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Variability and phasing of tidal current energy around the United Kingdom

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A B S T R A C T

Tidal energy has the potential to play a key role in meeting renewable energy targets set out by the United Kingdom (UK) government and devolved administrations. Attention has been drawn to this resource as a number of locations with high tidal current velocity have recently been leased by the Crown Estate for commercial development. Although tides are periodic and predictable, there are times when the current velocity is too low for any power generation. However, it has been proposed that a portfolio of diverse sites located around the UK will deliver a firm aggregate output due to the relative phasing of the tidal signal around the coast. This paper analyses whether firm tidal power is feasible with 'first generation' tidal current generators suitable for relatively shallow water, high velocity sites. This is achieved through development of realistic scenarios of tidal current energy industry development. These scenarios incorporate constraints relating to assessment of the economically harvestable resource, tidal technology potential and the practical limits to energy extraction dictated by environmental response and spatial availability of resource. The final scenario is capable of generating 17 TWh/year with an effective installed capacity of 7.8 GW, at an average capacity factor of 29.9% from 7 major locations. However, it is concluded that there is insufficient diversity between sites suitable for first generation tidal current energy schemes for a portfolio approach to deliver firm power generation.

1. Introduction

The European Union's ambitious target of meeting 20% of energy demand from renewable energy by 2020 [1] is driving interest and investment in the renewable sector. The UK 2020 target of 15% renewable energy implies a need for around 34% reduction in emissions [2]. Meeting these targets will require substantial investment in new on and offshore wind, wave and tidal energy developments, drawing on the UK's abundant resource potential. There is however concern regarding the integration requirements of the large capacities of new renewable generation implied by these targets given the inherent variability of the major renewables, and the relative timing of their output with electricity demand. In reality, no energy source is 100% reliable and scheduled or unscheduled outages do occur. Demand patterns are also variable, hence the power system and network have historically, and will continue to be required to be designed and managed to handle variability [3]. As tidal current energy generation is driven by the gravitational interaction of the Earth–Sun–Moon system, tidal energy production patterns can be reliably predicted over short timescales, some as short as a few hours (which can include non-tidal events) and longer timescales which can be as much as days to years, to assess the Annual Energy Production (AEP) over the project life time. Accurate predictions of the output and variability of individual tidal current sites and the impact of aggregation of output from various sites will be highly desirable to facilitate network planning and operation.

The Carbon Trust has commissioned a number of studies that have been used to assess the tidal current resource, its variability and its implications for development [4–6]. As part of the Marine Energy Challenge, Black and Veatch (B&V) [4] estimated the extractable tidal current resource to be 18 TWh/yr (±30% uncertainty) [4], that this 'Technically Extractable Resource' can meet about 5% of current UK demand and that the UK has around 50% of the EU tidal current resources. The study used output from the DTI Atlas of UK Marine Renewable Energy Resources [7], Admiralty Chart data from the UK Hydrographic Office [8], and local current meter data to select and characterise specific locations of tidal energy generation. It also applied a 'Significant Impact Factor' (SIF)

Abbreviations: AEP, Annual Energy Production; ADCP, Acoustic Current Doppler Profiler; BODC, British Oceanographic Data Centre; EMEC, European Marine Energy Centre; B & V, Black and Veatch; GEBCO, General Bathymetric Chart of the Oceans; GIS, Geographical Information System; IDW, Inverse Distance Weighting; NOAA, National Oceanic Atmospheric Administration; SIF, Significant Impact Factor; SPR, Scottish Power Renewables; TAP, Technically Acceptable Power.

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Nomenclature and units

A	area, m^2
a_o	amplitude/local tidal elevation, m
c	wave celerity, m/s
C_p	device efficiency, %
d	distance, m
g	acceleration due to gravity, m/s^2
h	water depth, m
P	power, W
p	peak weighting function
Q_{max}	maximum flow discharge, m^3/s
T,t	time, s
u, v	velocity, m/s
u	velocity at a known location, m/s
x,x_k	value at an unknown/known point
ρ	density (water), kg/m^3
λ	wavelength, m

to assess the 'Technically Acceptable Resource' that places a limit on the amount of available kinetic energy that can be harvested without undue impacts on the environment and the tidal current resource itself. This SIF value was estimated as being 20% of available kinetic energy flux [4], although understanding of the extraction limits has since advanced considerably as presented by Refs. [9,10]. It has also been demonstrated by other studies that the flux method has no physical justification and is an unsuitable way of assessing the resources as presented in Ref. [11].

Analysis of tidal current energy generation potential has been further progressed by Sinden [5] by extracting power output time series for wave and tidal energy. Comparing the variability of the identified tidal sites was conducted using data extracted from the Proudman Oceanographic Laboratory POL CS20 tidal model [12] (also the basis for the DTI Atlas tidal component [7]). Although the variations were examined at specific locations, and SIF constraints (as in [4]) were taken into account, the analysis assumed a scenario where all the sites are fully developed without any further constraints. Furthermore, this study also neglects any feedback effect at individual sites or between different sites.

First generation devices are considered to be the driver for tidal current energy development until at least 2025. Installation and operation in deeper water requires more radical 'second' and 'third' generation approaches that are, as yet, only in the very early stages of research and development. Therefore, an analysis based on just first generation device specification is required. The application of the SIF has since been superseded, for this reason a revision of the 'Extractable Power' considered by B&V [4] and Sinden [5] is also necessary.

Boehme et al. [13] examined tidal current resource variability in Scotland as part of the 'Matching Study' for the (then) Scottish Executive. It used the DTI Atlas and Admiralty charts to define current flows within Scottish waters. It applied a generic twin-rotor tidal turbine to estimate production levels and variability. The study estimated the Scottish tidal resource as 2.2 TWh/yr when a 750 MW installed capacity development scenario is considered. However, this study did not look at the far field effect of extraction power from tidal currents and no feedback effects were considered either.

1.1. Firm tidal power generation

An important area that these studies have not tackled directly is whether the aggregate outputs from tidal sites can represent a form of 'firm' or continuous (base load like) generation through diversity in the phasing of energetic sites. Two other studies have offered some analysis of this issue. Clarke et al. [14] suggest that aggregate output from a number of sites can provide base load. Unfortunately, the sites selected are less energetic and/or generally too deep for first generation deployment. For example, Sanda (Mull of Kintyre) has tidal current velocity above 2.5 m/s but the water depth at this site ranges from 100 to 120 m. While this site may eventually be developed for tidal current energy harvesting, it is not credible for first generation tidal projects. Hardisty [15] also reports that by careful selection of tidal current site locations, a continuous level of generation could be achieved. However, when interrogating the same data source as referenced in Ref. [15] (Admiralty TotalTide software [16]), the authors were unable to reproduce this outcome as the sites selected generally had current velocities below 1 m/s. For instance [15], purports to use data relating to tidal diamond SN040A (in Clyde, Scotland) and suggests that it has a Spring peak velocity of 2.1 m/s. Interrogating the same tidal diamond using [16] indicates that SN040A only reaches a Spring peak of 0.57 m/s, a value inappropriate for tidal current energy development. Other discrepancies with reported tidal diamond data were also found while attempting to recreate this analysis. The analysis concluded that a constant level of 45 MW can be generated from an installed capacity of 200 MW, a rather uneconomical scenario.

