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Characterising the spatial and temporal variability of the tidal-stream energy resource over the northwest European shelf seas

Peter E. Robins *, Simon P. Neill, Matt J. Lewis, Sophie L. Ward

School of Ocean Sciences, Bangor University, LL59 5AB, UK

HIGHLIGHTS

- Model characterisation of the European tidal-stream energy resource.
- The mean spring tide may underestimate the resource by up to 25%.
- Tidal-stream variability at lunar to tidal scales affects power generation by 15%.

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ABSTRACT

As devices move from full-scale prototype to commercial installations, it is important that developers have detailed knowledge of the tidal energy resource. Therefore, the spatial distribution of the tidal currents over the northwest European shelf seas has been examined to improve understanding of the tidal-stream energy resource. Using a three-dimensional hydrodynamic model (ROMS) at ~1 km spatial resolution, and applying device characteristics of the Seagen-S turbine, we show that the ratio of the amplitudes of the M_2 and S_2 tidal currents can lead to significant variability in annual practical power generation – variability that is not accounted for when considering only the mean peak spring tidal velocities, as is generally the case in resource feasibility studies. In addition, we show that diurnal inequalities (governed by K_1 and O_1 tidal constituents) and tidal asymmetries (governed by the relationship between M_2 and its compound tide M_4) over the northwest European shelf seas can further affect power generation at potential high-energy sites. Based on these variabilities, the spatial distribution of the tidal-stream 'capacity factor' has been calculated. We find that mean peak spring tidal velocities can under-estimate the resource by up to 25%, and that annual practical power generation can vary by ~15% for regions experiencing similar mean peak spring tidal velocities, due to the influence of other tidal constituents. Therefore, even preliminary resource assessments should be based on annual average power density, rather than peak spring tidal velocity.

1. Introduction

The tidal-stream renewable energy industry – where the kinetic energy inherent in the oceans is converted into low carbon electricity – is at a crucial stage of development, where single-device tidal-stream energy converters (TECs) have been installed and grid-connected at high-energy sites (e.g., www.marineturbines.com; www.openhydro.com). The next stage – the construction of offshore tidal energy farms, or TEC arrays – has been granted consent at several sites around the world (e.g., www.fundayforce.ca; www.emec.org.uk; www.thecrownestate.co.uk). Initial site selection for these locations has generally been informed by relatively superficial resource assessment modelling products (e.g., BERR Atlas of UK Marine Renewables; [1], with particular emphasis on the magnitude of the peak spring tidal currents. However, there are a number of tidal resource assessments in which mean peak spring tidal velocities are not used, for example, Ramos et al. [2]. A number of factors should be considered within any resource assessment, such as power generation, temporal variability within the resource, site conditions (e.g., distance to grid connection), as well as practical and socioeconomic constraints relating to grid infrastructure [3], governmental strategy on low carbon energy (e.g., the 'Renewables Obligation' for the UK; www.ofgem.gov.uk), and potential environmental impacts (e.g. [4–7].

Whilst the most attractive sites around the world suitable for tidal-stream development are well known, and are characterised

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* Corresponding author.
E-mail address: p.robins@bangor.ac.uk (P.E. Robins).

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by very strong tidal flow (e.g. [8,9]), a more detailed analysis of the resource is required in order to reduce investor risk and help developers choose the best locations for their technologies, as well as to advise governments on resource optimisation according to their strategic energy plan. We propose that particular emphasis has been placed on tidal current magnitude for site selection and not on its temporal variability, and the resultant net power. For example, a site which has a lower peak tidal current than another site may actually have a greater net resource, because the time series velocities are more consistent, more symmetrical between the flood and ebb phases of the tidal cycle, or less influenced by atmospheric processes. Indeed, both Hashemi et al. [10] and Lewis et al. [11] have demonstrated the impacts of waves and wave-tide misalignment on the tidal currents in the Irish Sea – the waves altering the predicted tidal currents by up to ±10%. Lewis et al. [12] have highlighted the implications of tidal current misalignment (for fixed-orientation, horizontal-axis turbines), as well as the limitations of the resource due to water depth of deployment. Neill et al. [13] show the role of tidal asymmetry for a semi-constricted channel in the Orkney archipelago.

Several tidal-stream resource assessments (e.g., [14,15]) have studied tidal phasing and optimisation methods. Neill et al. [15] introduce the issue of tidal phasing in relation to resource optimisation over the European shelf, to generate 'firm tidal power', or a continuous source of low-carbon electricity to the grid. Power generation from regions of greatest tidal-stream resource (e.g., Orkney, the Channel Islands, and the eastern Irish Sea) are approximately in-phase with one another and, hence, aggregated power generation at these sites will be characterised by modulation at the quarter-diurnal period (i.e., sub-optimal power will be generated around each period of slack water, approximately four times per day). However, little research has been conducted on the temporal variability of the tidal-stream resource, and how this varies spatially, which is essential when considering the ultimate goal of firm power generation.

