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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.

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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 and barriers to development within the industry, but also provides guidance on the development of complex national resource assessments (e.g. Ref. [10]).

2. Case study: the Irish Sea

The tidal hydrodynamics of the Irish Sea are considered to be the result of a Kelvin-type wave propagating (from the southwest) along St. George's Channel – with another wave propagating southwards through North Channel [10,16]. The interaction of these 2 K-type waves results in two degenerate (i.e. land based) amphidromes (regions of near-zero tidal range, but strong tidal currents); one around northeast Ireland and a second around southeast Ireland [16,17]. The bathymetry of the Bristol Channel is such that the tide in this region is close to a resonant standing wave, which results in relatively strong tidal currents, and one of the highest tidal ranges in the world [12]. Further, the high tidal ranges in the Eastern Irish Sea induce strong flow past/through bathymetric constrictions such as headlands and islands, and such regions offer attractive resources for tidal energy generation projects (e.g. Refs. [10,17]).

There are two main multiple-device tidal-stream energy sites/arrays currently under active development in the Irish Sea: the 10 MW S/MCT[1] Seagen site in North Wales – where tidal currents above 2.5 m/s are generated [17,18]. The second site is the 10 MW Tidal Energy Limited site in Ramsey Sound [19]. Furthermore, there are multiple potential tidal-stream energy sites throughout the Irish Sea: the Bristol Channel [20], eastern Ireland [9,14], and a Crown Estate tidal energy demonstration zone planned off Anglesey that has support from the Welsh Government, who themselves have a commitment of 4 GW low carbon energy generation by 2025 [19]. Consequently, it is appropriate and timely to quantify the Irish Sea tidal-stream energy resource. We aim to develop a high-resolution tidal model of the Irish Sea to quantify the tidal-stream resource, and to identify present limitations and future directions for efficient development of the tidal-stream industry.

3. Methodology

Applying velocities simulated by a 3D hydrodynamic tidal model (see Section 3.1), the Irish Sea tidal-stream energy resource was quantified (see Section 3.2). To investigate the effect of spatial resolution on resource assessment, three model resolutions were investigated: Course, Medium, and Fine; with fixed longitudinal resolution of 1/60° (~1.1 km), 1/120° (~0.6 km), and 1/240° (~0.3 km) respectively, with variable latitudinal resolution (trying to keep the aspect ratio of models cells constant in latitudinal direction); see Table 1. Initially, we assume 1st generation tidal-stream technology, which requires water depths in the range 25–50 m, and peak spring depth-averaged tidal velocities in excess of 2.5 m/s (e.g. Refs. [1,17]). The spring-neap tidal cycle, which dominates the tidal signal of the northwest European shelf seas, is described by the interaction between two tidal constituents: the M2 principle semi-diurnal lunar constituent with a period of 12.42 h, and the S2 principle semi-diurnal solar constituent with a period of 12.00 h [15]. Therefore, we define the peak *SV* (spring tidal velocity) as the maximum speed of the principle tidal ellipse constituent (*Cmax*) of the combined M2 and S2 constituents, and we shall call *SV* in this paper.

To identify limitations in the extraction of the tidal-stream resource, and to identify directions for future development in the industry to optimise this extraction, we investigate two additional

Table 1
The spatial resolution of three Irish Sea tidal models used to quantify the tidal-stream energy resource.

	Spatial grid resolution		
	Coarse	Medium	Fine
Longitude (fixed)	1/60°	1/120°	1/240°
Latitude (average)	1/101° (1101 m)	1/202° (556 m)	1/404° (278 m)

potential tidal-stream scenarios: (1) 2nd generation technologies, which we assume will be capable of exploiting currents with peak spring tidal flows (*SV*) above 2 m/s; and (2) 3rd generation technologies, that we assume can exploit currents with peak spring tidal flows (*SV*) in excess of 1.5 m/s (e.g. Sánchez et al., 2014). In both 2nd and 3rd generation technologies we also assume that deep water locations can be exploited - where water depths greater than 25 m are considered with no upper bound.

3.1. Tidal model details

The ROMS (regional ocean modelling system) simulates tidal hydrodynamics using a finite-difference approximation of the 3D RANS (Reynolds-averaged Navier–-Stokes) equations with hydrostatic and Boussinesq assumptions, and a split-explicit time stepping algorithm, on a horizontal curvilinear Arakawa C grid and terrain-following vertical coordinate system [21–23].

The primitive momentum balance in the x and y directions (Cartesian co-ordinates) are described by equations (1) and (2) respectively;

$$\frac{\partial u}{\partial t}+\vec{u}\cdot\nabla u-fv=\frac{-\partial\varnothing}{\partial x}-\frac{\partial}{\partial z}\left(\overline{(u'w')}-V\frac{\partial u}{\partial z}\right)+F_u+D_u \quad (1)$$

$$\frac{\partial v}{\partial t}+\vec{u}\cdot\nabla v+fu=\frac{-\partial\varnothing}{\partial y}-\frac{\partial}{\partial z}\left(\overline{(v'w')}-V\frac{\partial v}{\partial z}\right)+F_v+D_v \quad (2)$$

where u, v, and w are the mean components of velocity in the horizontal (x and y) and vertical (z) directions respectively (and together are the components of the vector velocity: $\vec{u}$). f is the Coriolis parameter, V the molecular viscosity, F and D denote the forcing and diffusive terms, respectively, with the subscript giving the direction (e.g. D_u). An overbar indicates a time average, and a prime (′) indicates a fluctuating turbulent quantity. $\varnothing$ is the dynamic pressure term, g is acceleration due to gravity, ρ and ρ_0 are total and reference densities for seawater such that the total in situ density at a given point (x,y,z) and time (t) is $\rho_0+\rho(x,y,z,t)$.

The Boussinesq approximation assumes density variations are neglected in the momentum equations except in their contribution to the buoyancy force in the vertical momentum equation, but also that the vertical pressure gradient balances the buoyancy force:

$$\frac{\partial\varnothing}{\partial z}=\frac{-\rho g}{\rho_0} \quad (3)$$

Continuity is described for an incompressible fluid, thus:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4)$$

Finally, the equations are closed by the parameterisation of the Reynolds stresses (where K_M is the eddy viscosity) as:

$$\overline{(u'w')}=-K_M\frac{\partial u}{\partial z},\ \overline{(v'w')}=-K_M\frac{\partial v}{\partial z}, \quad (5)$$

[1] Marine Current Turbines.

Further details of the ROMS model, including the discretized full equations and model verification details are found in a number of publications (e.g. Refs. [21–25]), and thus shall not be commented on further here (see also refer to www.myroms.org). Moreover, the ROMS model has been successfully employed for multiple tidal-stream energy resource studies at various sites around the British Isles [8,10,15]; however, it should be noted that many other suitable models exist, each with benefits and disadvantages, which could produce a similar result to our research.

To investigate the importance of model spatial-resolution within resource assessment, three computational grids were developed, each with 10 vertical layers in the Sigma coordinate system (evenly spaced throughout the water column) and orthogonal C-grid horizontal format, with fixed longitudinal resolution and variable latitudinal resolution between 51°N and 56°N, and from 7°W to 2.7°W: Coarse, 1/60° fixed longitudinal resolution (507 × 259 interior points); Medium, 1/120° fixed longitudinal resolution (1012 × 517 interior points); and fine, 1/240° fixed longitudinal resolution (2012 × 1033 interior points); see Table 1. Bathymetry was interpolated using a nearest neighbour approach with digitised Admiralty data on a regular grid at a constant horizontal resolution of 200 m (http://digimap.edina.ac.uk) and corrected for mean sea-level variations. The domain and the bathymetry of the Irish Sea tide model is shown in Fig 1. A minimum water depth of 10 m was imposed, with no wetting and drying, as the geographic scale of inter-tidal regions was relatively small in relation to the model resolution and extent of the Irish Sea [15].

A 32 day simulation was performed, with the first two days of simulation excluded from analysis to allow the model to spin-up from an initial stationary state. A drag coefficient (C_D) of 0.003 was assumed within the quadratic friction model parameterisation, which is consistent with previous studies (e.g. Ref. [8]). Further, the turbulence closure GLS (generic length scale) model was tuned to the κ-ε turbulence model (see Ref. [15]), as similar results were found across a number of case studies and GLS schemes [24].