Additionally, considering the local bathymetric data using the BERR Marine Atlas [17], which is an updated version of the DTI Marine Atlas [7], indicates that some of the sites identified in [15] are too shallow for full scale device deployment. Hence, the authors contend that the locations identified in [15] are not likely to be considered for large scale development of tidal current energy even if they are out of phase, as a majority of the sites suggested in this study are inappropriate for economic tidal current energy generation.

Given the identified deficiencies of existing efforts to assess the potential for firm tidal current energy generation, this paper is concerned with understanding the scope for portfolios of credible first generation[1] tidal current development scenarios to provide firm power. This involves a reassessment of the UK tidal current resource by identifying appropriate development locations incorporating the latest thinking on power extraction limits and examines aspects of generation yield, variability and temporal phasing.

1.2. Data sources

The majority of the data used in this study are publically available. Two different datasets are used to provide spatial and temporal accuracy. With additional processing, the datasets are combined to achieve considerable improvement in analysing the resource. The data obtained from the DTI Atlas of UK Marine Renewable Energy Resource [7] has been taken forward by The Department for Business, Enterprise and Regulatory Reform (BERR) and the underlying Marine Atlas data is now available through a web interface [17]. The Geographic Information System (GIS) data layers downloadable from the web interface are interrogated in the analysis presented using ArcGIS and integrated with manipulated Admiralty chart data [8] accessed utilising Admiralty TotalTide software [16] to provide time series at identified locations.

[1] In order to set the context of the analysis presented in this study, 'First Generation Technology' is defined as iterations of existing prototype devices that are already undergoing pre-commercial demonstration. A *second generation* of technology is defined as being able to be deployed in deep water of greater than 50 m. Examples of such generation technology solutions are under development, but are currently at the early stages of technology readiness, and hence unlikely to make a significant contribution to meeting 2020 electricity generation targets.

Acoustic Doppler Current Profiler (ADCP) data can also be used to measure current velocity, using the principles of the Doppler effect and reflecting sound off small particles in the water column [18]. ADCP data was made available to the author on request for Orkney by the European Marine Energy Centre (EMEC) [19] and for the Sound of Islay by Scottish Power Renewables (SPR) [20]. Measured buoy data was obtained from British Oceanographic Data Centre (BODC) for Anglesey [21]. Time series for all the sites need to be coincident in time, therefore this additional buoy and ADCP data had to be recreated using harmonic decomposition and prediction, in this case using the methodology advocated by the US National Oceanic Atmospheric Administration (NOAA) [22].

The paper is laid out as follows: Section 2 examines the theory behind tidal currents and their phasing around the UK. Section 3 sets out the methodology for assessing the resource available at first generation tidal sites and Section 4 reports on the outcomes of the analysis. Sections 5 and 6 discuss the implications and conclusion of the study.

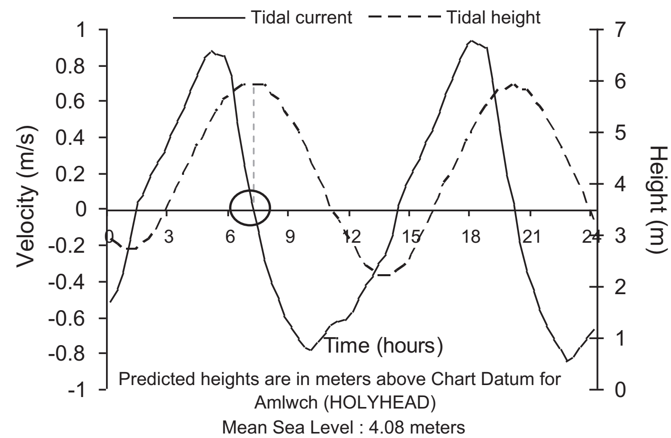

Fig. 1. Tidal current (solid line) and height data (dotted line) at Holyhead indicating relative phasing of current and surface elevation. Data obtained from TotalTide.

2. Tidal resource phasing

The timing of the tidal phasing stems from the fundamental concept of tidal wave propagation. The velocity of tidal wave propagation (wave celerity ‘c’) in shallow water is given by:

$$c = \sqrt{gh} \tag{1}$$

where c is the wave celerity (m/s), g is the gravitational acceleration (m/s^2), and h is the water depth (m). For the purpose of elucidating the discussion, a depth of 50 m is selected as being representative of UK coastal waters. From this, the wavelength λ of the tidal wave can be calculated as:

$$\lambda = cT \tag{2}$$

where T in this case is taken as the 12.4 h time period of the dominant tidal constituent (M2 – the diurnal pattern of the Moon). In the vicinity of the UK, the wavelength of the M2 tidal component is approximately 988 km which is approximately the length of the UK landmass. This would suggest that that there are substantial differences in phase around the UK coastline. However the topology of the British Isles serves to complicate matters.

In the deep ocean, tides predominantly propagate as progressive waves. As they approach near-shore regions on the northern European continental shelf, their behaviour tends towards a standing wave characteristic where high and low water coincides with slack tide. Near-shore tidal velocities tend to peak when the gradient of the surface elevation is at a maximum. Fig. 1 illustrates the current velocity and tidal heights for a randomly chosen location around the UK (Amlwch, near Holyhead – tidal diamond SN048J). Slack tide occurs when the tidal current (solid line) changes direction. The change in flood to ebb direction is at the time of high water indicating standing wave characteristics. The Holyhead data is generically representative of large swathes of UK coastal waters, so Fig. 1 represents broadly tidal wave characteristics throughout the UK waters. Although slight time lead/lag may be experienced at specific sites, the current will typically change direction coincident in time to the highest gradient of local surface elevation.

Fig. 2 shows the co-tidal lines around the UK that represent the time (in hours) of high water at each location. This broadly illustrates the phasing of tidal currents. Tidal interaction with local bathymetry and the costal topology also play an important role in the local phasing of tidal currents. In addition, the characteristics of tidal current generators, particularly the shape of the power extraction curve will also play a significant role in the phasing of power production. (This is in reference to the ramp rate of the device, see Fig. 10. The power generation is asymmetrical.)

The locations circled in Fig. 2 have been identified by B & V [4] as being sites of interest for tidal current energy extraction. Ideally a phase difference of 90° or 270° (around three or nine hours) between two locations is optimal for tidal sites to provide best potential for generating firm power. However, the locations highlighted in Fig. 2 experience high water at broadly similar times. This suggests that there is also a good likelihood that these locations will also exhibit tidal current patterns that are also in phase. Verifying the phase coincidence for major sites like the Pentland Firth and the Channel Islands will confirm the significance of the impact tidal current generation can have when integrated into the electricity network as these two locations alone have been identified as embodying a large percentage of the technically extractable UK tidal current energy resource. Sites in the Pentland Firth have already been identified as likely to witness the first significant tidal current energy developments, as established by the recent round of site leasing by the Crown Estate with 1.2 GW installed capacity of wave and tidal energy originally proposed for this region [23]. An additional 400 MW of tidal energy developments have since been leased in the Inner Sound region of the Pentland Firth [24]. As a result of these geographically clustered developments, there will likely be very small phase difference between the tidal sites. This will become relevant in Section 4 where specifics of site selection and their outputs are discussed. The ‘in phase’ character of the tidal sites is entirely coincidental and specific to the UK context under investigation; such coincidence of phasing of so many key locations in one country is unlikely to be replicated in other territories when the tidal current energy resource is accurately assessed.

