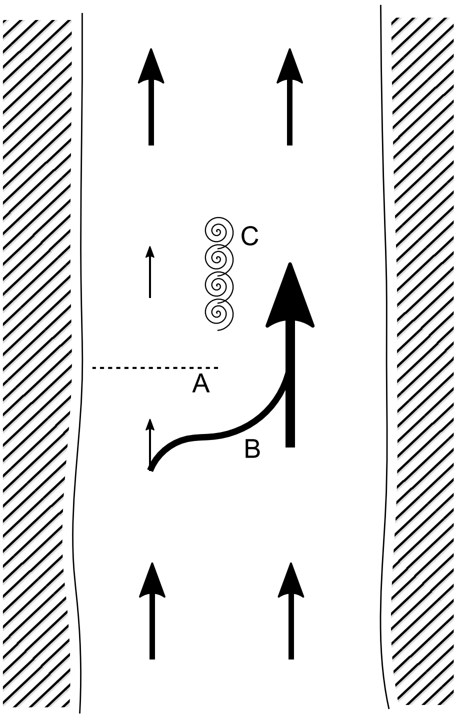


Figure 1: Illustration of the diversion of flow (B) around a tidal farm (A). Downstream of the farm there is turbulence (C) as the bypass flow mixes into the farm's wake.

Faced with the impedance of the turbines, some of the water that would have passed through the farm will instead divert to the unobstructed route around it, increasing in speed as it goes (marked "B"). This "bypass flow" carries kinetic energy that cannot be captured by the turbines, and due to its increased speed it loses more energy to seabed drag than the undisturbed flow would have. Downstream of the farm, the slow flow in the turbines' wake will merge with the accelerated bypass flow. The merging results in turbulence, marked "C". This turbulence is associated with a further loss of energy from the channel, which is caused by the presence of the turbines but cannot be captured by them [13–16].

One implication is that the greatest changes in seabed stress, and thus the greatest changes to benthic ecology, may be found not beneath the turbines but in the unexploited parts of the channel, where the flow is accelerated [17].

More importantly for this work, it means that the change to the flow, and hence the magnitude of associated environmental effects, is only loosely related to the power available for conversion to electricity. The ratio between the two will be influenced by factors such as the layout and positioning of tidal farms, the design and control strategies of the turbines, and the proportion of the channel cross-section that turbines occupy (known as the "blockage") [15,18,19].

O'Hara Murray and Gallego [20] demonstrated this using two simulated scenarios in the Pentland Firth, a major European tidal resource [3], which generate the same amount of electrical power but cause radically different levels of change to regional tidal conditions (Figure 2), due to different numbers of turbines in different layouts.