The open boundaries of the model were forced by tidal elevation propagating at a shallow water wave speed (Chapman boundary condition), and tidal velocities radiating out at the speed of external gravity waves (Flather boundary condition, with the velocity profile being prescribed using the radiation scheme called "Gradient") — which is described in Marchesiello et al. [26] and successfully used in previous ROMS simulations (e.g. Refs. [8,10,15]). The open boundary of the tidal model was forced with Finite Element Solution and data assimilated global tide product; FES2012 [27] using ten tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, Mf, and Mm). We found a substantial improvement in the validation of our coarse resolution model when the open boundary was forced with FES2012 data instead of another popular tidal product TPXO (http://volkov.oce.orst.edu/tides/TPXO7.2.html); as shown in Table 2.

The hourly time-series of elevation and current velocity from our tidal model was analysed using T-TIDE [28] for the 30 day simulation for 7 major tidal constituents (M2, S2, N2, K1, O1, P1, and M4 constituents); however, we shall only discuss the constituents that describe the spring-neap cycle (M2 and S2), which dominate the tidal signal around the UK, and are accurately separated within a 30 day signal.

3.2. Tidal model validation

Validation simulated tidal elevation was undertaken for M2 and S2 elevation components (amplitude and phase), using 7 tide gauges from the National Tidal and Sea Level Facility (www.ntslf.org) — the locations of which are shown as squares in Fig. 1, and the results are shown in Table 3.

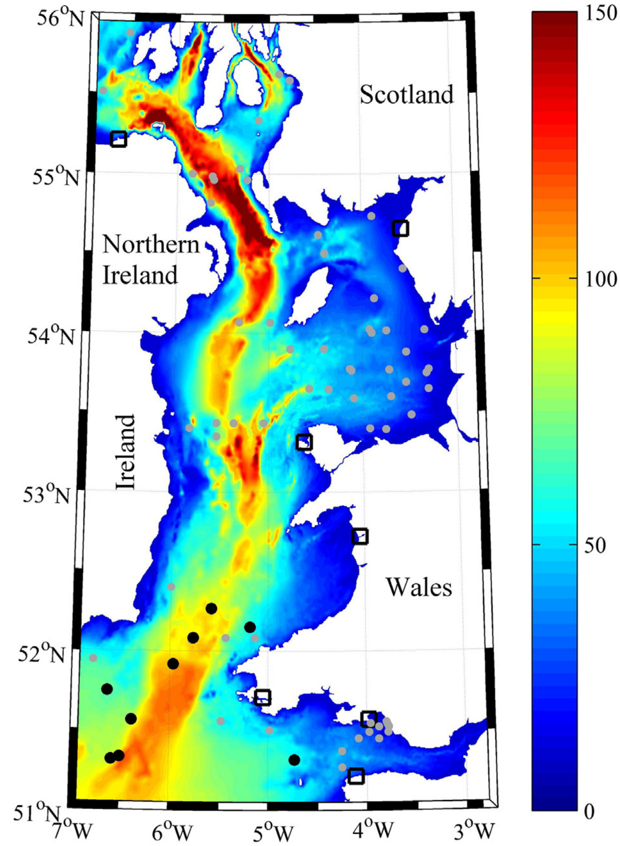

Fig. 1. The bathymetry of the Irish Sea (m), with locations of tide gauges (squares), depth-averaged (black filled circles) and depth specific (grey filled circles) M2 tidal ellipse observations used for model validation.

Tidal current validation was achieved using the M2 tidal ellipse descriptive parameters of the semi-major and semi-minor current axis (*Cmax* and *Cmin* respectively), as well as inclination (*INC*, °N) and phase (degrees relative to Greenwich) of the ellipse. Depth-averaged M2 tidal ellipse information at 9 sites within the southern Irish Sea [29], shown as black filled circles in Fig. 1, alongside a further 131 sites (see filled grey circles in Fig. 1) of M2 current observations were used that range between 3 m and 143 m below the sea-surface (mean depth of 35 m, standard deviation 27 m): East-West (*U*) and North-South (*V*) M2 amplitude and phase available from the British Oceanographic Data Centre (www.bodc.ac.uk).

The results of the validation are presented in Table 3, demonstrating the accuracy of our spring-neap cycle (M2+S2) tidal

Table 2
A comparison of tidal accuracy when the "coarse" model is forced with two tidal products (TPXO or FES2012). Model accuracy was determined using Root Mean Squared Error validation of the M2 tidal constituent at 7 tide gauges (elevation) and depth-averaged tidal ellipse information at 9 sites (see Fig. 1).

Source of boundary conditions:		TPXO	FES2012
M2 elevation (www.ntslf.org)	N	7	7
	amplitude	0.35 m (14%)	0.13 m (5%)
	phase	6°	6°
Depth-averaged currents (Jones 1983)	N	9	9
	Cmax	0.11 m/s (15%)	0.08 m/s (11%)
	Cmin	0.03 m/s (12%)	0.02 m/s (8%)
	INC	11°	6°
	Phase	14°	8°

elevations (RMSE of ~0.1 m/s). Our simulated M2 tidal currents were found to be accurate within 8–11%, which is comparable to similar modelling studies of the Irish Sea (e.g. Ref. [17]). Interestingly, it should be noted that the validation of our Irish Sea model improves only slightly with increasing model resolution (see Table 3); hence, we feel it is appropriate to compare the estimated tidal-stream resource estimated by our three model configurations.

3.3. Quantification of tidal-stream resource

Allowing a 2 day spin up period for the simulated dynamics to reach equilibrium, M2 and S2 tidal current ellipse information at every computational grid cell was calculated using the tidal analysis software T-TIDE [28] for the remaining 30 day period. To calculate the tidal-stream energy resource, we assume any secondary component of flow (i.e. the semi-minor ellipse velocity component; *Cmin*) cannot be exploited, and is in fact undesirable [30]. Instead, we assume the tidal current to be rectilinear at each location, hence energy can be harnessed on both the flood and ebb tidal current as a result of the semi-major ellipse velocity component (*Cmax*). Therefore, to calculate the pure spring-neap tidal velocity time-series ($\overline{U}_t$) available for energy extraction, Kelvin harmonic tidal current theory was used assuming a progressive tidal wave and zero tidal currents at times of high and low water (e.g. Ref. [31]). Phase (φ) and the semi-major ellipse velocity component (*Cmax*) of the M2 and S2 harmonic derived from our tidal analysis of simulated velocities thus:

$$\overline{U}_t = M2Cmax \times cos\left(\frac{2\pi}{12.42} + \varphi M2\right)t + S2Cmax \times cos\left(\frac{2\pi}{12} + \varphi S2\right)t \quad (6)$$

Hence, the peak spring tide velocity (*SV*) is calculated as the maximum of $\overline{U}_t$, which is shown in Fig. 2 for our high resolution model.

To quantify the undisturbed tidal-stream energy resource that is theoretically hydrodynamically suitable for development (i.e., irrespective of other factors such as distance to grid connection) and excluding inter-device and inter-array interactions [32], we use three methods in this paper. Firstly, to quantify the sea space available, the maximum potential area available for development is calculated. For example, the sea space where 1st generation sites could be developed is calculated as regions where water depths are in the range 25–50 m, with peak spring tide velocities (*SV*) above 2.5 m/s [1,17]. Secondly, to quantify the potential tidal-stream resource available, we calculate the undisturbed spring-neap