3. Methodology

The methodology aims to make best use of publicly available data to identify locations suitable for deployment of first generation tidal current devices and to generate credible time series of energy production from generic tidal current technologies at these locations. It also allows the latest methods on power extraction limits to be incorporated. The three main stages of the method outlined in Fig. 3 are:

1. Identification of locations suitable for large scale first generation tidal current device developments;

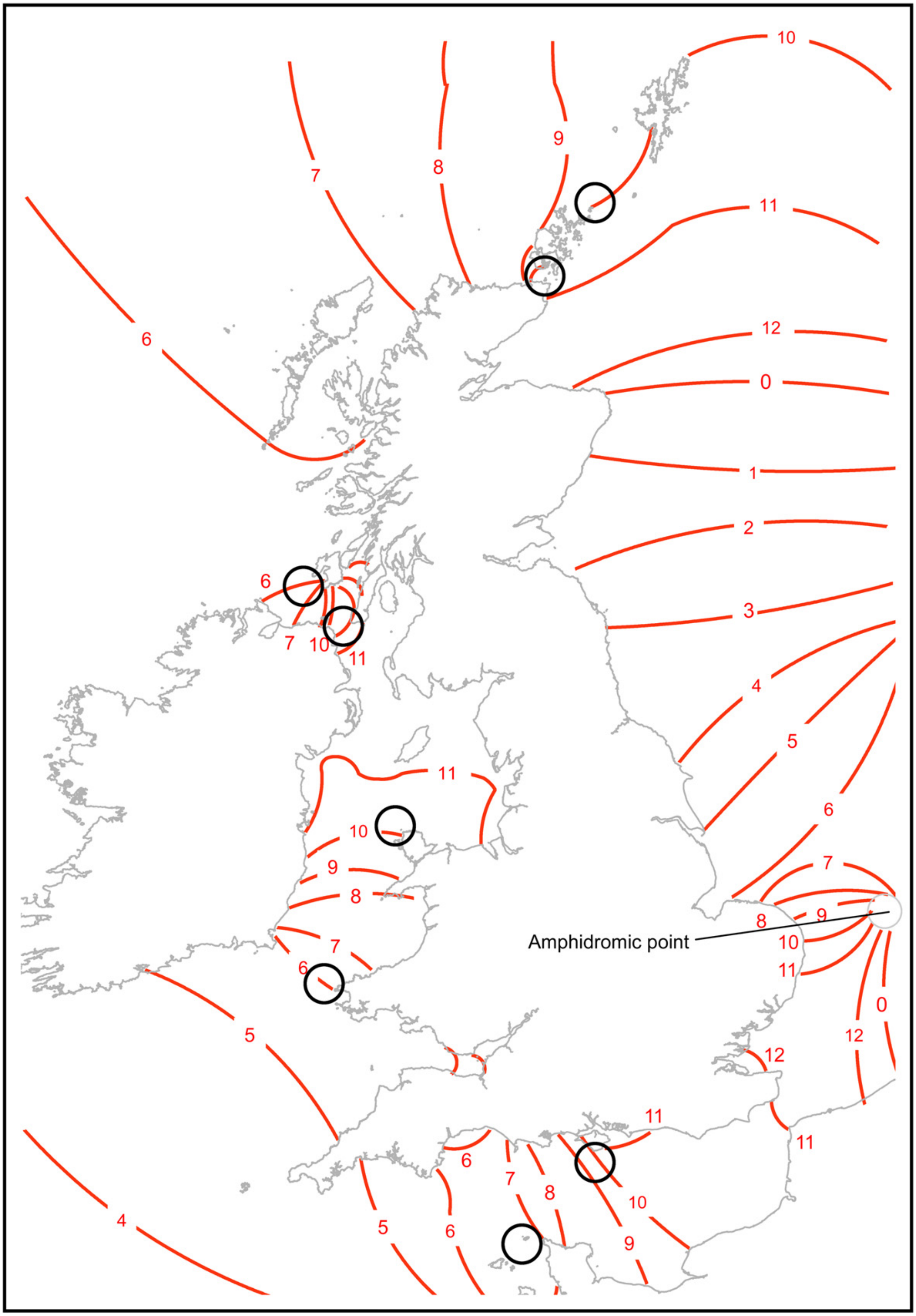

Fig. 2. Co-tidal lines for the coast of UK. Areas indicated by the circles are regions identified to be of interest for tidal current energy development.

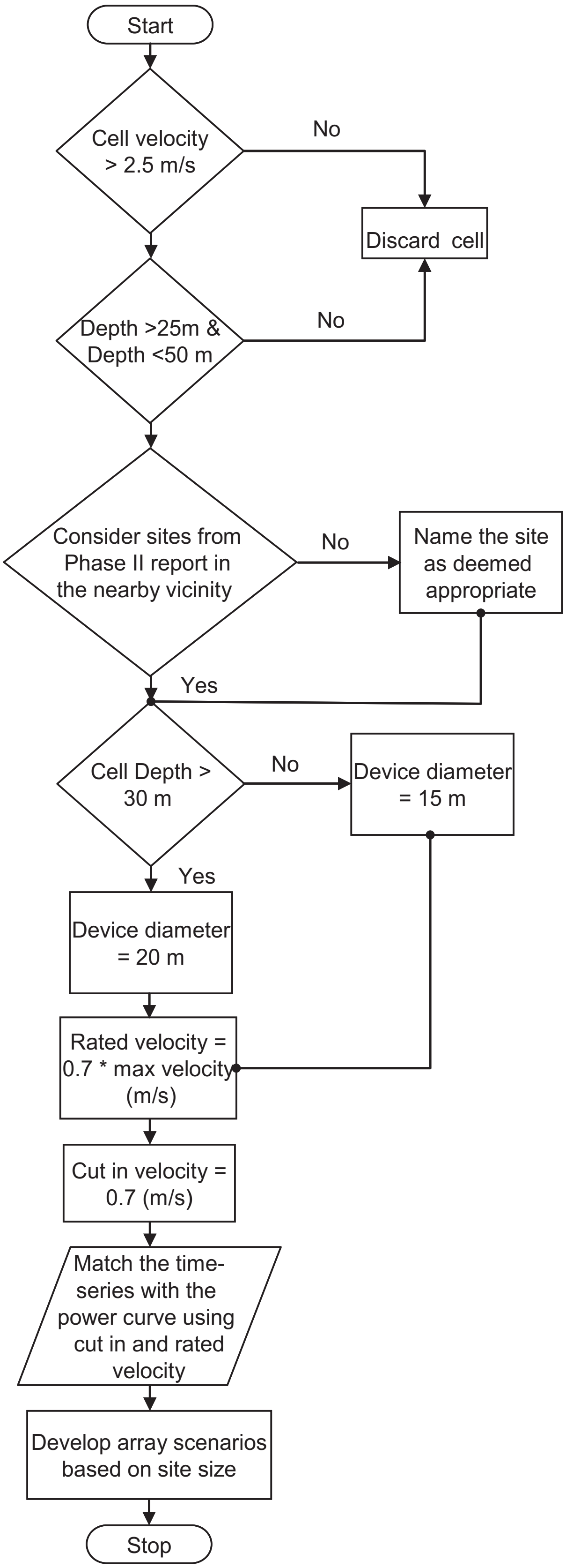

Fig. 3. Flowchart showing the steps embodying the methodology.

