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Optimal phasing of the European tidal stream resource using the greedy algorithm with penalty function

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ABSTRACT

The regular periodicity of astronomical tides allows their accurate prediction, and so it should be possible to determine how best to optimise the future distribution of arrays of tidal energy devices for any shelf sea region. By considering together the magnitude and phase of tidal currents over a shelf sea region, maximum aggregated power generation, with minimal periods of low generation, can be deduced. Here, we make use of the greedy algorithm to optimise future exploitation of the tidal stream resource over the northwest European shelf seas, a region which contains a world-leading tidal energy resource. We also apply a penalty function to the greedy algorithm, favouring the selection of future hypothetical sites where power generation would be out-of-phase with previously developed sites. Our results demonstrate that the Pentland Firth and Channel Islands would be optimal sites for parallel development for relatively low numbers of arrays, with important contributions from the Irish Sea for larger scale exploitation. Although there is minimal phase diversity between European tidal stream sites to deliver firm power generation, it is possible that the vertical tide could contribute to such baseload through the parallel development of lagoons or impoundments.

1. Introduction

In contrast to the stochastic nature of waves [1], the regular periodicity of tides allows their prediction far into the future [2], and this presents us with the opportunity to accurately quantify the role of tidal energy in the future energy mix. Most tidal energy is produced during periods of spring tides, and particularly at times of peak flood or ebb tidal currents. Although we cannot address the longer timescale variability problem of the spring/neap cycle, we could optimise exploitation of the tidal stream resource by maximising the opportunities offered by prioritising sites which are complementary in phase to one another over a semi-diurnal timescale. In this way, tidal energy, particularly tidal streams, could have a contribution towards supplying baseload to the electricity network [3]. Tidal streams can be exploited by a range of technologies that include horizontal axis turbines [4], vertical axis turbines [5], and hydrofoils [6].

Iyer et al. [7] demonstrated through an examination of the Atlas of UK Marine Renewable Energy Resources that there is insufficient diversity between UK tidal stream sites to deliver firm power generation. However, the conclusions of this study were based on a limited number of sites, since first generation tidal stream technology was assumed, which requires mean spring peak current speeds of 2.5 m/s, and water depths in the range 25–50 m. Further, the Atlas of UK Marine Renewable Energy Resources does not span international boundaries, and so the results are UK-centric. In the present study, we re-visit the problem of tidal phasing with fewer constraints on the resource, and by considering the entire NW European shelf seas, looking towards future energy security in terms of (a) future generations of tidal energy devices (which are likely to operate in deeper waters and be associated with lower cut-in and rated velocities), and (b) the possibility of a European supergrid, which would enable geographically discrete regions to aggregate their electricity generation into a unified electricity network *via* subsea and overland cables [8,9]. Further, we make use of an optimisation technique that has been successfully applied to a wide range of research topics, the greedy algorithm, [e.g. Ref. [10]], to optimise the aggregation of power from diverse tidal stream sites by maximising net power generation, while minimising periods when instantaneous power generation is below a threshold, by applying a penalty function.

After a description of the hydrography of the northwest European shelf seas, with particular emphasis on the tides (Section 2), we describe the three-dimensional (3D) oceanographic model of

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the region used to apply the greedy algorithm with a penalty function (Section 3). We consider a range of future tidal stream extraction scenarios, from first-generation arrays that will likely be developed over the next decade, through to extreme scenarios of many thousands of devices distributed over a number of locations throughout the NW European shelf seas (Section 4).

2. The northwest European shelf seas

The NW European shelf seas provide Europe with a world leading resource for the development of a marine renewable energy industry, and are therefore host to a large number of commercial projects and test centres, such as the EMEC (European Marine Energy Centre) wave and tidal test centre in Orkney, and the Marine Current Turbines/Siemens tidal array project in Anglesey (Irish Sea). Although the wave resource is substantial, [e.g. Ref. [1]], and there is scope for exploiting the potential energy contained in the vertical tide, [e.g. Ref. [11]], the focus of the present work is on the horizontal tide, i.e. tidal streams.