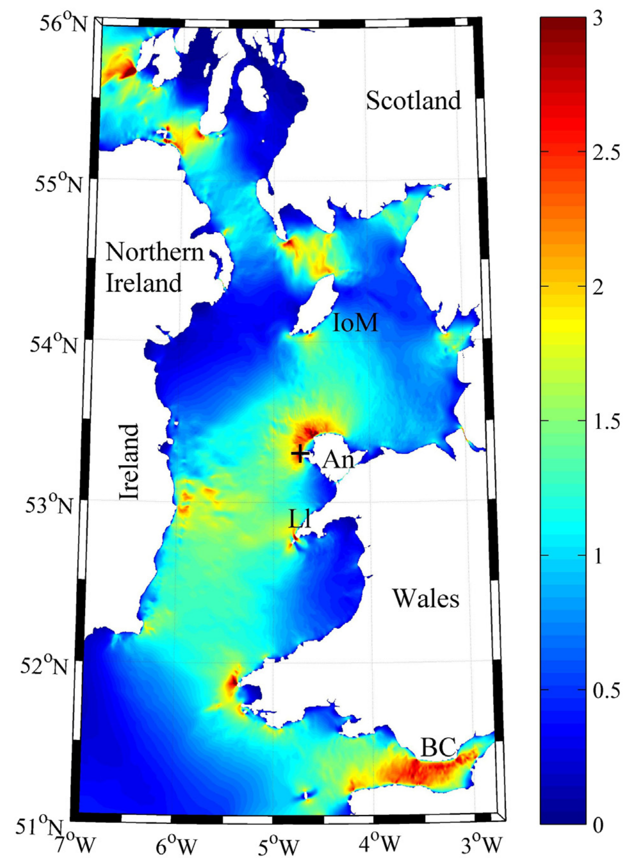

Fig. 2. The peak spring tide current velocity (*m/s*), simulated with the "fine" resolution (1/240°) model. Potential tidal-stream energy regions of Anglesey (An), Llyn Peninsula (Ll), Isle of Man (IoM), Holyhead (+) which is used in Fig. 3, and Bristol Channel (BC) are shown.

cycle mean kinetic energy, averaged over a 14.77 day period (KE_{s-n}) using the pure spring-neap tidal velocity time-series (U_t') at all applicable locations thus:

$$KE_{s-n} = \frac{1}{14.77days}\sum\left[\iiint\frac{1}{2}(\overline{U}_t)\delta m\right]\delta t \cong \frac{1}{n}\sum_{0}^{14.77days} \times \left\{\sum_{A}\left[\frac{1}{2}\rho(\overline{U}_t)^2 h_t \delta x \delta y\right]\right\}\delta t \quad (7)$$

Table 3
Tidal model validation (Root Mean Squared Error) of the M2 and S2 tidal constituent elevations and the M2 tidal ellipse (depth-averaged and depth specific locations; see Fig. 1) is compared for the three spatial resolutions (Coarse, Medium and Fine) of the Irish Sea.

RMSE validation		Model resolution		
		Coarse (1/60°)	Medium (1/120°)	Fine (1/240°)
Elevation (N = 7)	M2 amplitude	0.13 m (5%)	0.12 m (5%)	0.11 m (4%)
	M2 phase	6°	6°	4°
	S2 amplitude	0.08 m (9%)	0.08 m (9%)	0.08 m (9%)
	S2 phase	14°	14°	9°
M2 depth-averaged currents (N = 9)	Cmax	0.08 m/s (11%)	0.07 m/s (10%)	0.07 m/s (10%)
	Cmin	0.02 m/s (8%)	0.02 m/s (8%)	0.02 m/s (8%)
	INC	6°	5°	5°
	Phase	8°	7°	7°
M2 tidal currents at specific depths (N = 131)	U amplitude	0.10 m/s (9%)	0.11 m/s (10%)	0.11 m/s (10%)
	U phase	4°	4°	4°
	V amplitude	0.09 m/s (10%)	0.09 m/s (10%)	0.09 m/s (10%)
	V phase	6°	6°	6°

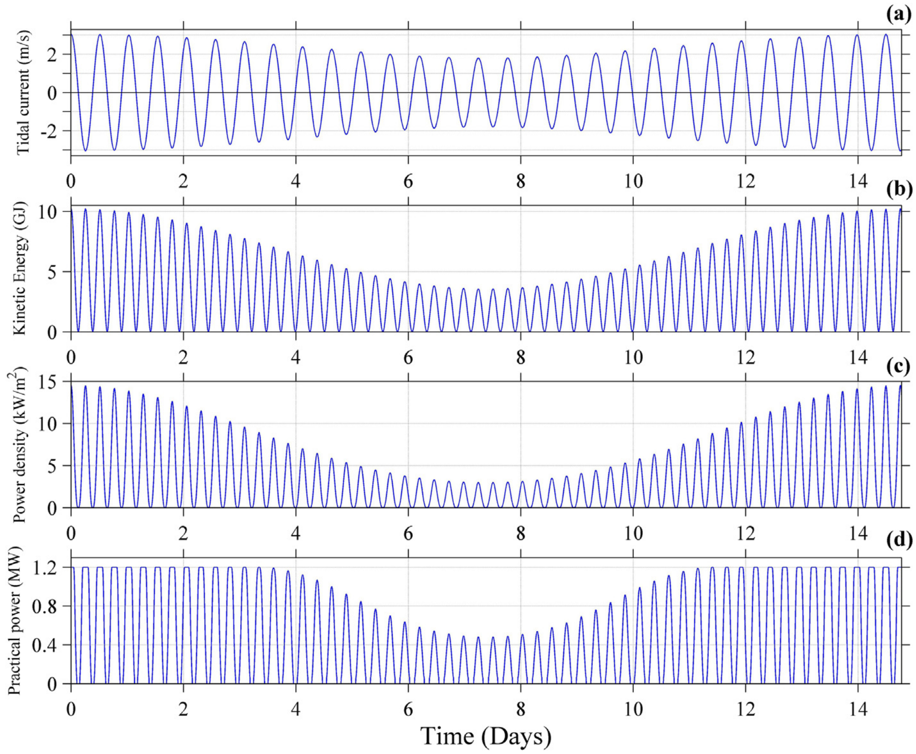

Fig. 3. Estimated tidal-stream energy available using three methods applied to the velocity time-series of a pure spring-neap tidal cycle (panel a) at 53.305 °N, 4.721 °W (see + in Fig. 3); power density (b), the instantaneous kinetic energy available (c), and (d) the practical power available using the 1200 kW Seagen-S power curve (see Fig. 4).

where n is the number of observations, m is mass, ρ is density, and the volume per computational cell is calculated as the multiple of cell width (δx), cell length (δy), and time-varying water depth (h_t). An example is shown in Fig. 3b (where KE_{s-n} is calculated to be 3.45 GJ), for a model cell within the Crown Estate tidal energy demonstration zone for 1st generation tidal-stream energy devices ($h = 35$m and peak spring currents are around 3 m s^{-1}) to the west of Anglesey (53.305°N and 4.721°W), the location of which is shown as a cross (+) in Fig. 2.

The kinetic energy measure of the tidal-stream energy resource (method 2, equation (7)) is a gross over-estimation of the available resource [33]; however, it is a useful measure of the spatial distribution of the tidal-stream energy resource. Typically, power density (PD) is used within resource estimates, calculated here as $PD = \frac{1}{2}\rho(\overline{U}_t)^3$ and shown in Fig. 3c; however, we chose not to use the traditional power density calculation (e.g., kWm^{-2}) to quantify the Irish Sea resource because estimates cannot be spatially aggregated to represent the resource over a region [33]. Moreover, no device feedbacks to the kinetic energy flux were included [5,32] because of uncertainties within array configurations, power extraction, rated velocities, and device cut-in speeds – which are beyond the scope of this study. Rather, our third approach to quantifying the potential Irish Sea tidal-stream energy resource was to calculate the practical power available (at each model grid cell) applying the measured power curve of the twin-rotor Seagen device (Fig. 4), which is already operating and grid-connected in the Irish Sea at Strangford Lough in Northern Ireland (see Fig. 2). Furthermore, the measured power at the point of extraction of this 16 m diameter, twin 600 kW rated MCT Seagen-S tidal-stream turbine is available (see www.marineturbines.com). The cut-in speed was measured as 1 m/s with each drive train rated at 600 kW at 2.68 m/s; see Fig. 4. Interestingly, the MCT curve demonstrates asymmetry between the flood and ebb phases of the tidal cycle; hence, we choose to apply the flood-ebb averaged power curve (Fig. 4) as a measure of the practical power available.