2. Estimation and validation of the tidal current time series at these locations;
3. Estimation of generic tidal generator size, rating and hence time series of energy generation at each identified location.

The final time series generated provide a suitable format to enable comparison between and aggregate assessment of the energy generation potential of specific regions for the UK as a whole.

3.1. Identification of locations suitable for first generation tidal devices

The first stage of the process outlined in Fig. 3 aims to identify sites that are viable for the deployment of first generation tidal current devices. Data accessed from downloadable GIS layers of the Atlas of UK Marine Renewable Energy Resources [17] are utilised for this purpose. This is a similar approach to that adopted by B&V [4]. The GIS data for the Marine Atlas itself is derived from the POL CS20 Model [12], which is obtained from 34 layers in the water column. The bathymetry data for [12] originates from the General Bathymetric Chart of the Oceans (GEBCO) and solves the 3-dimensional incompressible, Boussinesq, hydrostatic equations in spherical polar coordinates with a transformed vertical coordinate [7]. However [17], only presents a depth-averaged data. The output from [12] was also utilised in the analysis conducted by Sinden [5]. The Atlas provides mean Spring and Neap tide velocity magnitude and water depth data within the UK territorial waters at a spatial resolution of approximately 1.8 km^2. Fig. 4 shows the mean Spring peak current for the UK and several regions of particular interest for first generation tidal deployment.

Using ArcGIS, the Marine Atlas data [17] was interrogated to select specific cells meeting certain criteria. For a site to be considered economically viable for first generation tidal farms the mean Spring peak current velocity must exceed 2.5 m/s as suggested by Ref. [4]. Ref. [25] argues that this is one of the most important prerequisites for making tidal current energy cost effective. The second criterion is the need for the water depth to be within the range 25–50 m which is the expected operational parameter for first generation devices. Tethered and floating devices are at present still in a test phase and therefore only rigid or mounted structures are considered, which imposes a depth constraint. A list of all the sites selected using these criteria are indicated in Table 1 and Fig. 4. The number of (approximately 1.8 km^2) cells identified as meeting these criteria at each of the listed sites are included to give an estimate of the extent of each of the sites.

To simplify relaying the findings, where appropriate, the sites in a particular region have been grouped together. It is interesting to note that Table 1 does not include all the sites identified by B&V [4] as many of the sites identified by their analysis are in water depths greater than 50 m or do not meet the velocity criteria applied here. In some cases, smaller sites like Strangford Narrows – the test site for one of the few existing full scale tidal current energy technologies – have not been included in the Marine Atlas [17]. The Marine Atlas does not resolve the Narrows regions or similar narrow channels, and insufficient data to generate a time series of resource variability was available in the public domain. An additional variation is that although depth data from [17] suggests that the Sound of Islay is not deep enough to be considered for device deployment, SPR [20] indicate that the Sound of Islay reaches 48 m deep and therefore is appropriate for first generation development. This example is indicative of some of the limitations of the Marine Atlas as a data source – it has wide area coverage, however this is only achievable because the resolution is still relatively coarse (from an end-users context).

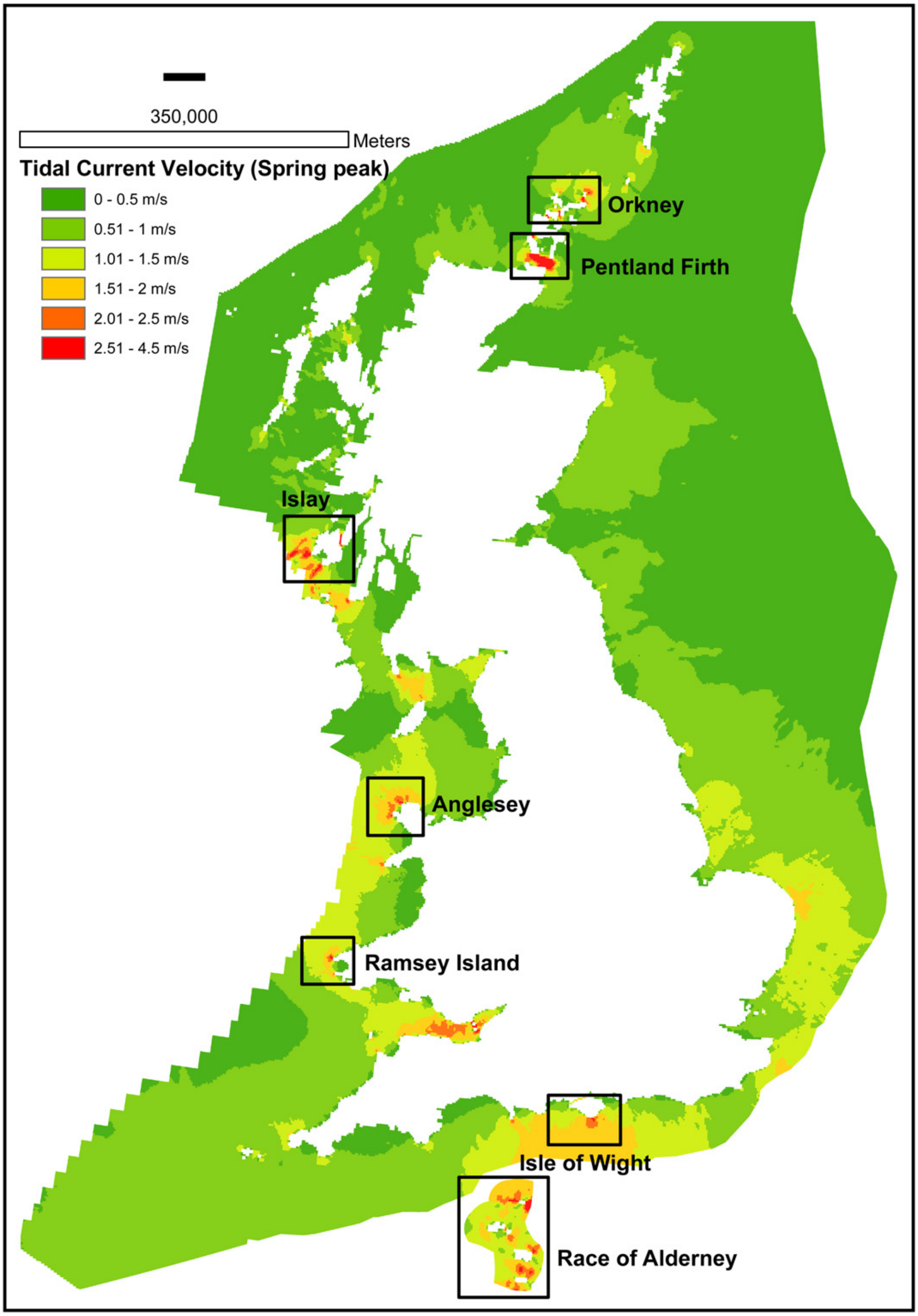

Fig. 4. Figure showing mean spring peak current and specific regions of interest. BERR Marine Atlas. ©Crown Copyright. All rights reserved 2008.

