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Realistic wave conditions and their influence on quantifying the tidal stream energy resource

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HIGHLIGHTS

- Waves are frequently aligned at an oblique angle to the tidal current.
- Wave angle must be considered for realistic oceanographic conditions.
- Waves have a significant impact on the tidal stream energy resource.
- The net tidal resource is reduced by ~10% per metre wave height increase.

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ABSTRACT

When selecting suitable sites for tidal stream energy arrays a wide range of factors must be considered, from the magnitude of the tidal stream resource, to realistic oceanographic conditions. Previous computational and laboratory-scale investigations into the impact of waves upon tidal turbines (such as turbine blade loadings) and turbine arrays (such as array configuration) typically assume that waves propagate "*inline*" to the tidal current (waves following or waves opposing the tidal current with a 20° tolerance limit). We investigated the wave climate at typical tidal stream energy sites across the British Isles. The wave climate was simulated at 18 sites using a 7-year (2005–2011) SWAN wave model simulation of the northwest European shelf seas. The principal semi-diurnal lunar constituent (M2) was also estimated at these sites using the three-dimensional ROMS tidal model. A significant proportion of the wave climate (between 49% and 93% of the time), including extreme wave events (>10 m wave heights), was found to be propagating in a direction which was "oblique" to the major axis of tidal flow (i.e. waves which propagate at an angle to the tidal current with a 20° tolerance limit) at all 18 selected sites. Furthermore, the average "*inline*" wave climate was 2.25 m less in height and 2 s less in wave period in comparison to the oblique wave climate. To understand the direct effect of waves upon the tidal stream resource, the dynamically wave-tide coupled COAWST modelling system was applied to an idealized headland case study, which represented the typical tide and wave conditions expected at first generation tidal stream energy sites. Waves were found to alter the simulated tidal velocity profile, which, because tidal stream power is proportional to velocity cubed, reduced the theoretical resource by 10% for every metre increase in wave height (R^2 94% with *22 degrees of freedom*) – depending upon wave period and direction. Our research indicates that wave angle should be considered when quantifying the impact of waves upon tidal turbines, such as computational fluid dynamic (CFD) studies, or laboratory-scale experiments of wake characteristics and turbine fatigue loading. Further, dynamically coupled tide-wave models may be necessary for a thorough resource assessment, since the complex wave-tide interaction affected the tidal resource; however, in situ observations of tidal velocity profiles during a range of wave events will be essential in validating such modelling approaches in the future.

1. Introduction

Accurate assessment of the power available for electricity generation at tidal stream energy sites is essential for successful device deployment. For example, the local wave climate may render some tidal energy sites inefficient. A number of marine renewable

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energy sites are now being developed around the world, and so understanding realistic oceanographic conditions at proposed tidal stream energy sites is a priority for the industry; such that operability, survivability and reliability can be optimised.

The tidal stream resource in the UK is substantial, with an estimated 30% of all UK electricity demand that could theoretically be produced by tidal power alone [1]. Further, there is a considerable wave energy resource in UK waters (e.g., [2]), however this energetic wave climate may affect the tidal energy resource [3–5]. The impact of tides on the practical wave energy resource has recently become the focus of research (e.g. [6,7]), whilst, we find, the majority of academic studies on tidal stream energy does not adequately account for realistic waves; therefore, the impact of waves on the tidal stream energy resource is the focus of this current work.

Variability within the tidal current (for example, turbulence and the velocity profile) results in variability to the loadings upon the support structure, the tidal turbine and the gearbox – hence increasing potential failure and reducing potential performance [8–10]. Over-engineering is likely to affect the viability of commercial tidal stream energy projects (e.g., [11]) whilst, conversely, maintenance is likely to be costly and difficult (e.g. [12]). Indeed, O'Rourke et al. [13] highlighted that current restrictions to tidal stream energy development were installation, maintenance, and loading conditions. The addition of wave forces and momentum will increase fatigue and loadings that could increase the potential damage to the tidal turbine and its support structure (e.g., [14–16]); therefore, the implications of wave loading upon tidal stream devices, in terms of fatigue and turbine spacing (within an array), has rightly become the focus of recent research [17,18]. Additionally, the amount of time when the tidal turbine cannot produce power (which we call downtime) could have a significant effect upon the viability of a site. Further, the period of extreme storm waves and sea-states that may interrupt maintenance programs should be considered when selecting potential tidal stream energy sites.

A major assumption within research of surface wave loading upon tidal stream turbines is that wave propagation is aligned with the rectilinear tidal flow; with either "waves following" (propagating with the tidal current), or "waves opposing" (propagating against the tidal current). As waves propagate into coastal waters, shallow water processes transform their height (H), period (T) and direction (θ) [19], such as shoaling and refraction due to bathymetric features. During extreme storm events, waves above 18 m in height have been observed in UK waters [20], which may have been the result of a crossing sea state of two crossing (by at least 90°) wave groups [21]; hence, it appears that waves can propagate at angle to the tidal current direction, and in doing so can become highly nonlinear, which may be an important consideration within tidal stream energy design.