We apply the Seagen power curve (Fig. 4) to the pure spring-neap tidal velocity time-series ($\overline{U}_t$) at all applicable locations and assume two devices per fine model resolution grid cell; hence giving the practical power time-series in Fig. 3d. As the twin rotor MCT device (Fig. 4) has an overall device width of 40 m [31], our assumption of turbine density is consistent with the turbine spacing assumptions of many other studies; a minimum lateral spacing of 3 device widths, and a minimum downstream spacing of 10 device widths (although potentially less if turbines are staggered in an array) to eliminate wake effects (e.g. Refs. [13,31,34]). It should be noted that many commercial devices now exist – all with various power curves and array configurations that could greatly alter our practical power estimate presented here. Further, we assume that the tidal-stream energy device can yaw, so that the swept area of the horizontal axis turbine is perpendicular to the tidal current at all times.[2] Moreover, array configuration and actual device density at potential sites is unknown, particularly for larger arrays; however, we use this third approach to gain a first order estimate of the device-specific potential practical resource available within the Irish Sea using current operational grid-connected technology.

4. Results

Using the combined M2 and S2 tidal ellipse semi-major axes (calculated from tidal analysis of our hydrodynamic model simulation) throughout the Irish Sea as a metric for peak spring tidal velocity (SV), and utilising the gridded bathymetry data (see Fig. 1),

[2] The validity of this assumption is examined within the discussion.

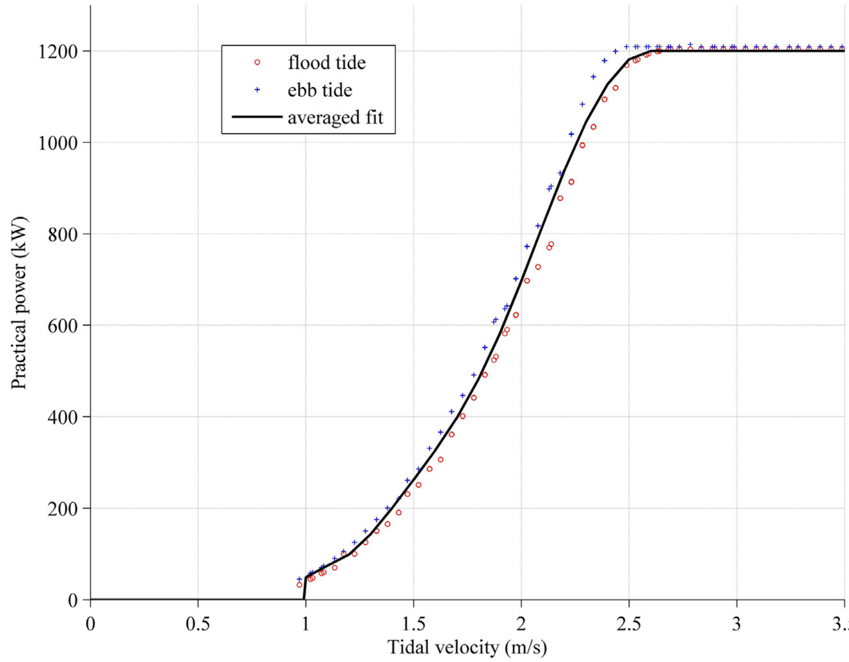

Fig. 4. The measured power curve of the 16 m diameter, twin drive train 1200 kW rated (at 2.68 m/s) Seagen-S tidal-stream turbine (available here www.marineturbines.com) – with our flood-ebb averaged power curve shown as a black line (averaged fit).

we quantified the current and future tidal-stream energy resource of the Irish Sea. The results of our current tidal-stream resource quantification is shown in Section 4.1, assuming a turbine device deployment criteria which we call "1st generation"; sites where *SV* exceed 2.5 m/s and water depths (h) are within the range 25–50 m. The future tidal-stream energy resource of the Irish Sea is quantified in Section 4.2 assuming 2nd generation sites (i.e. $SV > 2$ m/s and h that exceed 25 m), and 3rd generation sites (i.e. $SV > 1.5$ m/s and h that exceed 25 m). Tidal-stream energy resource estimate differences between the three hydrodynamic model grid resolutions are discussed in Section 4.3.

4.1. The first generation tidal-stream resource

We find that around 90 km^2 of the Irish Sea (~0.12% of its areal extent) is suitable for 1st generation tidal-stream energy development; see Table 4. Based on our analysis of simulated tidal currents (see Table 4), approximately 4 TJ (Terra Joules) of undisturbed kinetic energy (spring-neap averaged) is available to produce electricity within 1st generational tidal-stream energy sites, which equates to an annual practical estimate of ~24 GWh, assuming no device feedbacks to the resource, and based on current operational technology (see Fig. 4). Practical considerations may further reduce the area of 1st generation sites found in Table 4, such as distance to a suitable grid connection, sea bed morphology and other commercial constraints (e.g. commercial shipping routes and fishing). Therefore, we find that sea space in the Irish Sea is severely limited for present tidal-stream energy technology – hence, the industry may wish to focus on developing technology to extend the area of available resource (e.g. harvest deeper water and lower tidal-stream sites).

4.2. Tidal-stream resource including future deployment criteria

Approximately 800 km^2 (around 1% of the entire Irish Sea) and 6000 km^2 (~6% of the entire Irish Sea) is suitable for 2nd and 3rd generation tidal-stream energy development respectively (see Table 4), which would greatly reduce the sea space pressure we predict at 1st generation sites (see Section 4.1). Further, we find the undisturbed kinetic energy available for tidal-stream energy production increases by factors of ~7 and ~37, respectively, when moving from 1st generation sites to 2nd generation sites (which

Table 4
The Irish Sea tidal-stream energy resource for three device deployment criteria (1st to 3rd generation) and three model spatial resolutions, quantified as; the areal extent (Area, km^2), average undisturbed spring-neap cycle (M2+S2) kinetic energy flux (TJ), and the annual practical power available (GWh) - based on an operational device.

		Model spatial resolution		
		1/60°–1.1 km	1/120°–556 m	1/240°–278 m
1st generation (*SV* > 2.5 m/s 25 < h < 50)	Area (km^2)	90	93	91
	Mean kinetic energy (TJ)	3.76	4.16	4.01
	Annual practical power available (GWh)	23	25	24
2nd generation (*SV* > 2 m/s & h > 25 m)	Area (km^2)	1018	825	800
	Mean kinetic energy (TJ)	50.34	32.12	29.36
	Annual practical power available (GWh)	142	115	111
3rd generation (*SV* > 1.5 m/s & h > 25 m)	Area (km^2)	6164	6128	6046
	Mean kinetic energy (TJ)	161.48	154.58	149.37
	Annual practical power available (GWh)	165	184	182

also include 1st generation sites) and 3rd generation (which also include 1st and 2nd generation sites); see Table 4.

The practical annual resource of the Irish Sea, assuming the Seagen-S 600 kW rated turbine device (see Fig. 4), increases by a factor of ~8 between 1st and 3rd generation sites (as shown in Table 4), with the majority of this increase between 1st and 2nd generation sites (i.e. an increase between 1st and 2nd generation sites by a factor of ~ 6). It should be noted that the Seagen device is rated for peak flows of around 2.7 m/s; hence a much greater practical resource would be available if lower rated turbines were applied (potentially similar to our kinetic energy resource estimation), subject to the appropriate array configurations (i.e. turbine density per hydrodynamic model grid cell).

Grouping tidal-stream energy resource estimates into discrete peak spring current (*SV*) and water depth (*h*) bins of 0.05 m/s and 5 m respectively, the potential future resource (including improvements to turbine deployability) was calculated for both areal extent (sea space) and the undisturbed kinetic energy flux; shown in Fig. 5a and c. The area available within the Irish Sea suitable for tidal-stream energy development increases exponentially when peak spring-tide velocities (*SV*) reduce below 2.5 m/s and all water depths are considered (see Fig. 5b). Relaxing the water depth criteria for site selection ($h > 25$ m, rather than 25–50 m), the annual practical resource estimate for 1st generation tidal-stream energy sites was calculated (using the fine resolution model) to increase from 24 to 26 GWh. Therefore, water depth does not appear to be a significant limitation to improving the tidal-stream resource limitation of 1st generation technology ($SV > 2.5$ m/s) within the Irish Sea.