It should also be noted that the majority of the identified sites are located in Scotland in relatively close proximity to each other, the Pentland Firth alone houses six major sites.

3.2. Estimation and validation of tidal current time series

The next stage of the analysis is to generate credible tidal current time series data for each of the sites identified in Table 1. The first step is to use information from the UK Hydrographic Office (UKHO) Admiralty chart data [8], often referred to as 'tidal diamonds', as their respective positions are indicated on Admiralty charts by diamond symbols. The TotalTide software package [16] contains fundamentally the same information as the Admiralty charts but provides a convenient means of interrogating the tidal current data through time at the tidal diamond locations. The limitation of the TotalTide data is that it only encapsulates the variability of the currents as described by the two dominant tidal harmonic constituents, M2 and S2 [26]. Another limitation is that the tidal diamonds do not always

Table 1
List of all the sites considered in this study as identified using the methodology in Fig. 2.

Region	Site name	Marine atlas	Tidal diamond	ADCP	Buoy
Pentland Firth	Pentland Skerries	✓	✓		
	S. Ronaldsay P.Firth	✓	✓		
	S. Ronaldsay/P.Skerries	✓	✓		
	Duncansby Head	✓	✓		
	Inner Sound	✓	✓		
	Stroma P.Firth	✓	✓		
Orkney	Westray Firth	✓	✓	✓	
	N. Ronaldsay Firth	✓	✓		
Islay	Islay North	✓	✓		
	Islay Centre	✓	✓		
	Islay South	✓	✓		
	Sound of Islay			✓	
Anglesey	Anglesey North	✓	✓		✓
	Anglesey South	✓	✓		✓
	Ramsey Island	✓	✓		
	Race of Alderney	✓	✓		
	Isle of Wight	✓	✓		

coincide spatially with the locations of specific cells of interest within each site. Therefore, to allow generation of time series of current flows, 'pseudo diamonds' were created at these points based on interpolation from surrounding tidal diamonds. This approach is similar to that applied by Boehme et al. [13]. It is understood that this is not the most accurate method of generating data, however given the lack of model data, and the wide spatial coverage of the locations being considered in this study, it is thought that this is the best option available. However, as the industry matures, the need for such models has been identified and is currently being addressed by the Energy Technology Institute (ETI) project [27] that aims to make high resolution model datasets available.

Following the interpolation technique the data is further enhanced by combining with additional datasets such as in-situ measurements where available. The inverse distance weighting (IDW) interpolation methodology [28] was applied to create a site specific flow velocity for irregularly spaced data. The methodology is applied to the tidal diamond data, where the interpolated value u at a given point x is given by:

$$u(x) = \frac{\sum_{k=0}^{N} w_k(x) u_k}{\sum_{k=0}^{N} w_k(x)} \quad (3)$$

where u_k denotes the point the data is being interpolated from and w_k is the weighting, defined as:

$$w_k = \frac{1}{d(x, x_k)^p} \quad (4)$$

d is the distance between the two points the unknown value and x_k the point the data is being interpolated from. $p = 2$ is adopted as recommended by [28]. Selection of the value of p enables the user to prescribe how sharp a peak the function exhibits by giving greater influence to nearby data points. A low value of p provides a smoother solution, with more 'smearing' of peaks.

Multiple calibrations between different tidal diamonds were employed to find IDW's that best represented the sites. An example case study for the Anglesey sites is presented in [29], which identifies multiple sets of IDW's within a prescribed distance, and follows a structured exclusion criterion which systematically eliminates tidal diamonds based in their statistical correlation. The data is also compared to the Marine Atlas, the mean annual kW/m^2 value is obtained for the specific location and compared to the IDW's. Because the tidal diamonds only capture the very basic harmonic constituents, it is thought that the time series would benefit from some input from the Marine Altas which provides better 'average' parameters, however cannot generate time series. Therefore, to improve the accuracy of the data set, the time series was scaled up to the Spring peak current value obtained from the nearest grid cell reported in the Marine Atlas. This maintains the local phasing and Spring-Neap variability as prescribed by the tidal diamond data obtained from the TotalTide software, while also utilising the improved resolution of the numerical model output to identify local peak current velocities. Outputs from the numerical model as time series are unfortunately not available in the public domain, hence the need to combine various data sources. Using this approach helps maintain the correct phase of tidal propagation and provides credible current velocity estimates at each of the sites of interest, an example is shown in Fig. 5 where the different IDW's are compared to in-situ measured buoy data at the Anglesey site.

Although tides are highly spatially variable as highlighted in [29], the methodology presented represents a consistent means of combining datasets without the need to perform full scale site assessment modelling, necessitating an extensive and expensive in-situ survey data and numerical modelling campaign beyond the scope of this analysis (and although highly desirable is, as yet, unavailable on a UK wide scale).

The time period for this analysis had to be recent, so as to make comparison to recent demand trends. With this thought, the analysis was conducted for the year of 2009. The choice of the year is such that demand data is easily available and the nodal factor is as close to unity as possible for the 18.6 year nodal cycle. For the present period, this happens to be in the year 2011. The authors consider in-situ data measurements to be the preferred 'gold-

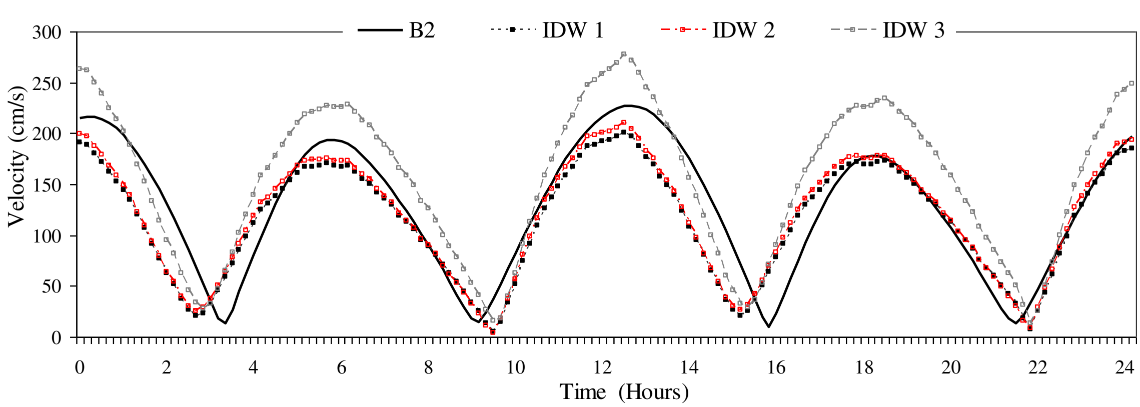

Fig. 5. Velocity magnitude comparison of buoy with IDW 1, IDW 2 and IDW 3.

standard' data source, and were obtained where possible. ADCP measurements are very accurate when set up correctly and hence are highly desirable for conducting detailed site analysis and characterisation. The ADCP data used for analysis at the (EMEC) Orkney location is a 1 month long measurement taken in 2005 and hence does not coincide in time with the tidal diamond time series obtained for all the other locations. Therefore harmonic constituents for theses locations were determined from the ADCP data records using least-squared analysis. 23 principal constituents were obtained following the recommended practise of the NOAA in their Tidal Current Analysis Procedures and Associated Computer Programs documentation [22]. The principal constituents were then used to recreate the time series coincident in time and in temporal resolution to all the other time series created from tidal diamonds. Fig. 6 shows a scatter plot of the original measured data vs. the predicted data generated using harmonic analysis for ADCP measurements taken at EMEC (survey 7).