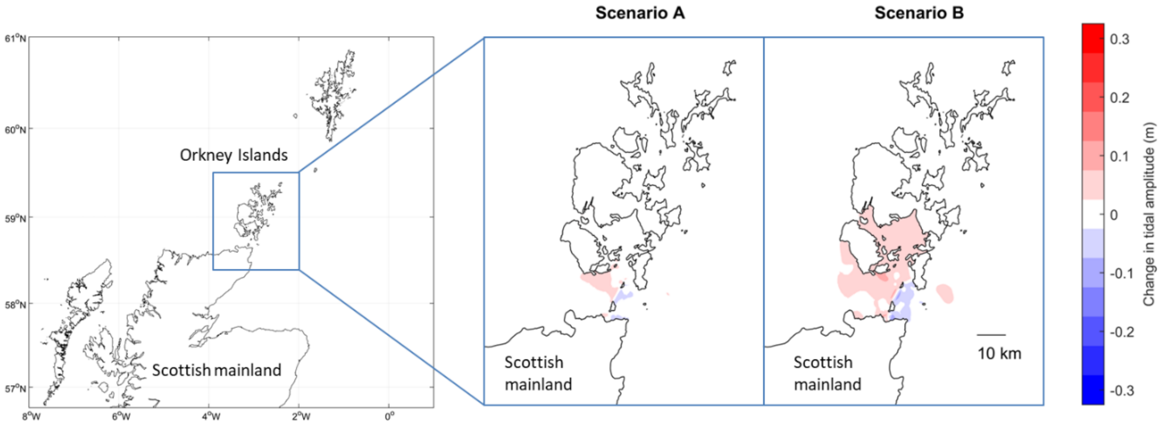


Figure 2: Predicted changes to semi-diurnal tidal amplitude resulting from two turbine layouts which both extract a mean power of 1.4 GW. Figure adapted from O'Hara Murray and Gallego[20].

In order to minimise the environmental impact of a given level of electricity generation – or, conversely, to produce as much electricity as possible for an acceptable level of impact – it is therefore desirable to think "strategically" rather than "tactically" when placing tidal farms [21,22]. Fortunately, the environmental and economic incentives are aligned when it comes to tidal layouts: those that maximise the extractable power for a given number of turbines will tend to be similar to those that minimise the resulting environmental change, as both will aim to minimise the bypass flow. In practice it will be necessary to leave unexploited sections in many channels, *e.g.* for navigation, or to allow free passage of marine mammals. The best way of laying out large-scale arrays while not occupying the entire channel is an area of active research [e.g. 15,23–25], but it is clear that what is optimal for a small number of turbines is not necessarily part of the optimal solution for a high level of exploitation – hence piecemeal development without overall planning is unlikely to deliver the best results.

When developers are planning large arrays, they will use hydrodynamic models to predict the effects of their proposed developments [26]. However, they can currently only take into account other arrays that have already been built, or at least consented; a lack of forward knowledge limits their "strategic" view. Similarly, the consideration of cumulative impacts during environmental impact assessment (EIA) does permit some note to be taken of inter-array interactions in the EIA process, but only by looking backwards to older developments when considering a new one; it is not the same as forward planning. It has recently been suggested that the Strategic Environmental Assessment approach may be more effective in achieving similar goals for wind power [27].

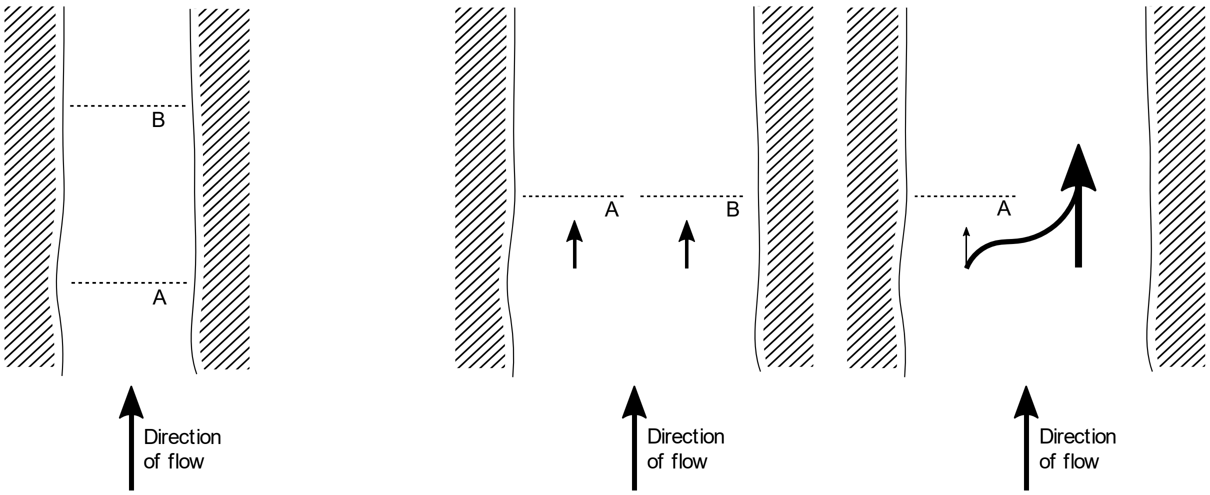
The Scottish Government has conducted extensive work to identify suitable areas for tidal energy, based on finding areas of high flow speed that do not conflict with other sea uses, environmentally designated areas, etc. [28,29]. Importantly, this guidance does not currently consider the location of tidal farms within the areas identified, or potential interactions between developments. We note that the Initial Plan Framework ([29]) is a mid-process document, so it is possible that these issues could be taken into account before the plan is finalised.