Tidal current misalignment to the turbine has been shown to increase the loading and failure potential of a turbine (e.g. [22]); hence wave – tidal current misalignment is likely to further increase the fatigue and extreme loadings of a tidal turbine. Furthermore, as turbulence and wave processes affect the thrust, torque, and tip-loss/stall characteristics of turbine blades [8,23], the effect of *oblique* wave events is likely to affect turbine performance, wake properties (hence array configuration), and fatigue loading estimates. Events when waves cross sea currents are well documented [24,25] – yet the occurrence of oblique wave events at potential tidal stream energy sites has yet to be quantified. Indeed, within the tidal stream energy literature, we could find no studies of wave impacts upon tidal turbines which included wave angle; either *via* laboratory studies (e.g. [18]) or computational fluid dynamic (CFD) modelling (e.g., [15,26]). We hypothesise that there will be many instances when waves will not propagate *inline* to the tidal flow (waves following or waves opposing the tidal flow); hence a significant *oblique* wave climate may be present at a proposed tidal stream energy site (i.e. times when waves are travelling at an angle that is oblique to the rectilinear tidal flow).

Surface waves add additional momentum and mass to the mean flow in the form of Stokes velocities, and the generation of radiation stresses [27]. Further, surface waves significantly affect the apparent bed roughness felt by the tidal flow near the bed, due to turbulent momentum transfer of these higher frequency oscillatory wave velocities [28–30]. Hence, surface waves can have a considerable influence on mean velocity profiles in coastal waters (e.g., [31]). Excluding inter-device interactions, device characteristics (e.g. cut-in and power-rated velocities), and tidal flow by-pass [32], the tidal stream power density is approximately proportional to the cube of the tidal velocity (e.g. [33]); thus any small change in tidal flow could result in a significant change in the available tidal resource. Furthermore, when we consider instances when electricity is not generated due to storm waves, or periods of calm sea-state suitable for maintenance work, the local wave climate could have a significant impact on the annual net power available at a proposed tidal stream energy site.

Non-linear interactions between waves and currents, in a coastal setting, have been the focus of much research over the last decade [30], including the effects of tides on modifying the wave energy resource [6]. However, little research has been performed on the effect of waves on the tidal stream resource. Observations from flume experiments (e.g., [34,35]) and CFD models (e.g., [29]), show an increase in upper water-column velocities occurs when waves propagate in the opposite direction to the tidal flow – whilst the converse is true when waves propagate in the same direction as the tidal currents. The specific effect of surface waves on the velocity profile is dependent on bed roughness and wave angle; for example, an increase in near bed tidal velocities was found when waves are propagating in a direction that is perpendicular to the tidal current for a smooth bed, with the opposite occurring (reduction in near bed velocity) when the bed is rough [34–37]. Nevertheless, the apparent bed roughness (the seabed friction experienced by the tidal flow due to the physical bed roughness combined with the relative roughness which is a function of the wave orbital velocity) is the dominant factor in wave-current interaction processes (e.g. [28–30,37,38]). However, the net effect over a tidal cycle is that the presence of waves can increase the apparent bed roughness (experienced by the tide), which reduces depth averaged tidal velocities (albeit slightly), and alters the velocity profile (e.g. [37–39]).

In shallow-water coastal regions, and at times of major storm wave events, the effect of wave-current interaction can be significant [38]. Observations by Prandle and Wolf [39] in 12.5 m water depth found that the depth averaged speed of the principal semi-diurnal lunar constituent (M2) decreased by 5% with each 1 m increase in wave height (wave direction unknown) – which we call the Prandle and Wolf relationship in this paper. Although modification of bottom friction reportedly had little effect on depth averaged tidal currents in water depths greater than 50 m [40], most turbines will likely be deployed in water depths less than 50 m [41]; hence, the direct effect of surface waves on the tidal resource may be significant.

As an example, we can estimate the change in the tidal stream power available if the presence of waves reduces the depth averaged peak tidal velocity ($\bar{u}$) by 0.1 m/s – from 2 m/s to 1.9 m/s (which equates to a 2 m wave height based on the Prandle and Wolf relationship [39]). The net power density (P) can be estimated over a tidal cycle assuming $\int_0^{12.42\text{ h}} P_t = \frac{1}{2}\rho(\bar{u}_t)^3 dt$ (where $\rho = 1025$ kg/m^3) and the sinusoidal tidal velocity ($\bar{u}_t$) has a period of 12.42 h. In our example, we estimate the total net power density