ADCP data for Sound of Islay was gathered in 2009 for a duration of 31 days. A similar approach as suggested for the Orkney data is applied here to recreate the time series. Similarly, recording current meter data measurements for Anglesey were obtained from the British Oceanographic Data Centre (BODC) [21]. The minimum data length used in the analysis was 29 days which enabled a detailed harmonic analysis to be conducted. Three sets of buoy measurements were available, buoys B1 and B2 were on the same mooring string and measured current velocity at 30 m (near seabed) and at 3 m (near surface) respectively. Buoy B3 was located 1.07 km from B2, this provided the opportunity to assess spatial variability between the buoys as well as variability across the water column. Details of this analysis are presented in [29].

Where ADCP data is obtained, velocity from the 'mid bin' of the water column is used, usually where the hub will be placed. This is done so that the resource is not under estimated compared to depth-averaged data. Tidal diamond data is measured near surface (at about 5 m from surface). This data has not been processed further. Measurements at different varying depths is likely to cause some inaccuracies, see Fig. 7 showing ADCP profile measurements from Sound of Islay averaged over time. The current velocity is broken down into ebb, flood and overall so as to ignore the slack period. However, all the sites do not demonstrate a similar vertical velocity profile, and therefore using a generic 1/7th or 1/10th profile to 'correct' the data to mid-depth would introduce additional inaccuracies. It is thought that not processing the tidal diamond data will not lead to any considerable differences. Therefore although mentioned velocity as v, for tidal diamond data its near surface and for ADCP data it is mid-depth velocity.

3.3. Estimation of generic tidal generator size, rating and production time series

The third stage of the method uses a simple generic model of a horizontal axis tidal current device to estimate time series of power generation at each site from local current velocity time series. For the purpose of assessing energy extraction, it is assumed that each device would be aligned perpendicularly to the principal current direction to maximise energy capture. In narrow channels, the current flow is predominantly bidirectional and therefore this assumption holds. However, even within the channel bathymetry and depth variation can affect the uniform flow as shown in Fig. 8, all the three ADCP measurements are for the EMEC site, note how the harmonic prediction fails to capture all the variability for survey 10.

Two device models are used to reflect the differences required for operating in different water depths: in cells with minimum water depths of 25–30 m a device rotor diameter of 15 m provides appropriate surface and seabed clearance, avoiding conflict with vessel navigation in the region. In depths greater than 30 m, a device diameter of 20 m is specified.

An appropriate rated current velocity for each cell is determined by taking 70% of the Spring peak velocity of the specific cell. This follows similar practise to [4], utilising understanding of the optimal economic balance between capturing maximum available

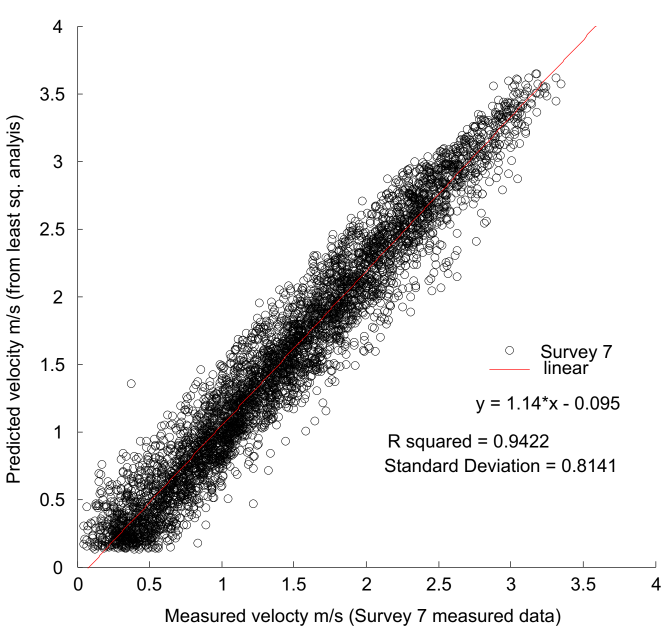

Fig. 6. Scatter plot of survey 7, measured vs. predicted data.

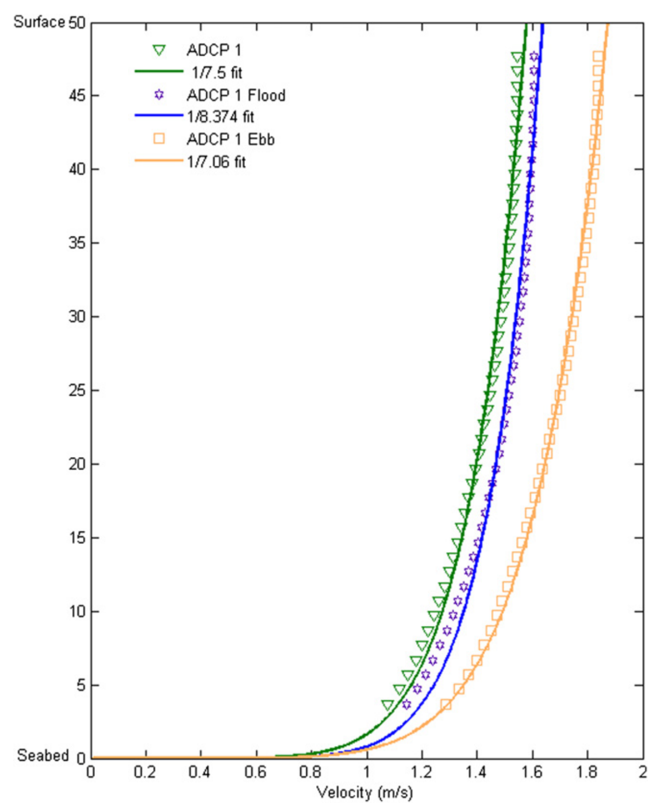

Fig. 7. Average vertical velocity profile for ADCP 1.

