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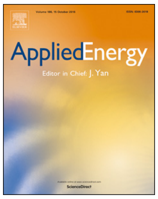

Tidal stream resource characterisation in progressive versus standing wave systems

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HIGHLIGHTS

- Investigating the tidal stream resource in standing and progressive wave systems.
- Progressive systems produce power-asymmetry over a tidal cycle.
- Such asymmetry is greater for floating-platform than bottom-mounted technology.
- These effects are exacerbated in shallow waters and where tidal range is large.
- Flow asymmetry is minimised in standing wave systems.

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ABSTRACT

Characterisations of the tidal stream resource and its variability over various timescales are crucial for the development of the tidal stream energy industry. To date, no research has compared resource sensitivity in standing wave (when peak currents occur midway between high and low water) and progressive wave (where peak currents occur at high and low water) tidal systems. Here, we compare the flow regimes of standing wave versus progressive wave systems and the associated variations in tidal stream power with applications to device deployment options (floating-platform turbines versus bottom-mounted turbines). We use a validated 3D numerical model (ROMS) of a globally-significant tidal energy shelf sea region (Irish Sea), to test the hypotheses that the influence on potential extractable energy, and suitability for different devices, may be markedly different between these contrasting systems. Power density was also calculated and compared for floating versus bottom-mounted devices using *in-situ* current data (ADCPs) obtained from a standing wave site and a progressive wave site. We show that progressive wave systems are characterised by velocity-asymmetry over a tidal cycle (i.e. stronger peak flows at high water than at low water), leading to power-asymmetry. Such power asymmetry was shown to have more of an effect on floating device technology, where an assumed turbine depth tracks the sea surface, in contrast to bottom-mounted technology, where the hub height is fixed at a certain position above the sea bed. Shallow, high-flow regions where tidal range is large contained up to 2.5% more power density from bottom-mounted compared with floating turbines; however, there were areas where floating devices were exposed to higher mean currents over a tidal cycle. Standing wave systems, where flow asymmetry is minimised, did not particularly favour either technology. The results highlight the requirement for detailed resource assessments to consider the vertical plane, and are applicable to all potential tidal stream energy sites.

1. Introduction

Exploiting the abundant potential global tidal energy resource could provide us with a renewable and largely predictable source of power that has the potential to reduce our reliance on fossil fuels, thus helping to meet global targets for renewables [1]. Shelf sea regions that exhibit large tidal ranges or strong tidal currents contain significant potential for tidal energy extraction, such as the northwest European shelf seas

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surrounding the United Kingdom [2–4]. Whereas tidal impoundments (lagoons or barrages) exploit the potential energy of the rising and falling tide, in-stream tidal turbines harness the kinetic energy of tidal currents. These resources can be predicted over long timescales using ocean models, which to some extent can capture hourly-to-decadal variability in current speeds and, hence, available power; however, the vertical variability of the resource within the water column is less well understood, because many tidal resource assessment models are based on depth-averaged 2D assumptions.

Considerable research, development and innovation (RD&I) into tidal stream energy technologies and resource characterisation are being conducted throughout the United Kingdom. The world's first fully-operational grid-connected tidal stream array (3 × 100 kW turbine array) has been deployed by Nova Innovation in Shetland, Scotland (www.novainnovation.com). In addition, phase 1A (4 × 1.5 MW turbine array) of the 400 MW MeyGen project in the Pentland Firth, Scotland, is completed and grid connected (www.atlantisresourcesltd.com). Both of these schemes have adopted bottom-mounted tidal stream devices, where the turbine hub height is located at a fixed distance above the sea bed.

Across Europe, there has been significant development of turbines deployed from floating platforms, advantages and disadvantages of which are outlined in Table 1. For these floating devices, the platform is usually tethered to the seabed to constrain horizontal movement, but is free to move vertically with changes in sea surface elevation. The turbine is mounted at a fixed depth relative to the platform, and so the hub height tracks the free surface, and consequently the turbine encounters a different flow regime over time than a fixed hub height turbine would at the same location (Fig. 1), particularly when the tidal range is large. Several prototype floating tidal stream energy devices have been designed and tested *in situ* (e.g. [5]), including Bluewater's BlueTEC device which was installed in the Wadden Sea (2015, www.bluewater.com), Oceanflow's Evopod (1/4 scale) demonstration at Sanda Sound, Scotland (2014, www.oceanflowenergy.com), and Hydra Tidal's Morild II was deployed in 2010 for two years in the Lofoten Islands, Norway (hydratidal.wix.com).