Once sites with a minimum peak flow speed (*SV*) of ~2 m/s are considered, the greatest increase in the tidal-stream energy resource is through the inclusion of the additional sea space and kinetic energy flux offered by deeper water sites; see Fig. 5b and d. For example, a similar increase to the total kinetic energy available was found for peak flows above 1.8 m/s with 1st generation water depth sites ($25 < h < 50$ m) when compared to deeper water ($h > 25$ m with no upper limit) sites with peak flows that exceed 2 m/s; see Fig. 5d. Therefore, we find that once turbines that can operate efficiently at sites where $SV > 2$ m/s, the industry would be advised to consider the development of deeper water sites. Hence, we find our 2nd generation (deployment at sites where $SV > 2$ m/s and water depths that exceed 25 m) and 3rd generation ($SV > 1.5$ m/s and $h > 25$ m) tidal-stream energy device deployment assumption to be reasonable.

In Fig. 5c, the distribution of the spring-neap averaged undisturbed kinetic energy shows that the 1st generation resource is distributed over a limited number of sites, in regions where the tidal flow is accelerated by topographic features (e.g. headlands); for example mainly around Anglesey and South Wales (see Fig. 2). By relaxing the hydrodynamic (*SV* and water depth) selection criteria to include 2nd and 3rd generation technology (see Fig. 5c), we see a much greater number of potential tidal-stream energy sites within the Irish Sea; the geographic distribution of which are shown in Fig. 6.

As shown in Fig. 6, we find 2nd generation technology would allow the expansion of well-known tidal-stream energy regions (for example around Anglesey), but it also indicates many new smaller regions potentially suitable for community renewable energy schemes; for example, around the Isle of Man, the Llyn peninsula, multiple areas along the south and west Wales coastline (for locations please see Fig. 2). The regions associated with the tidal amphidromic systems around east and northeast Ireland which are shown as the 3rd generation sites in Fig. 6, can be seen in two clusters within Fig. 5c; the deeper water kinetic energy cluster of 3rd generation sites (red 3rd generation region where $h > 100$ m in Fig. 5c) is associated with the region of the north coast of

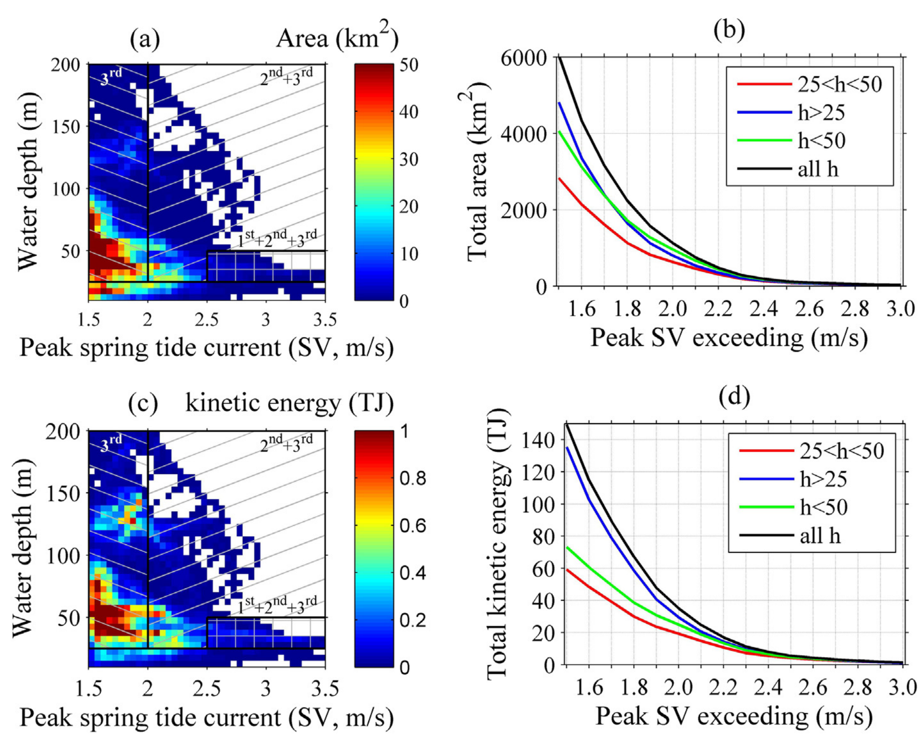

Fig. 5. The potential tidal-stream resource of the Irish Sea calculated with the "fine" resolution model. The distribution of area (panel a) and undisturbed kinetic energy flux (panel c) has been discretised into 5 m water depth and 0.05 m/s peak spring tidal velocity (*SV*) groups, with the total resource for a range of *SV* exceedance and water depth criteria shown in panels b and d, respectively.

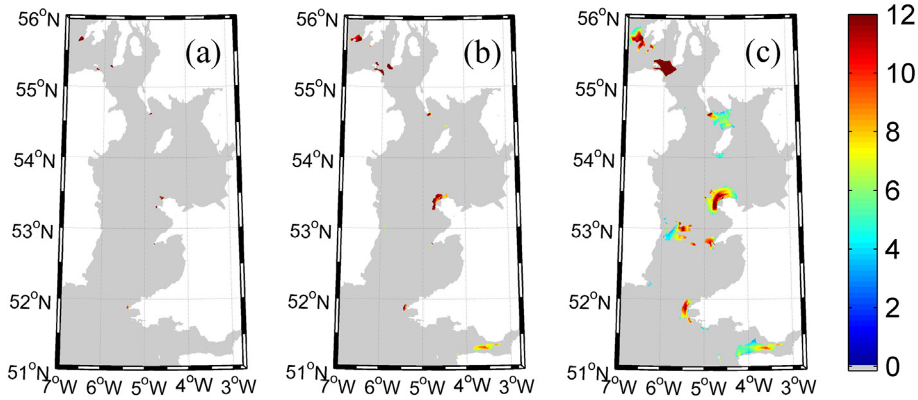

Fig. 6. Irish Sea undisturbed mean kinetic energy flux (GJ) estimated for (a) 1st generation, (b) 2nd generation, and (c) 3rd generation site criteria using the "medium" resolution model. Regions unsuitable for tidal-stream energy development are shaded grey.

Northern Ireland and the shallow water 3rd generation region of Fig. 5c (*SV* < 2 m/s and h < 100 m) is associated with the amphidromic point region off the east coast of Ireland (see Fig. 6c).

4.3. Resource sensitivity to model grid resolution

Differences between resource estimates for the three hydrodynamic model resolutions were found to be negligible for 1st generation tidal-stream resource assessment (see Table 4), but these differences greatly increased when analysing sites with *SV* velocities below 2.5 m/s (i.e. 2nd and 3rd generation sites), even though all three models individually validate similarly – see Table 3. Differences of estimated area and total undisturbed kinetic energy of the tidal-stream resource between the three spatial model resolutions increased when site selection criteria were relaxed is shown in Fig. 7. We find difference in the estimated tidal-stream energy resource between our medium and fine resolution models for 2nd and 3rd generation tidal-stream energy sites (Table 4 and Fig. 7). Therefore, coarse spatial resolution hydrodynamic models (i.e. > 1 km spatial resolution) appear to be sufficient for 1st generation tidal-stream energy resource assessment within the Irish Sea; however, as the industry evolves towards exploiting lower tidal-stream and deeper water sites, higher spatial resolution models (i.e. ~500 m resolution) will be important for accurate calculation of the resource. Furthermore, we use the medium resolution model (1/120°–556 m; see Table 1) in our analysis of tidal current misalignment (see Discussion) because little difference between the fine and medium resolution models was found for 2nd and 3rd generation tidal-stream energy sites (see Table 4).

5. Discussion

We found that the horizontal resolution of the 3D hydrodynamic model only influenced our resource estimate when considering technology beyond 1st generation sites (Fig. 7), yet there was no significant variation in model accuracy (Table 3). O'Rourke et al. [9] concluded model resolution less than 5 km was incapable of resolving local bathymetric features, and thus unsuitable for resource assessment. We find, however, that model resolution ~1 km sufficient to quantify the 1st generation tidal-stream resource, but that grid resolution at ~500 m is required to fully assess the resource including future developments to the tidal-stream energy industry (i.e. beyond 1st generation sites). Indeed, methodologies for assessing tidal-stream energy resources, outlined in industry guidelines such as the IEC (international electrotechnical commission) 2014 report (see www.iec.ch), suggest early reconnaissance stage resource assessments can be made with kilometre scale model resolution, whilst model resolution should be less than 500 m at the feasibility/design stage.