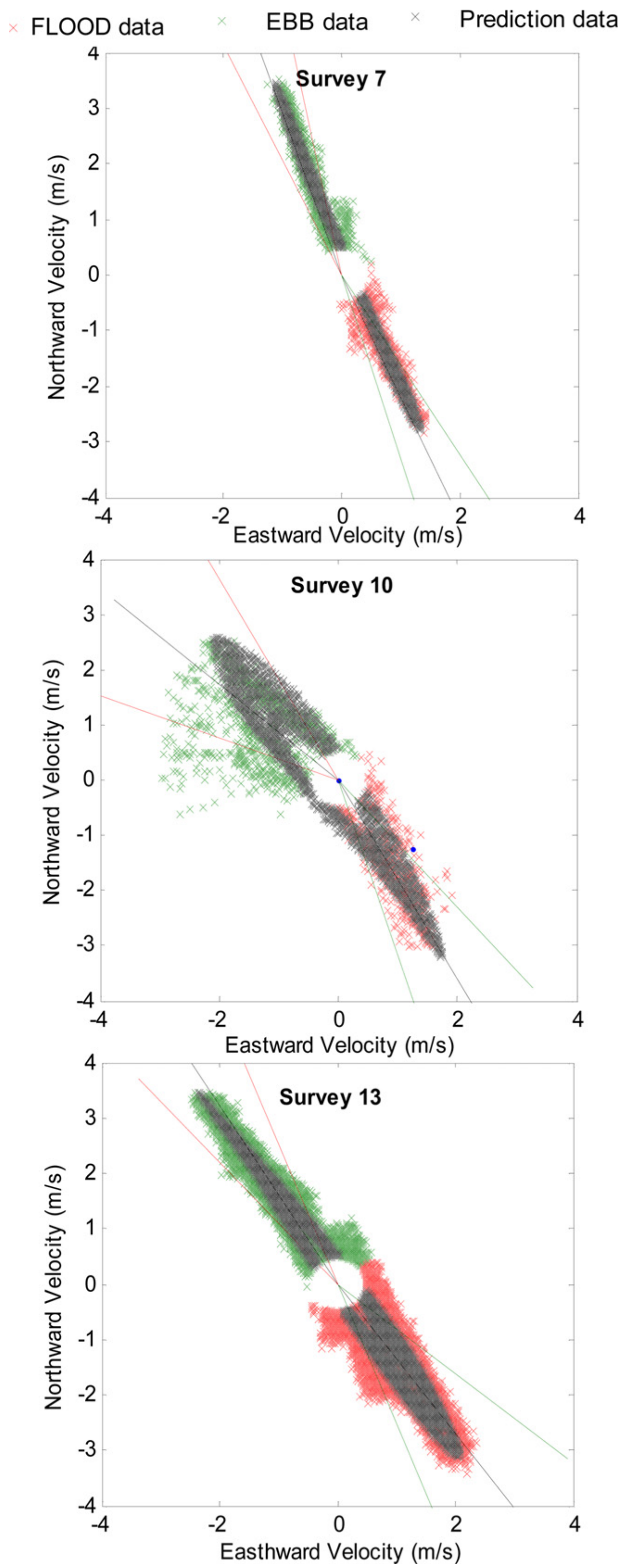

Fig. 8. *X*–*Y* scatter plot for survey 7, 10 and 13 from EMEC. Comparison between measured and predicted data.

energy and the cost of the energy capture device. However, later discussions with the authors of [4] highlighted that this method does not fully consider the site economics, and they have since moved on to an in house cost optimisation model. If the device was rated to coincide with maximum Spring peak velocity, then the drivetrain would have to be rated to operate for a condition that occurs only for a short instant each month, and the structural support element of the device would similarly have to be designed to withstand the thrust acting on the turbine for only a minute fraction of the operational period, particularly important for a pitch controlled device, hence the reasoning for using 70% of the Spring peak velocity. Having established the rated velocity, the power can be assessed across the operational cycle as:

$$P = \frac{1}{2} C_p \rho A v^3 \quad (5)$$

where C_p is the device efficiency and assumed to be 40% on the basis of [30], the water density, $\rho = 1025$ kg/m^3, A (m^2) is the rotor swept area and v (m/s) is the current velocity, mid-depth for ADCP measurements and near surface for tidal diamond data. Fig. 9 illustrates the hypothetical power curve for a generic 0.5 MW rated turbine, and demonstrates the difference in rated velocity necessary to generate 0.5 MW with a 15 and a 20 m rotor diameter. A cut in velocity of 0.7 m/s is assumed for all the hypothesised generic tidal turbines.

Multiple tidal devices populate each of the 1.8 km^2 cells. EMEC standards [31] suggest devices are spaced two and a half diameters between the rotor axis perpendicular to the current and ten diameters apart parallel to the current. Because full scale tidal arrays are yet to be deployed, there is limited knowledge of the wake propagation, however this is a sensible spacing to begin with. In this study the assumed device array spacing is more conservative with three diameters apart laterally and ten diameters spacing upstream/downstream of each device. This means that 480, 15 m diameter devices or 270, 20 m diameter devices can populate each 1.8 km^2 cell. It is acknowledged that actual array layout is unlikely to be as regimented, employing staggering of devices, and would have to adapt to the real world variability of appropriate bathymetric conditions (e.g. bed slope). The device rating varied for each cell based on the local bathymetry (impacting diameter) and maximum Spring peak velocity (impacting rated velocity) reported for that cell as previously outlined.

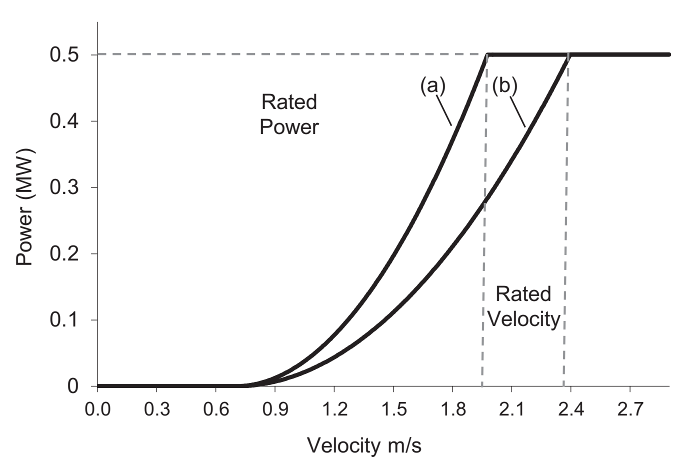

Fig. 9. Hypothetical power curve for a generic 0.5 MW tidal current device: (a) rated velocity of 1.98 m/s with 20 m diameter rotor; (b) rated velocity of 2.39 m/s for a 15 m rotor.

4. Analysis

This section reports the results obtained from application of the methodology described in Section 3 when applied to the sites identified in Table 1 as being suitable for first generation tidal current sites (also see Fig. 4). The power potential of each site, the phasing of the sites and the impact of the environmental extraction limits at each location are presented.

4.1. First generation tidal current resource

The installed capacity of each cell was calculated from the relevant cell rated velocity and peak power output. These are aggregated for each site as shown in Table 2 along with a breakdown of the number of turbines. This shows that, overall, first generation sites would support an installed capacity of 13.4 GW of tidal current devices. The installed capacity is a simple assessment of the number of devices that can be placed in each of the identified cells without considering any impact this may have on the current flow velocity or the environment. There is a substantial range of installed capacity, with the largest single site capacity identified as 3855 MW in the Race of Alderney and the smallest being the 105 MW Anglesey South site. The largest regional group is the Pentland Firth at 4352 MW. For the purposes of the analysis presented here, the interaction of devices with wakes generated by upstream devices and device downtime due to planned or unplanned maintenance have been ignored, as these aspects are likely to be highly site- and project-specific. These aspects are more appropriate for consideration at a project assessment scale as opposed to a higher level national assessment.