Funke et al. [30] experimented with optimisation techniques between a number of hypothetical tidal farms in the Pentland Firth, allowing for economic as well as physical factors. They found that any of the farms could be adjusted to provide greater profit to its operator, at the cost of a reduced level of generation from the region as a whole. This points to the potential for a "tragedy of the commons" scenario.

2.2. Tidal arrays affect each other

Thus far we have considered a single tidal farm, partially occupying a channel. We have shown that this farm, if large enough, can alter the flow in the part of the channel that it does *not* occupy. It follows that in a channel with more than one tidal farm, each farm has the potential to alter the flow at the location(s) of the other(s).

To illustrate these effects, in Figure 3 we present three simple scenarios involving two tidal farms "A" and "B". In scenario (a) they are positioned upstream / downstream of each other; in scenario (b) they are alongside each other in the same channel; and in scenario (c) they occupy adjacent channels. Real layouts will be more complex than those shown here, but most real scenarios can be described as one of, or a combination of, these three templates.



(a) Upstream / downstream

(b) Side-by-side

(c) Parallel channels

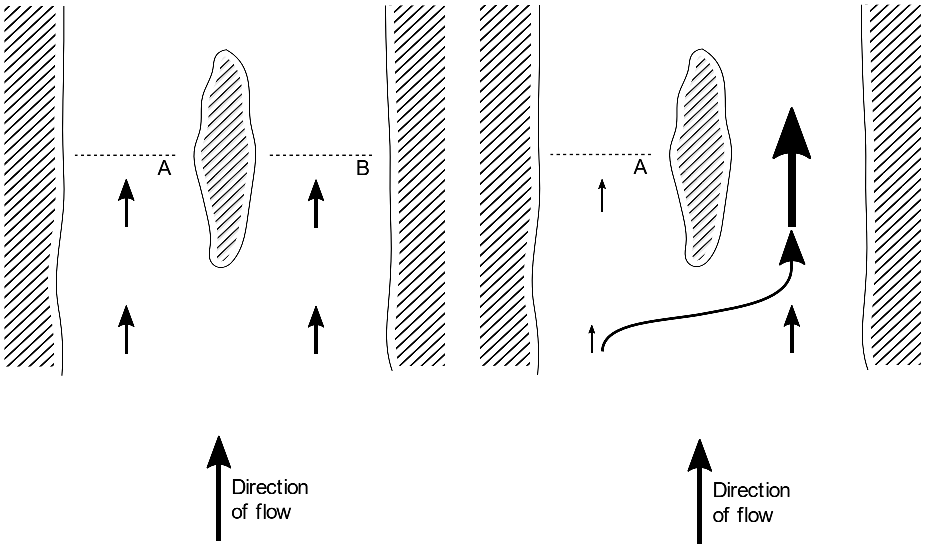


Figure 3: Three idealised scenarios showing interactions between two tidal farms A and B. In scenarios (b) and (c), we also show the effect of farm B being absent or inoperative.

Scenario (a) is easily understood: the presence of one farm reduces the power available to the other, and if one farm stops operating the other will benefit.

Scenarios (b) and (c) exhibit a phenomenon peculiar to tidal power: that each farm depends upon the other for its efficacy, and if one farm stops operating then the other *loses* performance. In both of these examples, if Farm B stops operating it leaves an unimpeded route which some of the flow that would have powered Farm A diverts into, reducing the power available to A. The magnitude of this diversion will vary greatly, especially when islands are present, depending on the geometry of the natural system [31].