Quantifying the tidal-stream energy resource of the Irish Sea, we found an area of ~90 km^2 suitable for development of 1st generation sites; hence, it appears that competition for sea space will be very high at suitable sites. Further, the undisturbed kinetic energy flux of 1st generation sites is ~4 TJ, which equates to an average of 1 GW throughout the year using the measured power curve of the Seagen-S 600 kW twin drive train tidal turbine (Fig. 4) – assuming a density of two devices per 270 m^2 Although our estimate does not include device feedbacks between energy extraction and the resource [32], and device density/array configuration is currently unknown, it appears that 1st generation tidal-stream energy sites within the entire Irish Sea could meet ~25% of the 2025 Welsh Government's marine renewable target of 4 GW [19].

Applying The Carbon Trust's UK estimate of the tidal-stream resource [1,4,5], 1st generation sites within the Irish Sea contribute less than 1% to the practical resource of the UK. Moreover, the total practical tidal-stream resource is likely to be considerably less when one considers environmental impacts [17], installation (e.g. distance to grid connection and cabling costs) and maintenance costs, but also wave effects (see Ref. [15]), which could render some regions unsuitable for development. Therefore, the practical resource is likely to be significantly lower than estimated in this paper; however, increasing the deployability of tidal turbines is required to fully realise the potential of tidal-stream energy. Indeed, analysis of the distribution of simulated undisturbed kinetic energy flux with our high resolution model revealed the industry would be advised to develop technology suitable for economically harvesting peak spring tide flows at or below 2 m/s, beyond which the development of deeper water locations (*h* > 50 m) should be a priority.

When considering tidal phasing solutions to the problem of energy storage and constant electricity production, or "base load" [1,10]; lower peak velocity sites and deeper water locations could be important regions to develop, as well as the inclusion of shallower water sites (*h* < 25 m): see green coloured sites in Fig. 8. Certainly with the correct strategy, electricity from 2nd generation tidal-stream energy sites (including all water depths) could theoretically be constantly produced because the phase of the M2 tidal velocity at 1st and 2nd generation sites accounts for 76% of the 12.42 h tidal cycle (i.e., potentially less than 3 h down time) – see Fig. 8. Therefore, 2nd and 3rd generation sites are essential to develop for the Irish Sea marine renewable industry. Further although little benefit to the total Irish Sea resource was

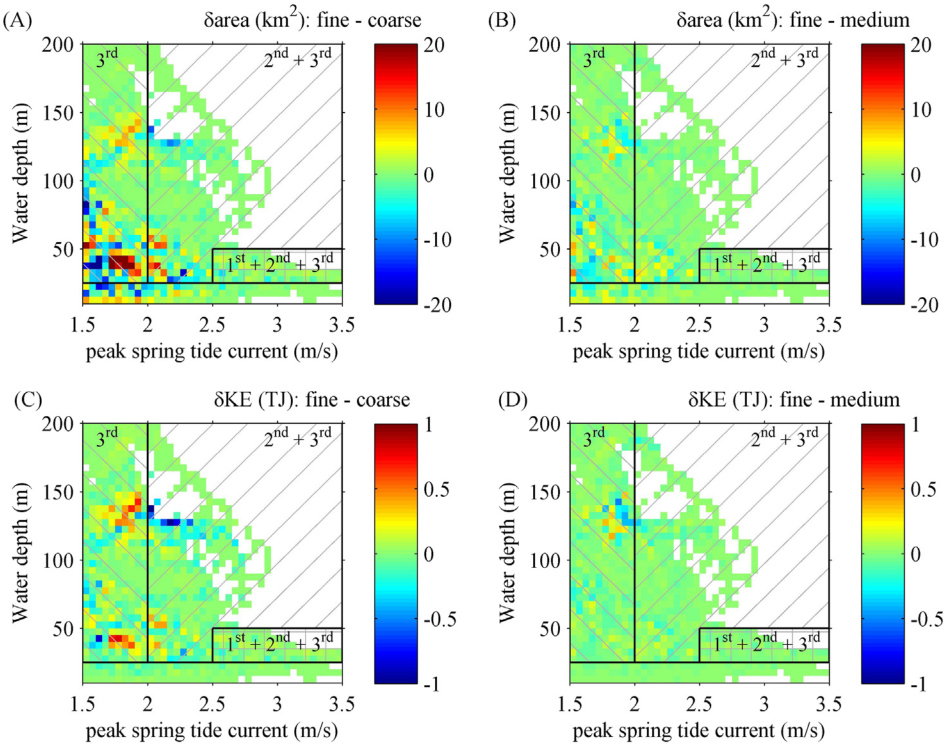

Fig. 7. Irish Sea tidal-stream energy resource estimate differences (1st to 3rd generation are shaded) between three model spatial resolutions: coarse (1/60°), medium (1/120°), fine (1/240°). Areal extent differences are shown in the top panels A and B. Differences in mean spring-neap kinetic energy flux estimate (TJ) are shown in the bottom panels C and D.

found in the development of shallow water turbines (i.e. h < 25 m), the shallow water tidal-stream resource maybe important for phasing solutions to produce constant electricity (see Fig. 8), as well as other practical considerations, such as cabling cost. Hence, to fully and accurately quantify the potential future tidal-stream energy resource (and provide a development roadmap for industry and policy makers), future work should apply phasing solution techniques, such as evolutionary genetic algorithms [10], to high resolution (<1 km horizontal resolution) 3D hydrodynamic models with multiple tidal constituents that

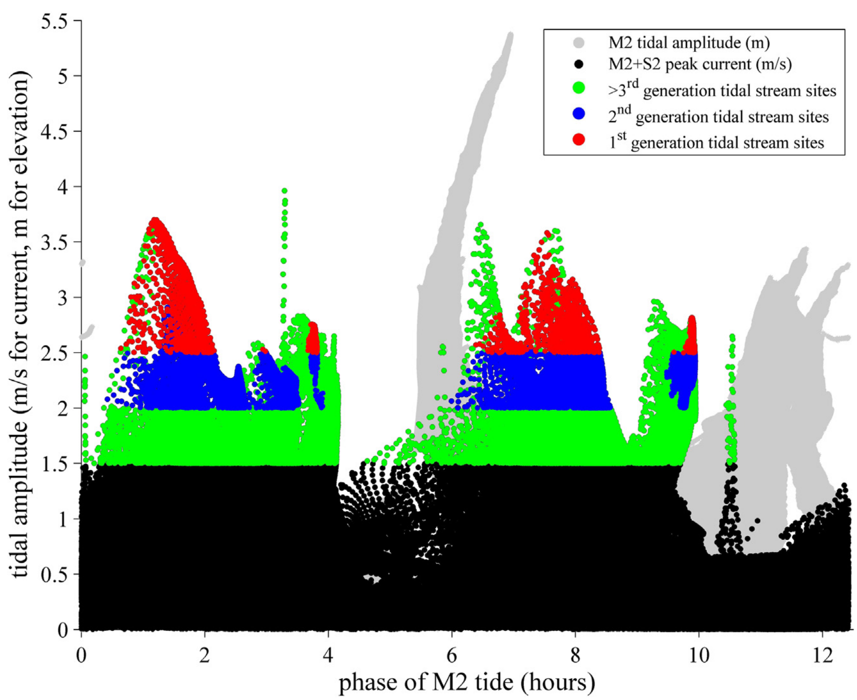

Fig. 8. The potential tidal energy phasing of the Irish Sea (1st to >3rd generation — i.e. be deployed in all water depths), shown as the peak spring tide amplitude (M2+S2) of the horizontal (currents) and the M2 vertical (elevations) tide, relative to the M2 phase for the entire domain of the "fine" resolution model.

