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Designing large arrays of tidal turbines: A synthesis and review

Ross Vennell [a,*], Simon W. Funke [b,c], Scott Draper [d], Craig Stevens [e], Tim Divett [a,e]

[a] Ocean Physics Group, Department of Marine Science, University of Otago, Dunedin, New Zealand
[b] Department of Earth Science and Engineering, Imperial College London, UK
[c] Center of Biomedical Computing, Simula Research Laboratory, Norway
[d] Centre for Offshore Foundation Systems, University of Western Australia, Australia
[e] NIWA, Wellington, New Zealand

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ABSTRACT

Much of the global tidal current energy resource lies in the accelerated flows along narrow channels. These channels have the potential to produce 10–1000 s of MW of electricity. However, realizing 100 MW of a channel's potential is much more complex than installing 100 1-MW turbines because large scale power extraction reduces tidal currents throughout the channel, changing the resource. This synthesis and review gives an overview of the issues and compromises in designing the layout of the large tidal turbine arrays required to realize this potential. The paper focuses on macro- and micro-design of arrays. Macro-design relates to the total number of turbines and their gross arrangement into rows, while micro-design adjusts the relative positions of the turbines within a grid and the spacing between rows. Interdependent macro-design compromises balance the total number of turbines, array power output, the power output of each turbine, the loads the turbines experience, turbine construction costs, maintaining navigability along the channel and any environmental impacts due to flow reduction. A strong emphasis is placed on providing physical insights about how "channel-scale dynamics" and the "duct-effect" impact on the compromises in array design. This work is relevant to the design of any "large" array which blocks more than 2–5% of a channel's cross-section, be it 2 turbines in a small channel or 100 turbines in a large channel.

Contents

* Corresponding author. Tel.: +64 3 479 8307.
E-mail address: ross.vennell@otago.ac.nz (R. Vennell).

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1. Introduction

Power generated from tidal currents could make a significant contribution to the global demand for renewable energy. Most of this resource lies in the concentrated energy of flows along narrow tidal channels [1–6]. The power which can be extracted from a channel is limited by tidal dynamics [7, hereafter GC05]. This limit, or “potential”, ranges from Mega Watts for small channels, to Giga Watts for large channels. To realize this potential large arrays of tidal turbines must be installed within many channels, so as to cumulatively make a significant contribution to global demand. However, turbines within large arrays perform very differently to isolated turbines [8]. Together the works [9, hereafter V10, 10,11,8] demonstrate that, for large arrays there is no simple relationship between the total installed capacity of the turbines in the array and the array's total output, because the output of an individual turbine depends on the size of the array, how the turbines are arranged and the channel they are installed in. Importantly, the output of each turbine determines how many turbines are required to produce a given total array output, which strongly affects the cost of building an array [8].

This paper gives an overview of some of the issues and compromises involved in designing the arrangement of tidal turbines within large arrays. These complex issues extend to the gross design specifications for loads on the turbines and their output, which change as an array grows [11]. A clear understanding of these large array issues is critical at a time when tidal current power is about to move beyond the deployment of single turbines to deploying arrays of turbines. This understanding is also critical to those assessing the tidal stream resource available at numerous proposed array sites in order to determine how much power can realistically be produced from a site.

The large tidal turbine arrays required to realize a significant fraction of a channel's potential are very different to similarly sized wind turbine farms. While wind farms are too small to affect the weather systems which drive air past their blades, tidal turbine arrays must reduce tidal flows throughout the channel in order to realize a significant fraction of its potential, see Section 2.2. These large arrays are ones which can affect “channel-scale dynamics” or have the power coefficients of their turbines enhanced by the “duct-effect” [8]. The interaction of channel-scale dynamics and the duct-effect leads to key “array-effects” which are relevant to array and turbine design, see Section 2.1. A large array does not necessarily have a large number of turbines, see Section 2.6. Two turbines in a small channel are a “large” array, if they extract a significant fraction of its potential. Conversely, 100 1-MW turbines in the 100 km long Cook Strait NZ would be a “small” array because the Strait's potential is huge, 14 GW [5].

Threads within this synthesis and review address four questions (1) how do we arrange and tune turbines within large arrays to maximize array output? (2) how does the array layout affect the output per turbine, structural loads and construction costs? (3) how do we model and tune large arrays? and (4) what physical insights are relevant to developing a language which can be used to discuss large arrays? These threads are intertwined, e.g. our ability to investigate beneficial turbine arrangements is limited by the computational effort required to model and optimize large arrays. This computational effort is significantly increased because turbines must be “tuned” for a particular channel and array layout, in order to maximize array output [11].

The design of an array's layout has profound impacts on the number of turbines required to realize a given power output, the turbine designs required to withstand loads and their construction costs [11,8]. The array layout may also be constrained by water depth or local bathymetry. It is also likely constrained by the need to maintain navigation along the channel for vessels and marine life, and by the need to keep the flow reduction due to power extraction small enough to minimize environmental impacts, such as changes in sediment transport [12,13]. All of these aspects impact on array and turbine design, resulting in many compromises. Designing large arrays in channels is complex and warrants a review of the interplay between the array power output, turbine output, navigability and flow reduction, with the number of turbines in the array and their arrangement, loads and design specifications.

This review does not extend to the detailed design of turbines, e.g. blade design and tip speed ratios, but provides gross specifications for the output and loads that a turbine must meet to realize the estimated power production, along with some of the issues and compromises in designing the layout of turbines within large arrays. This work deliberately focuses on sites within tidal channels, as these hold much of the global potential. Other types of sites, such as headlands on open coastlines [14], arrays far from any coastline [15] or arrays near the shoreline [16] require further work.

For grid arrays of turbines the first major decision is the gross or “macro” array design. Macro-design decisions relate to the total number of turbines in the array, how many are placed in each row across the channel and how many rows to install, see Section 4. In contrast, “micro” array design exploits adjustments of the relative positions of the turbines within the grid to boost array output, see Section 5. Macro-design is about the total number of turbines required to produce a given power output, thus has a much larger impact on array and turbine output than micro-design. Consequently, macro-design will be addressed first with a synthesis of some of the compromises in arranging turbines within tidal turbine arrays (Section 2).

Designing both macro- and micro-arrangements of turbines within arrays requires hydrodynamical models, which require additional compromises in order to make them computationally feasible. Thus, this paper requires 3 interrelated mini-reviews (i) approaches to modeling arrays and optimizing the turbines within them (Section 3), (ii) macro-design of arrays (Section 4), and (iii) micro-design of arrays (Section 5). The synthesis and