Draper et al. [32] used numerical modelling to examine the maximum power available from exploiting one, two, or all three subchannels of the Pentland Firth. They found that any given subchannel could provide 40-60% more power if the others were also developed. For example, “the deployment of tidal devices across the Inner Sound could remove up to 122 MW if exploited in isolation or between 108 MW and 320 MW if other tidal devices are operated in combination within the Pentland Firth” [32]. Real developments will not extract the maximum possible power, for both environmental and economic reasons, and hence the magnitude of this effect will be less in reality.

Theoretical work by Vennell [8,33,34] has shown that the optimal design of tidal turbines, their control strategy, and their layout, depends on the presence of other turbines and the proportion of the channel cross-section that is exploited. Similar results have been obtained through computational modelling [25,35], Schluntz and Willden noting that “rotors designed for high blockage perform poorly in unblocked flow conditions” [35].

It is clear from these studies that with multiple large tidal farms in an area, the optimal design and even the financial viability of one farm could depend upon the presence, and performance, of another. Policymakers will need to consider the possibility of a planned array not being built or, once operational, not performing as expected. Some important policy questions are raised:

- Does the developer or operator of the unbuilt or underperforming tidal farm have a liability with respect to the effect on other installations?
- Does the marine licencing authority, or marine landlord, have any responsibility for any negative impacts of newly authorised/leased developments on existing tidal arrays?
- Similarly, when some of the environmental effects of a tidal farm will depend on the operation of other tidal farms that are present, is an EIA for a single farm meaningful in isolation? If the impact of farm A increases because farm B is not operating, who is responsible for this?

3. Possible management approaches

Given the implications discussed above, an ideal approach to planning and regulating tidal power would have the following attributes: (1) It would permit holistic planning of all tidal energy developments in a region; (2) It would allow forward visibility to developers so that they could design their arrays taking into account others that were not yet constructed; (3) It would discourage array operators from extracting more power than permitted; (4) It would provide appropriate compensation if the failure of one farm to generate was detrimental to another.

Below we outline three possible approaches, which sit on a spectrum of management priorities at different levels of control. Other approaches also exist and sit between or beyond these examples.

3.1. Prioritising the free market

This approach, which approximates the status quo, maintains a free market, underpinned by a legal system which prioritises private property rights.

On land, property owners have the right to enjoy the "beneficial attributes" of their land. These rights may be protected by laws which place limitations on the activities of third parties that may harm them. So-called "natural rights" are considered necessary for the enjoyment of the property, including the right to extract water [36]. If activities on adjacent land are preventing the "comfortable enjoyment" of the property, then a land owner may make a claim of nuisance and, if the nuisance is established in law, it may be stopped by injunction. Landlords are not generally liable for the actions of tenants unless they knowingly permit an activity that will cause a nuisance [37]. On land, an activity which has been granted planning permission is not generally deemed capable of causing a nuisance, on the basis that this has been considered in the planning process [38].

In Scottish waters, Crown Estate Scotland administers the territorial seabed for purposes of "economic development, regeneration, social wellbeing, [and] environmental wellbeing" [39 s. 7.2.b]. Similar arrangements apply to the rest of the UK. The Crown Estate can lease areas of seabed for purposes such as renewable energy. A lease, as a property right, should provide the right to the "potential benefit stream", i.e. profit garnered from the energy resource, as on land [40]. The lease-granting authority should, in turn, provide protection over that potential benefit. However, example leases provided by The Crown Estate make no mention of potential income, which suggests that risk regarding future benefits currently lies with the developer.