Here, we investigate the spatial and temporal variability of the magnitude of the tidal currents and potential power production across the northwest European shelf seas, with the aim of improving our understanding of the net tidal-stream energy resource and optimising energy yield. We have simulated tidal flow over the shelf using the three-dimensional Regional Ocean Modelling System (ROMS), applied at higher spatial resolution (~1 km) than has previously been achieved at this scale (e.g., [10,15]). Although a 3D model has been implemented, results are presented on the basis of depth-averaged velocities. These waters are some of the most energetic in the world in terms of tidal energy dissipation (i.e., dissipating approximately 10% (0.25 TW) of global tidal energy; [9], and this study will therefore add considerable value to the European marine renewable energy industry in terms of resource assessment and potential optimisation strategies, and our methodology could be applied to other regions of the world with an energetic tidal resource.

This paper is structured as follows: Section 2 describes the theory of tidal variability over the northwest European shelf seas; model characteristics and validation are described in Section 3; analysis of the tidal current variability is presented in Section 4, enabling the tidal-stream energy resource to be mapped according to the criteria explained above; our discussions and conclusions (Sections 5 and 6, respectively) are then presented in the final sections.

2. Tidal variability

Tidal currents are driven by oceanic pressure gradients associated with the gravitational attraction between the Earth and the Moon (lunar) and the Sun (solar), and their respective rotations [16,17]. In most locations, the largest tidal constituent is the principal lunar semi-diurnal (M_2), which has a period of approximately 12.42 h – exactly half the time required for the Earth to rotate once relative to the Moon. In the same way, the 'principal solar semi-diurnal' (S_2) tidal constituent, which has approximately half the force of M_2, has a period of 12 h – half a solar day. The propagation of tidal currents in the deep ocean is primarily governed by the linear superposition of M_2 and S_2, which are in-phase every ~14.75 days, producing aggregated tidal currents (springs), and out-of-phase in between, producing minimum tidal currents (neaps). Sub-optimal power generation will occur during neap tides and full power potential is not realised during spring tides at some sites. Here, we describe only tidal currents; in addition, ocean currents may comprise other, non-tidal drivers, such as wind and density gradients, which may contribute to, or reduce, the available power resource.

We considered variability in the tidal currents over the lunar (spring-neap) cycle. Variability in the magnitude of S_2 tidal currents, relative to M_2, occurs due to differences in quadratic friction (with more friction at spring tides), and rotation between the two harmonics, which causes differences in the positions of their respective amphidromic points [18]. Here, lunar variability in tidal currents was quantified according to the following ratio (R):

$$R = 1 - (\overline{U}_{S2}/\overline{U}_{M2}) \tag{1}$$

where $\overline{U}_{M2}$ and $\overline{U}_{S2}$ denote the amplitudes of the depth-averaged tidal velocity at each model cell. The inverse ratio has been used in Eq. (1) so that higher values signify a large M_2 velocity amplitude relative to S_2, which is desirable for energy exploitation at lunar timescales, given two sites of similar mean spring peak flow.

Beyond the well-known spring-neap tidal cycle that describes the interaction between M_2 and S_2, a number of other harmonic signals exist within the tide that vary spatially. Firstly, we look at the daily modulation of the tide, as two consecutive tides can be significantly different due to the declination of the Moon [16], and are described by the interaction between the diurnal K_1 and O_1 harmonics. The 'tidal form' varies around the globe, arising from local differences in semi-diurnal and diurnal forcing constituents, resulting in tides that range from strongly semi-diurnal to strongly diurnal [19]. Pond and Pickard [19] classifies the Form ratio as:

$$F = \frac{(H_{K1} + H_{O1})}{(H_{M2} + H_{S2})} \tag{2a}$$

where H signifies the amplitudes of tidal elevation; $F > 3$ indicates diurnal tides, whereas $F < 0.25$ indicates semi-diurnal tides. Here, we classify the daily modulation of the tidal currents over the northwest European shelf seas, defined by the tidal current Form ratio (Fu):

$$Fu = \frac{(\overline{U}_{K1} + \overline{U}_{O1})}{(\overline{U}_{M2} + \overline{U}_{S2})} \tag{2b}$$

which is based on the sum of the depth-averaged tidal current amplitudes of the two principal diurnal constituents to that of the two principal semi-diurnal constituents. If the tide is strongly semi-diurnal, then equal amounts of power will be generated on two consecutive tides. As the diurnal inequality strengthens, in regions where the combined $\overline{U}_{K1}$ and $\overline{U}_{O1}$ diurnal current amplitudes are significant, power generation may become sub-optimal for one of these tides per day, hence, variability in peak power generation per tide per day. The northwest European shelf seas are strongly semi-diurnal, and F is generally less than 0.25; however, small variations in F, and hence Fu, will potentially generate significant variability in the amount of practical power produced. Based on this, we hypothesise that, for sites with similar peak