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Resource assessment for future generations of tidal-stream energy arrays

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ABSTRACT

Tidal-stream energy devices currently require spring tide velocities (*SV*) in excess of 2.5 m/s and water depths in the range 25–50 m. The tidal-stream energy resource of the Irish Sea, a key strategic region for development, was analysed using a 3D hydrodynamic model assuming existing, and potential future technology. Three computational grid resolutions and two boundary forcing products were used within model configuration, each being extensively validated. A limited resource (annual mean of 4 TJ within a 90 km^2 extent) was calculated assuming current turbine technology, with limited scope for long-term sustainability of the industry. Analysis revealed that the resource could increase seven fold if technology were developed to efficiently harvest tidal-streams 20% lower than currently required ($SV > 2$ m/s) and be deployed in any water depths greater than 25 m. Moreover, there is considerable misalignment between the flood and ebb current directions, which may reduce the practical resource. An average error within the assumption of rectilinear flow was calculated to be 20°, but this error reduced to ~3° if lower velocity or deeper water sites were included. We found resource estimation is sensitive to hydrodynamic model resolution, and finer spatial resolution (<500 m) is required for regional-scale resource assessment when considering future tidal-stream energy strategies.

1. Introduction

Future energy security for the UK and greenhouse gas-induced climate change concerns have driven investment in renewable, low carbon energy technology, with a target of 15% renewable energy in the UK by 2020 (e.g. Ref. [1]). Tidal-stream energy, the extraction of kinetic energy from tidal currents to generate electricity (typically using an in-stream turbine), is becoming an increasingly favoured form of renewable energy due to a number of attractive features [2]. For example, the regular and predictable periodicity of the tide, as well as the high energy density, make tidal-stream energy a more reliable source of low carbon energy than other stochastic forms – such as waves and offshore wind (e.g. Ref. [3]).

A number of studies have been commissioned by The Carbon Trust [4,5], which have estimated that 18 TWh per year is extractable within 1450 km^2 of UK waters by tidal-stream energy alone, which would meet 5% of the UK's existing electricity demand [1]. However, the tidal-stream energy industry can be considered to be in its infancy [2], with only a few UK projects currently in advanced stages of planning; for example, the 400 MW MeyGen project in the Pentland Firth within a potential 1 GW of tidal-stream capacity that has been leased by the Crown Estate (see Ref. [6]).

Assessment of the available tidal-stream resource is an essential first step towards successful site selection and device deployment (e.g. Ref. [7]). However, site selection is not simply a case of identifying regions with large tidal currents; instead resource assessment and site selection should consider a wide range of factors, including temporal and spatial variability of the resource (e.g. Ref. [8]). Detailed observational campaigns are not sufficient (or economically feasible) at the scale required for detailed resource assessment. Therefore, tidal-stream resource assessments typically make extensive use of validated hydrodynamic models (e.g. Ref. [3]). A review of the methodology and rationale behind resource assessment through hydrodynamic modelling can be found in Blunden and Bahaj [7].

Tidal-stream energy resource maps have been generated for the UK, leading to products such as the Atlas of UK Marine Renewable Energy Resources (see www.renewables-atlas.info). Tidal-stream

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Nomenclature

A	swept area of tidal turbine (m^2)
C_D	drag coefficient within the quadratic friction model
$Cmax$	semi-major axis of the tidal current ellipse (m/s)
$Cmin$	semi-minor axis of the tidal current ellipse (m/s)
D_u,D_v	diffusive terms in the momentum equation (equations (1) and (2))
F_u,F_v	forcing terms in the momentum equation (equations (1) and (2))
g	acceleration of gravity (assumed 9.81 m/s^2)
h	water depth to mean sea level (m)
h_t	Total water depth at time t (m)
INC	inclination of the semi-major axis of the tidal current ellipse from North (°N)
KE_{s-n}	undisturbed spring-neap cycle mean kinetic energy averaged over a 14.76 day period (J)
K_M	eddy viscosity (m^2/s)
M2	principle semi-diurnal lunar constituent (period 12.42 h)
m	mass (kg)
MCT	marine current turbines
NRMSE	normalised root mean squared error (%)
n	number of observation values
PD	power density of the tidal current (W/m^2)
P	power available from kinetic energy extraction of tidal currents (W)
ROMS	regional ocean modelling system
RMSE	root mean squared error
S2	principle semi-diurnal solar constituent (period 12.00 h)
SV	spring tide peak depth averaged velocity (m/s)
t	time (s)
u,v,w	velocity components in the x (east − west), y (north-south) and z (vertical) directions respectively (m/s)
$\overline{U}_t$	depth-averaged tidal velocity at time t (m/s)
$Vreal^{ebb}$	ebb tidal current direction
V^{ebb}	theoretical ebb tidal current direction if parallel to flood current direction (i.e. $\theta = 0°$)
δ	x ROMS model cell width in the east-west direction (m)
δ	y ROMS model cell length in the north-south direction (m)
φ	phase of the tide (degrees relative to Greenwich)
ρ	density of sea-water (assumed to be 1025 kg/m^3)
f	Coriolis parameter (s^{-1})
V	molecular viscosity (m^2/s)
$\varnothing$	dynamic pressure term
θ	tidal current misalignment between peak flood and the plane of the ebb direction (degrees)