Despite the level of technological advancement of floating devices, there has been little consideration within resource assessments of the possible changes in energy yield that results from such technologies, compared with ‘conventional’ bottom-mounted devices. In particular, few studies have considered tidal stream resource variability over the vertical water column, other than the work of Sanchez et al. [6,7] and Thiébaut and Sentchev [8]. Several recent resource assessment studies have looked beyond simply characterising the peak M_2 tidal flows and suitable water depths, to address: (i) resource variabilities at tidal timescales caused by coastal effects (e.g. [9,10]); (ii) astronomical tidal variations generating daily-to-interannual resource variability (e.g. [3,11]), and (iii) the effects of wave-current interactions on the resource (e.g. [12,13]).

Sanchez et al. [6] used 3D hydrodynamic model simulations to compare the potential annual power generation from floating (upper 65% of the water column) versus bottom-mounted devices (lower 65% of the water column), using the power curve of the Evopod floating device. They found that the annual electricity production in the estuary, the Ria de Ortigueira (Spain), increased by 40% using a floating device rather than a bottom-mounted device, because of higher velocities higher up the water column. Sanchez et al. [7] subsequently reported that the simulated impacts on estuarine circulation were comparable when energy was extracted by theoretical floating or bottom-mounted devices. A more recent study by Thiébaut and Sentchev [8] considered the tidal energy resource off the coast of Brittany, focussing on tidal asymmetry. Comparing vertical variations in observational flow data, Thiébaut and Sentchev [8] estimated that the monthly mean technical resource was up to 50% greater in the upper half of the water column than in the lower half, again due to higher velocities in the upper half of the water column.

In this paper, we use models and observations to examine variability in the tidal stream resource over the vertical in relation to the phasing of surface elevations and tidal velocities that produce either standing or progressive wave systems. To our knowledge, prior to this work, no study has investigated the simulated differences in power density from floating and bottom-mounted devices when positioned at similar hub heights in these different flow regimes, which is an important consideration, particularly for relatively shallow tidal stream energy sites. The tidally-energetic Irish Sea is used here as a case study, but the principle findings highlight relevant considerations for potential tidal stream development sites across the globe.

2. Standing and progressive tidal waves

Where a tidal current is described as a *standing wave*[1] system, slack water coincides with high and low water, with peak flood and ebb flows occurring at mid-tide (Fig. 2a). Conversely, if peak tidal currents occur at high and low water, with slack water at mid-tide, then the tidal current is referred to as a *progressive wave* system (Fig. 2b). In a progressive wave system, the peak currents are more affected by water depth changes than for a standing wave system, with the potential for weaker peak currents at low water than at high water, because of the increased influence of sea bed friction compared with total water depth [14]. This effect will be more pronounced in shallow waters, and for larger tidal ranges. Conversely, the effect is reduced as the wave moves towards a standing wave system, because peak flood and ebb currents occur in similar water depths (i.e. around mean sea level, MSL). In reality, few locations are purely standing or progressive, but are more likely to be characterised as ‘mixed’ or partially-progressive wave systems.

Within shelf sea regions, there is often considerable variation in the nature of the tidal wave. As the ocean tide propagates onto shelf seas, tidal wave reflections within coastal basins, bays, and estuaries result in the formation of standing waves [15]. Where the basin length aligns with the wavelength of tidal oscillations, resonance occurs and the tide is amplified, producing large tidal ranges, such as in the Bristol Channel, United Kingdom [15] and the Bay of Fundy, Canada [16]. Tidal propagation through topographically complex regions such as island archipelagos can generate large pressure gradient forces that can influence the nature of the tidal wave – changing from standing to progressive within a few kilometres (e.g. [17,18]). Long channels or estuaries (relative to the tidal length scale) experience progressive wave systems towards their head because of a significant damping effect of bottom friction that delays the flow relative to the elevation [19].

Here, we develop an ocean model for the Irish Sea (described in Sections 2 and 3). We simulate 3D tidal current velocities in relation to the phasing of the surface elevations and, hence, characterise the tidal regime (standing through to progressive) throughout the Irish Sea. By simulating current speeds likely encountered by both bottom-mounted and floating tidal energy devices, we then calculate the expected differences in power density between the two schemes, under realistic conditions within the Irish Sea. We extend this analysis to data from two ADCPs, obtained from contrasting standing vs progressive wave systems in the Irish Sea. These results are presented in Section 4, followed by our Discussions (Section 5) and Conclusions (Section 6).

3. Study region – The Irish Sea

The Irish Sea is a semi-enclosed mesoscale basin, characterised by strongly semi-diurnal Kelvin-type tides that are macro tidal in the east, with the tidal range exceeding 12 m at Avonmouth (Bristol Channel; [20]). In the west, one partial amphidromic system dominates, to the east coast of Ireland, which is a degenerate amphidrome [21]. As a

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[1] Where ‘tides’ are characterised as shallow water ‘waves’.

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