It is useful to look at the partially analogous situation in wind power. Wake effects from large offshore wind farms can reach for 45 km, and these can affect the output and thus the LCOE of other farms [41]. Planning for offshore wind development in Scotland is highly centralized, with potential areas designated by a nationwide sectoral plan and leases awarded by The Crown Estate. Responsibility for siting thus lies with national authorities, but there appears to be nothing in the sectoral plan which stipulates placement for resource optimisation [42]. Similar research in other jurisdictions has shown that legal stipulations for placing onshore wind turbines are "haphazard", and that siting usually follows incumbent zoning practices rather than being designed for maximisation of the resource [43]. The siting of wind developments at sea appears to be emerging within a free market, with little consideration of the effects of new entrants on in situ developments, and no liability held against the permitting authority. Potential may exist for nuisance claims; precedent exists for energy resources, in that US courts have previously decreed that obstruction of sunlight used as an energy source could be claimed against under nuisance law [44].

In the tidal case, future developments might be detrimental or advantageous to an existing one. In circumstances where tidal farms are mutually dependant, it seems unlikely that a claim of nuisance could be brought against a neighbour for *failing* to do something (e.g. failing to build a tidal farm or to operate an existing one). Such interdependent deployments would presumably depend upon private contractual arrangements between the two developers. A free-market approach would not permit holistic planning, nor give forward visibility to developers. In the absence of private agreements as to the amount of energy extracted, there would be little to prevent the "tragedy of the commons" scenario noted above.

3.2. "First Come, First Served": prioritising in situ arrays

This is a reactive management approach that protects the rights of existing developments, giving precedence to those who are first to exploit the resource. It is enforced through responses to changes in the situation rather than as a proactive plan; access to the resource is ultimately moderated by impacts felt by established exploiters.

An example of this approach can be seen in the arrangements for grid access for generators in the archipelago of Orkney, Scotland. The combined capacity of the wind generators in Orkney is greater than the capacity of the grid to export electricity. Pre-2009 wind farms have guaranteed grid access, while later ones were offered "non-firm" connections. When winds are strong and local loads are low, generation is constrained on a "last in, first off" basis – i.e. the most recently-connected wind farms are the first to be ordered to stop generating [45]. The first movers are thus protected, and new entrants carry all of the risk.

A disadvantage of this policy is that new entrants will often introduce new methods that are intrinsically more efficient and profitable, but they cannot displace older, less efficient generators. In principle (as per the Coase Theorem [46]) this problem could be avoided if new entrants were allowed to bargain with incumbent generators to acquire their rights.

If applied to tidal energy this approach would clearly restrict new developments which were disadvantageous to existing ones, even if they would lead to a greater total output. Complementary developments should face no such barrier. It does not permit holistic planning, and does not provide forward visibility. Detrimental interactions between arrays, if provable, would be easily dealt with, but once again it is likely that private arrangements would be needed to mitigate the risk of interdependent farms not performing.

3.3. Unitization: prioritising resource optimisation

Out of the three solutions outlined here, this exhibits the highest degree of intervention by authorities, and is the only one to address the identified need for strategic planning. It is drawn from the history of the oil and gas industry.

Ownership of oil was initially based on the “rule of capture”. This principle was inherited from the treatment of wild animals: animals are only considered to be owned from the moment that they are caught, at which point they belong to the captor. It is common for underground oil reservoirs to overlap boundaries (e.g. property lines, or national borders). Once oil was discovered, landowners on either side of a boundary were effectively in a race to extract, and thus claim ownership of, the resource. “Competitive drilling” resulted in sub-optimal recovery, increased costs and the potential to flood markets with oil [47]. In the 1930s various US states introduced “pooling” and later “unitization”. Pooling is the regulation of the number of wells and the distances between them. Unitization, which has become an international norm, involves transboundary cooperation to manage the extraction of a reservoir as a whole. One developer may extract the resource, with revenues shared between the holders of the extraction rights.

Unitization is intended to manage production in the national interest, prioritising the maximisation of the resource. In the UK, the aim of unitization is “maximising the recovery of UK petroleum” [48], and international unitization agreements are driven by similar motives.