energy resource maps are typically based on hydrodynamic tidal models with spatial grid resolution in the order of kilometres. The accuracy of tidal-stream energy resource maps is unclear; for example, Black and Vetch [5] found differences of up to 2 m/s between products. Furthermore, the importance of model spatial resolution is unknown for resource assessment; however coarse resolution hydrodynamic models (i.e. > 2 km horizontal resolution) are generally considered to be unsuitable because of their inability to sufficiently resolve bathymetric and flow features [9]. Moreover, the importance of phasing strategies for tidal energy have recently been realised (e.g. Ref. [10]), yet the model spatial resolution within this approach is unknown.

Presently, 1st generation tidal-stream energy technology requires peak flows in excess of ~2.5 m/s, coincident with water depths between 25 and 50 m [1]. Regions of such high-tidal current speeds are sparse, and typically the result of topographic/bathymetric flow enhancement; for example, phase difference-driven flows through straits such as the Pentland Firth (e.g. Ref. [11]), or accelerated flows past headlands (e.g. Ref. [12]). Sea space is limited at 1st generation regions (e.g. Ref. [8]), which, due to the potential concentrated exploitation of the resource, would lead to feedbacks between the resource and the environment [13]. Furthermore, the potential sea space of these 1st generation sites needs to be better quantified, and future directions for the most effective and beneficial development (optimisation) of tidal-stream energy technology needs to be understood.

For the sustainability of the industry, future development of tidal-stream turbine technologies is likely to be directed towards deeper water operation, with lower cut-in and rated speeds [8]. Further, Carballo et al. [3] considered tidal-stream energy for peak tidal currents above 1.5 m/s for a resource assessment in a relatively shallow estuary. Certainly, lower flow tidal turbine technology will allow a much greater area to be developed and reduce the competition for sea space, especially if the high current regions around amphidromic points could be harnessed. The potential power (P) available from kinetic energy extraction (i.e. assuming no device feedback to the resource) within tidal currents (U_t) can be calculated (at time = t) as: $P_t = 0.5\rho A(U_t)^3$; where ρ, the density of seawater, is assumed to be 1025 kg/m^3 and A is the swept area of the turbine (m^2). Hence, the development of tidal-stream turbines operating in deeper water may prove to yield much more practical power (than a shallow water deployment) because, excluding installation and cabling costs, a larger swept area (A) of the turbine blades can be achieved over a greater water depth - hence more power is available for extraction.

There are presently three main types of tidal-stream turbines used to generate electricity: (1) horizontal axis turbines, similar in concept (but very different in practice) to the majority of wind turbines [14]; (2) vertical axis turbines, where blades rotate on an axis perpendicular to the tidal current, and (3) hydrodynamic lift force energy devices, sometimes called reciprocating devices [14]. At present, only the horizontal axis tidal-stream energy convertor is a proven, grid connected, design [14]; for example, the first 1.2 MW rated turbine is installed at Strangford Lough in Northern Ireland [2] (see also www.marineturbines.com, 2008). Therefore, in this paper our analysis will focus on the resource assessment for horizontal axis tidal turbines − however, we hope the conclusions of our work can be applied to other technologies.

We develop a high-resolution 3-dimensional (3D) hydrodynamic model suitable for regional/mesoscale resource assessment, investigating the potential tidal-stream energy resource, including future advances in tidal turbine technology that would increase deployment possibility (i.e. beyond the 1st generation criteria: 25–50 m water depths and peak spring tide flows >2.5 m/s). Furthermore, we investigate some of the uncertainties within resource assessment that have not currently been addressed, such as the importance of hydrodynamic model spatial resolution and the assumption of rectilinear flow (or a device's ability to yaw and face the tidal current) within resource assessments (e.g. Ref. [15]). Therefore, this study not only seeks to identify current limitations

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