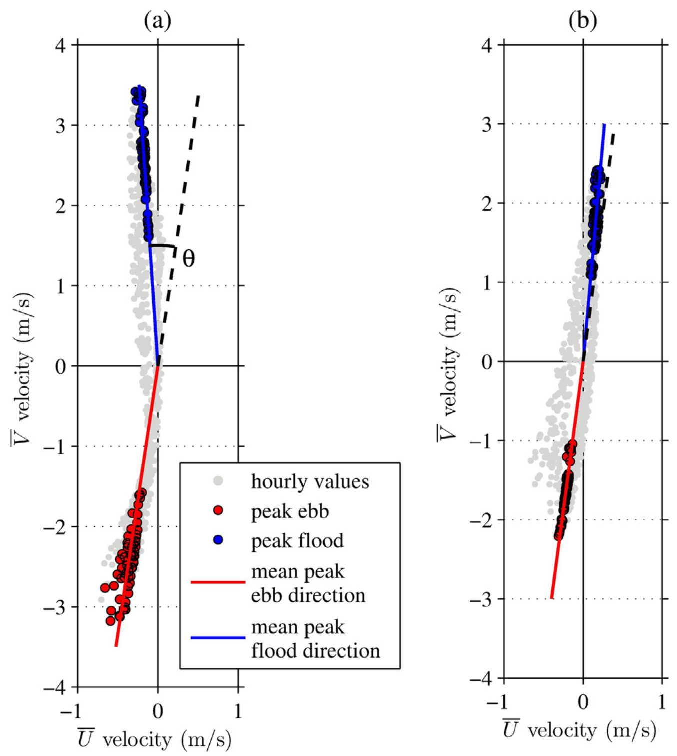

Fig. 9. An example of tidal current misalignment (a) and near rectilinear flow (b), shown as the peak flood-ebb tidal current directional asymmetry (θ) averaged over a spring-neap cycle. Panel (a) shows tidal current misalignment (θ) of 15.1°, calculated from simulated velocities at 53.305 °N, 4.721 °W, and panel (b) shows a contrasting site (θ here is 2.4°) ~3 km to the west (53.305°N, 4.763°W).

include device feedbacks to the resource, a variety of power curves, and infrastructure cost.

Although the development of some shallow water sites (h < 25 m) may be required for a phasing strategy to provide constant electricity generation (see Fig. 8), we found a limited resource in shallow waters (the difference between the blue and black line of Fig. 5: h < 25 m) with the greatest potential resource beyond *SV* > 2 m/s sites is within deeper water regions (h > 50 m); however this result could vary around the world (e.g. Ref. [35]). Tidal-stream energy sites located in water deeper than 50 m may require floating structures, or other innovations such as the tethered “Deep Green” technology developed by Minesto (www.minesto.com); the technologies of which could be considered to be “deployment ready” [2]. Therefore, as tidal-stream turbines may be installed further offshore in the future, including the effect of waves on turbine performance and the impact to the resource [15,36], should be a priority for the industry and research - including infrastructure costs (e.g. cabling costs).

Our analysis assumes rectilinear tidal flow, or the ability of a device to yaw; such that electricity can be generated equally during both the flood and ebb phases of the tidal angle. Some turbine designs are fixed and cannot yaw to account for asymmetry in the angle of the flooding tidal current in comparison to the ebbing tidal current. Therefore, some previously recognised sites may be unsuitable for development because of turbine inefficiency, and failure potential from tidal current misalignment with the turbine [30], as well as the estimated resource being lower than calculated for fixed orientation devices.

The direction (degrees clockwise from north; °N) of the depth-averaged peak flood and ebb tide was identified, and the directional asymmetry between the flood and ebb tide was calculated as the angle (θ, averaged over a spring-neap cycle) between the observed flood tidal current direction and the direction of the flood tide; hence if the current was near-rectilinear (flood direction = 180° from ebb current) θ would be near-zero; see Fig. 9.

The spatial distribution of tidal current misalignm $Vreal^{ebb}$ ent is shown in Fig. 10a for all potential tidal-stream energy sites in the Irish Sea (i.e. 3rd generation sites). Directional asymmetry exceeded 90° for a limited number of cases (<1%) due to localised eddy systems such as re-circulating flows around headlands (e.g. Ref. [12]). Detailed analysis revealed no strong linear relationship between tidal current misalignment and water depth (R^2 regression score below 1%), or between tidal current misalignment and peak tidal velocity (R^2 regression score of 6%); however it appears more likely that flow will be rectilinear in deeper water and in lower flow tidal energy sites (especially at sites where spring tidal

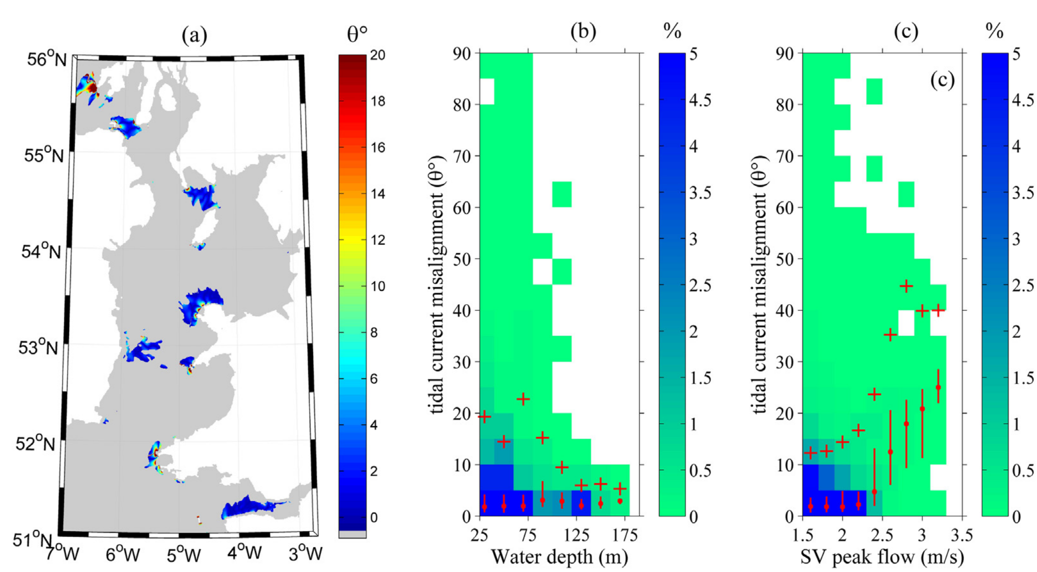

Fig. 10. The spring-neap averaged peak tidal current misalignment (θ, see Fig. 9), for all potential tidal-stream energy sites (*SV* > 1.5 m/s and h > 25 m) in the Irish Sea (Panel a). The distribution of θ is compared by grouping all sites into 20 m water depth bins (for Panel b) and 0.2 m/s tidal velocity bins (for Panel c). The percentage of potential sites is coloured (%), the median of each bin shown (circles) with 25th and 75th percentiles (solid lines) and the 95th percentile (+).

Table 5
The distribution of calculated tidal current misalignment (θ) during times of peak tidal current - grouped into 1st, 2nd and 3rd generation tidal-stream energy sites within the Irish Sea.

	25th percentile	50th percentile (median)	75th percentile	95th percentile
1st generation	11°	20°	26°	44°
2nd generation	1°	3°	9°	27°
3rd generation	2°	2°	4°	18°

flows are below 2.3 m/s); see Fig. 10. Indeed, grouping the calculated tidal current misalignment (θ) into 1st generation, 2nd generation (that also includes all the 1st generation sites) and 3rd generation (that include 1st and 2nd generation sites) tidal-stream energy sites (see Table 5); we find that θ is greatly reduced from an average of 20° to 2–3°, as shown in Table 5.

Our estimate of the tidal resource including flood-ebb tidal current misalignment was calculated using the major axis of realistic ebb current flow ($Vreal^{ebb}$) within the kinetic energy flux estimation (equation (7)), instead of the assumed, rectilinear, major axis of ebb current flow (V^{ebb}) at each 1st generation site, thus: $Vreal^{ebb} = V^{ebb}cos(\theta)$. Hence, by applying this mean flood-ebb tidal current misalignment to our estimation of the tidal-stream energy resource, we estimate the 1st generation undisturbed kinetic energy may be over-estimated ~6% unless tidal devices at such locations can yaw. As θ reduces to 3% for 2nd generation tidal-stream energy sites (2% for 3rd generation sites), we find that flood-ebb tidal current direction misalignment has a negligible effect upon the undisturbed kinetic energy flux estimation of the resource (i.e. < 1%). Therefore, it appears that yawing devices may be important for some 1st generation sites in the Irish Sea, whilst other sites could be deemed unsuitable for development.