There are four key features of unitization: (i) resource estimation; (ii) a development plan; (iii) determination of financial interests; (iv) redetermination (because the size of the recoverable resource is never certain before production starts); and (v) a framework for dispute resolution [49]. Contractual agreements such as those used in unitization have been described as the most “straightforward economic solution” to the problem of common-pool resources [50]. As such, it has been championed for use in other renewable resources, e.g. fisheries [51]. However, despite their theoretical proficiency, acceptance of such prescriptive techniques is not easily achieved.

In a tidal context, appointing a single operator to exploit a region for the benefit of all leaseholders would allow for optimal planning, would naturally handle inter-array interactions of all sorts, and would avert the risk of one farm’s owner extracting more than the optimum power at the expense of others. It is not clear how, and whether, new entrants could join the group with additional investment to increase the level of exploitation. Such an event might involve complex multi-party negotiations if the new optimum required modifications to existing farms.

4. Measuring the wrong thing?

When a water company is permitted to extract water from a river, their license specifies the amount of water that may be removed – not the size of the pipe that may be installed. The current approach to planning tidal energy extraction, based on installed capacity, is analogous to the size of the pipe – although regulators do consider the expected environmental impacts of developments.

The parameter which has the most influence on both the far-field impact of one tidal farm, and on that farm’s effects on its neighbours, is the power that it removes from the flow. For this reason, it may be advantageous to plan and consent on the basis of power removed rather than generation capacity. This would mean that the parameter with the environmental and inter-array influence was controlled directly by the regulator, and the developer had a financial imperative to maximise the yield of electricity within this constraint.

Such a method may turn out to be important if a non-unitized management approach is adopted, in order to establish whether one farm has indeed had a detrimental effect on another. A solution does not necessarily require high precision, but it does need great reliability, as it could become central to legal proceedings.

Unfortunately, calculations of the power extracted from the flow require further research to be sufficiently reliable, and hence this is not a change that can be made at present.

5. Discussion & conclusions

The studies referenced here demonstrate that interactions between arrays can, in theory, be strong enough that regional planning is required to achieve optimal results.

Unlike other resources, interactions between tidal farms are not limited to a new entrant adversely affecting an existing enterprise. With tidal energy it is possible for the *absence* (or underperformance) of one development to adversely affect another. This dependence of arrays on one another may raise legal issues when they are not constructed or operated as expected.

The magnitude of these effects in realistic scenarios is unclear. Draper et al. [32] demonstrated a very large effect (see Section 2.2), but as they simulated the maximum possible power from a region regardless of environmental considerations, this should be seen as an upper bound. Vazquez and Iglesias [52] coupled a LCOE calculation to a hydrodynamic model and used this to demonstrate that short-range wake interactions between turbines can increase LCOE. A useful next step would be to take a similar approach to quantify the effects of inter-array interactions on LCOE and flow alterations, using realistic levels of energy extraction.

Governance of tidal energy should include decisive policies on dealing with the human and physical consequences of competing developments. The goal of optimising for the most efficient use of the resource strongly favours an interventionist, centrally planned approach, as exemplified here by the oil and gas concept of unitization. Such planning could equally be accomplished by government authorities, but this may not be politically acceptable. Unitization also provides a solution to the difficulty of ensuring the fair operation of interdependent arrays, but other approaches such as private contracts providing redress for non-performance might also serve.

It is important that an appropriate policy framework should be in place before tidal developments reach such as size as to need it, as implementing a regional plan will surely be much more difficult if non-optimal farms are already in the water. We hope that this preliminary analysis will stimulate discussion and further work on the topic.

Acknowledgements

Funding: This work was supported by the UK's Natural Environment Research Council (grant number NE/R006903/1) and Engineering and Physical Science Research Council (the EcoWatt2050 project, grant number EP/K012851/1).

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