The NW European shelf seas, located on the northeastern margin of the North Atlantic, are generally shallower than 200 m (Fig. 1). The Celtic Sea, Malin Sea and northern North Sea are exposed to Atlantic waters, with water depths in the range 100–200 m, with the exception of the deeper (600 m) Norwegian Trench in the northeastern North Sea. The Celtic Sea borders the Irish Sea to the north, a semi-enclosed water body containing a north-south orientated channel of depth 250 m. To the east of the Celtic Sea, the English Channel connects to the southern North Sea.

There are regions of the NW European shelf seas which contain some of the largest tidal ranges in the world, e.g. the Bristol Channel and the Gulf of St. Malo. There are three M2 (principal lunar semi-diurnal constituent) amphidromic points of near-zero tidal range in the North Sea, a further one in the North Channel of the Irish Sea, and two degenerate amphidromic points: one in the English Channel, and the other in St. George's Channel [12] (Fig. 2a). Tidal currents are generally high in the Irish Sea and English Channel, and moderately high in the Celtic Sea and in the southern and western North Sea [13,14]. Since friction gradually removes energy from the tides at the bottom of the water column, the total attenuation in large seas, e.g. the North Sea, is pronounced [15,16]. In the North Sea, the propagation of the tidal wave is cyclonic. The tidal wave enters the North Sea by travelling southward along the east coast of Scotland, where the tidal currents and elevations are much greater than near Denmark and Norway, at the end of the tide's transit.

Regions of high tidal currents throughout the NW European shelf seas are concentrated in areas where there is a bathymetric enhancement or topographic restriction (Fig. 2b), e.g. through straits such as the Pentland Firth [17] and the Alderney Race [18], or past headlands such as Portland Bill in the English Channel [19] and the Skerries to the northwest of Anglesey [20]. However, the sea space at such competitive high energy sites is limited, and it is likely

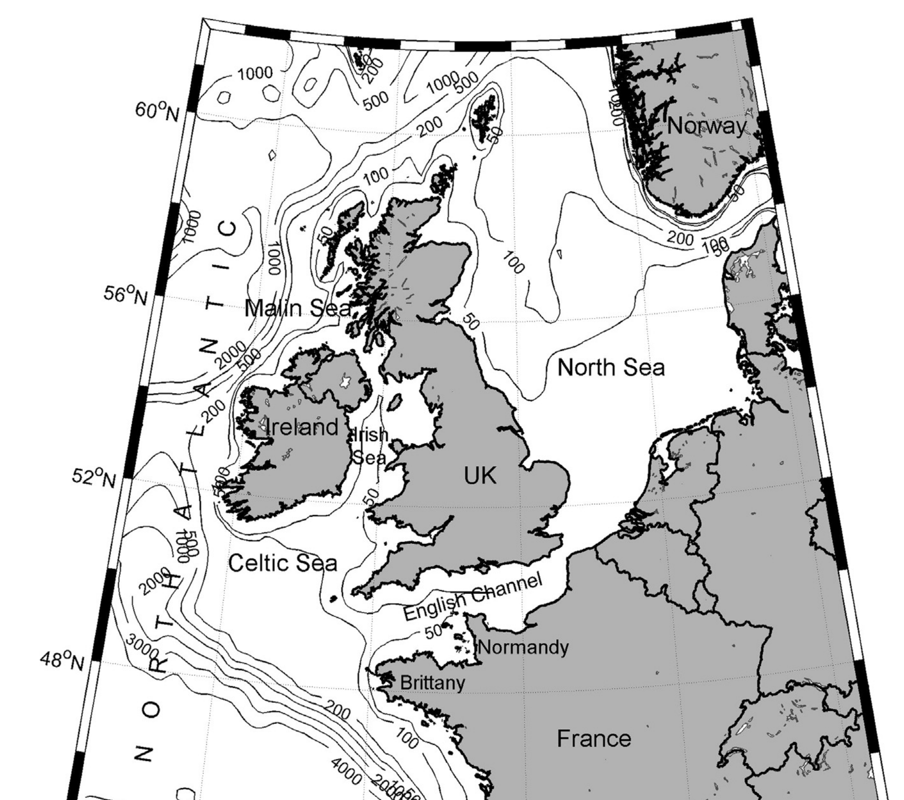

Fig. 1. The northwest European shelf seas. Contours are bathymetry in metres.