6. Conclusions

The tidal-stream energy resource of the Irish Sea is limited when 1st generation sites are considered ($SV > 2.5$ m/s and water depths in the range of 25–50 m), with a number of development and engineering difficulties such as flood-ebb current misalignment. Therefore, as competition for sea space intensifies, and to fully realize the potential of this low carbon and renewable energy industry, 2nd generation technology to efficiently harvest lower tidal velocity ($SV > 2$ m/s) sites would be recommended for the Irish Sea, after which tidal-stream energy convertors capable of deeper water deployment ($h > 50$ m) were found to yield the greatest increase to the potential resource. Furthermore, developing technology to harvest peak spring tide velocity flows (SV) above 1.5 m/s, and all water depths, would allow (with the correct strategy) constant electricity (base load) to be generated due to the greater diversity of tidal phasing between sites; however, more research is required on this topic, and a blend of renewable technologies as well as a centralized development strategy is likely to be required to achieve this goal. Finally, this study demonstrates that Irish Sea 2nd generation tidal-stream energy resource assessments will require hydrodynamic models with spatial scales less than 1 km; otherwise the kinetic energy resource could be overestimated.

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References

[1] Iyer A, Couch S, Harrison G, Wallace A. Variability and phasing of tidal current energy around the United Kingdom. Renew Energy 2013;51:343–57.
[2] O'Rourke F, Boyle F, Reynolds A. Tidal energy update 2009. Appl Energy 2010a;87(2):398–409.
[3] Carballo R, Iglesias G, Castro A. Numerical model evaluation of tidal-stream energy resources in the Ría de Muros (NW Spain). Renew Energy 2009;34(6):1517–24.
[4] Black and Veatch. Phase I. UK tidal-stream energy resource assessment. London: The Carbon Trust; 2004.
[5] Black and Veatch. Phase II. UK tidal-stream energy resource assessment. London: The Carbon Trust; 2005.
[6] Allan GJ, Lecca P, McGregor PG, Swales JK. The economic impacts of marine energy developments: a case study from Scotland. Mar Policy 2014;43:122–31.
[7] Blunden LS, Bahaj AS. Tidal energy resource assessment for tidal-stream generators. J Power Energy 2007;221:137–46.
[8] Neill SP, Hashemi MR, Lewis MJ. The role of tidal asymmetry in characterizing the tidal energy resource of Orkney. Renew Energy 2014;68:337–50.
[9] O'Rourke F, Boyle F, Reynolds A. Tidal current energy resource assessment in Ireland: current status and future update. Renew Sustain Energy Rev 2010b;14:3206–12.
[10] Neill SP, Hashemi MR, Lewis MJ. Optimal phasing of the European tidal-stream resource using the greedy algorithm with penalty function. Energy 2014;73:997–1006.
[11] Adcock TA, Draper S, Houlsby GT, Borthwick AG, Serhadlıoğlu S. The available power from tidal stream turbines in the Pentland Firth. Proceedings of the royal society A: mathematical. Phys Eng Sci 2013;469(2157). 20130072.
[12] Lewis M, Neill S, Elliott A. Inter-annual variability of two contrasting offshore sand banks in a region of extreme tidal range. J Coast Res 2015;31(2):265–75.
[13] Neill SP, Jordan JR, Couch SJ. Impact of tidal energy converter (TEC) arrays on the dynamics of headland sand banks. Renew Energy 2012;37(1):387–97.
[14] O'Rourke F, Boyle F, Reynolds A. Marine current energy devices: current status and possible future applications in Ireland. Renew Sustain Energy Rev 2010c;14:1026–36.
[15] Lewis M, Neill S, Hashemi MR. Realistic wave conditions and their influence on quantifying the tidal-stream energy resource. Appl Energy 2014;136:495–508.
[16] Robins PE, Neill SP, Giménez L, Jenkins SR, Malham SK. Physical and biological controls on larval dispersal and connectivity in a highly energetic shelf sea. Limnol Oceanogr 2013;100:172–85.
[17] Robins PE, Neill SP, Lewis MJ. Impact of tidal-stream arrays in relation to the natural variability of sedimentary processes. Renew Energy 2014;72:311–21.
[18] Serhadioglu S, Adcock TA, Houlsby GT, Draper S, Borthwick AG. Tidal stream energy resource assessment of the Anglesey Skerries. Int J Mar Energy 2013;3:98–111.
[19] Fairley I, Evans P, Wooldridge C, Willis M, Masters I. Evaluation of tidal-stream resource in a potential array area via direct measurements. Renew Energy 2013;57:70–8.
[20] Ahmadian R, Falconer R, Bockelmann-Evans B. Far-field modelling of the hydro-environmental impact of tidal stream turbines. Renew Energy 2012;38(1):107–16.
[21] Shchepetkin AF, McWilliams JC. Regional ocean model system: a split-explicit ocean model with a free-surface and topography-following vertical coordinate. Ocean Model 2005;9:347–404.
[22] Haidvogel DB, Arango H, Budgell WP, Cornuelle BD, Curchitser E, Di Lorenzo E, et al. Ocean forecasting in terrain-following coordinates: formulation and skill assessment of the regional ocean modeling system. J Comput Phys 2008;227(7):3595–624.
[23] Shchepetkin AF, McWilliams JC. Correction and commentary for "Ocean forecasting in terrain-following coordinates: formulation and skill assessment of the regional ocean modeling system". J Comp Phys 2009;228(24):8985–9000. by Haidvogel et al., J. Comp. Phys. 227, pp. 3595–3624.
[24] Warner JC, Sherwood CR, Arango HG, Signell RP. Performance of four turbulence closure methods implemented using a generic length scale method. Ocean Model 2005;8:81–113.
[25] Hashemi MR, Neill SP, Davies AG. A coupled tide-wave model for the NW European shelf seas. Geophys Astrophysical Fluid Dyn 2014. http://dx.doi.org/10.1080/03091929.2014.944909. ahead-of-print: 1–20.
[26] Marchesiello P, McWilliams JC, Shchepetkin A. Open boundary conditions for long-term integration of regional oceanic models. Ocean Model 2001;3:1–20.

[27] Carrère L, Lyard F, Cancet M, Guillot A, Roblou L. FES2012: a new global tidal model taking advantage of nearly 20 years of altimetry. In: Proceedings of meeting 20 Years of Altimetry, Venice; 2012.
[28] Pawlowicz R, Beardsley B, Lentz S. Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE. Comput Geosciences 2002;28: 929–37.
[29] Jones JE. Charts of the 01, k1, n2, m2 and s2 tides in the celtic sea including m2 and s2 tidal currents. Institute of Oceanographic Sciences; 1983. p. 59. Report No. 169.
[30] Galloway PW, Myers LE, Bahaj AS. Quantifying wave and yaw effects on a scale tidal-stream tur-bine. Renew Energy 2014;63:297–307.
[31] Neill SP, Litt EJ, Couch SJ, Davies AG. The impact of tidal-stream turbines on large-scale sediment dynamics. Renew Energy 2009;34(12):2803–12.
[32] Draper S, Borthwick AGL, Houlsby GT. Energy Potential of a tidal fence deployed near a coastal headland. Philosophical Trans R Soc 2013;371:20120176. Part A.
[33] Garrett C, Cummins P. Limits to tidal current power. Renew Energy 2008;33(11):2485–90.
[34] Myers LE, Bahaj AS. An experimental investigation simulating flow effects in first generation marine current energy converter arrays. Renew Energy 2012;37(1):28–36.
[35] Sánchez M, Carballo R, Ramos V, Iglesias G. Tidal-stream energy impact on the transient and residual flow in an estuary: a 3D analysis. Appl Energy 2014;116(1):167–77.
[36] Hashemi MR, Neill S, Robins P, Davies A, Lewis M. Effect of waves on the tidal energy resource at a planned tidal-stream array. Renew Energy 2015;75: 626–39. http://dx.doi.org/10.1016/j.renene.2014.10.029.