The gross annual energy yield from each of the cells is calculated from the tidal current time series at each cell matched with the device power curve identified as appropriate for that cell. As reported in Table 2, the results from each cell within a site are summated and suggest that over 35 TWh/year could be produced across each of the sites, which equates to approximately 10% of UK electricity demand [32].

However, this scenario only considers the available resource and the level of technology and does not account for the changes in the tidal hydrodynamics as a result of these installations. Therefore this is a technical *unconstrained* estimate of the available resource. A technically *acceptable* value for energy extraction that accounts for velocity reduction as a result of these installations and the environmental effects is discussed in Section 4.4.

4.2. Site economics

The productivity of each site broadly reflects the installed capacity, although the match between current flow conditions and generator characteristics means that the production from each site varies. For example, the Race of Alderney has the highest energy yield despite not possessing the largest installed capacity. This is reflected in the site capacity factors as presented in Table 2 (the ratio of production from a given generator to the production of the same generator operated at rated output with 100% availability). The overall average capacity factor across all the sites is 29.9% but the values for individual sites vary between 23.3 and 43.6%. For comparison, the average load factor for onshore wind across the UK in 2009 was 27.4% [33].

Capacity factor can be used as a simplified indicator of how ‘economic’ a site is by indicating how well the capital investment in generation capacity is being utilised. A low capacity factor is indicative of a lower economic performance on a per kW basis but the overall investment may still perform very well. The variation in capacity factor may partially also be a consequence of the simple generic turbine sizing utilised under-rating device characteristics at some of the higher capacity factor sites, and being too large for low capacity factor sites. The important point in decision-making however, is the balance between revenue from energy sales and the cost of the installation. With the cost of the devices and

Table 2
All the sites with installed capacity, annual energy yield and capacity factor.

	Site name	No. of cells	No. of device (20 m)	No. of device (15 m)	Installed capacity MW	Yield TWh/yr	Capacity factor %
Pentland Firth	Pentland Skerries	2	540		708	1.8	28.8
	S. Ronaldsay P.Firth	1	270		194	0.4	26.2
	S. Ronaldsay/P.Skerries	5	1350		759	1.7	25.2
	Duncansby Head	1	270		205	0.6	32.6
	Inner Sound	3	270	960	813	1.4	23.3
	Stroma P.Firth	7	1890		1673	3.9	24.7
	Regional Total				**4352**	**9.7**	
Orkney	Westray Firth	2	540		620	2.6	32.4
	N. Ronaldsay Firth	1		480	180	0.2	23.8
	Regional Total				**800**	**2.9**	
Islay	Islay North	7	810	1920	875	2.5	32.5
	Islay Centre	12	2160	1920	1526	4.5	33.2
	Islay South	8	1620	960	879	2.6	33.3
	Sound of Islay	2	40		23	0.1	43.6
	Regional Total				**3302**	**9.6**	
Anglesey	Anglesey North	4	270	1440	418	1.0	26.2
	Anglesey South	1	270		105	0.3	32.4
	Regional Total				**523**	**1.3**	
	Ramsey Island	3	540	480	**340**	**0.7**	24.8
	Race of Alderney	19	3658	1178	**3855**	**10.4**	30.0
	Isle of Wight	2		960	**255**	**0.7**	29.6
	Total				**13,427**	**35.2**	

Bold numbers are regional totals.

importantly the grid connections not part of the selection criteria, it would be anticipated that sites further from land represent a more challenging investment, particularly at prices of £52,000/MW/km for subsea of 132–275 kV HVAC cable [34]. It is important to highlight that such additional externalities will impact on potential site selection, as distance to shore as an example is an important criterion differentiating projects.

4.3. Site phasing

The generation time series are now used to examine the relative phasing of production from each site. Fig. 10 is a plot for a typical Spring peak day, highlighting that the majority of generation contributions are from the Pentland Firth, Islay region and the Race of Alderney. The periods of generation at rated output can be clearly seen in many of the traces particularly for the Pentland Firth, as can the asymmetric nature of the production cycle with aggregated output ramping up slower than it ramps down highlighting the difference between the ramp rates. The location of the individual sites determines their phasing and in terms of tidal wave propagation, Islay and Pentland Firth are in phase due to the coincidence of the local tidal phasing at these locations. The Race of Alderney is out of phase by approximately 1 h. The aggregate effect can be seen in the total power output generated which highlights the intra daily variability. What is notable is that the base of aggregate generation is much wider than any of the individual outputs: this shows that there is a portfolio aggregating effect exploiting the phase variations between sites. However, this effect is not sufficient to generate significant firm output as none of the large sites are appropriately out of phase. Even the smaller contributions from the Orkney, Anglesey, Isle of Wight and Ramsey Island sites are more or less in phase with each other, and with the Pentland Firth and Islay.

4.4. Technically acceptable power extraction

So far the analysis has not taken any account of the fact that there is a limit to the amount of energy that can be extracted from the tidal system. The original SIF of 20% extractable kinetic energy used in many tidal assessments has been substantially revised in [9] to reflect improved understanding of the hydrodynamic mechanisms that underlie the tidal current resource.

The numerical modelling carried out by the authors in support of [9] assesses representations of various relevant hydrodynamic mechanisms – tidal streaming, resonance and hydraulic currents, the flow phenomena that create tidal current conditions necessary for economic project development:

1. Tidal streaming: To maintain continuity, when a body of water is forced through a constraint such as a narrow channel, the flow accelerates.
2. Hydraulic currents: When two adjoining bodies of water are out of phase, a hydraulic current is created in response to the pressure variation induced as a result of the varying water levels in the different water bodies.
3. Resonance: Occurs as a result of standing wave when the incoming tidal wave and the reflecting wave interfere constructively. This can create large tidal amplitudes and associated currents.

Any energy extraction will affect the underlying hydrodynamics. Fig. 11 is a compendium of key non-dimensional parameters for a hydraulic current case conducted by [9]. Both upstream and downstream boundary conditions were specified with a sinusoidal elevation imposed with a phase shift between the two boundaries to drive the pressure gradient. The parameters have been expressed as a fraction of the maximum value and the parameters evaluated over the complete ebb and flood cycle. Q is the flow discharge, U represents the velocity and P is power. Reading the graph from right to left, when there is no power extraction ($Q/Q_{max} = 1$, ratio of flow over maximum flow) velocity and flow are unchanged. Moving along the axis when ($U/U_{max} = 0.8$), 80% of the power can be extracted with a 20% reduction in the velocity and a 40% reduction in head loss. In the case when P/P_{max} peaks, U/U_{max} is approximately half (56%), and Q/Q_{max} reduces by nearly 70%. Looking past peak power extraction, the overall power that can be extracted reduced due to a significant reduction in U and Q, the ratio of the flow over maximum flow continues to decrease and consequently the velocity continues to reduce. This has also been demonstrated analytically for hydraulic current tidal flow regimes by Refs. [10] and [35]. A 'Technically Acceptable Power' (TAP) limit has also been indicated by the dotted vertical line as the region of the curve, where P/P_{max} has the highest gradient. This region indicates maximum economic gain per MW installed and is within the acceptable environmental constraints.

The parameters needed for this calculation are shown in Table 3 where ρ is water density, g is the acceleration due to gravity, Q_{max} is

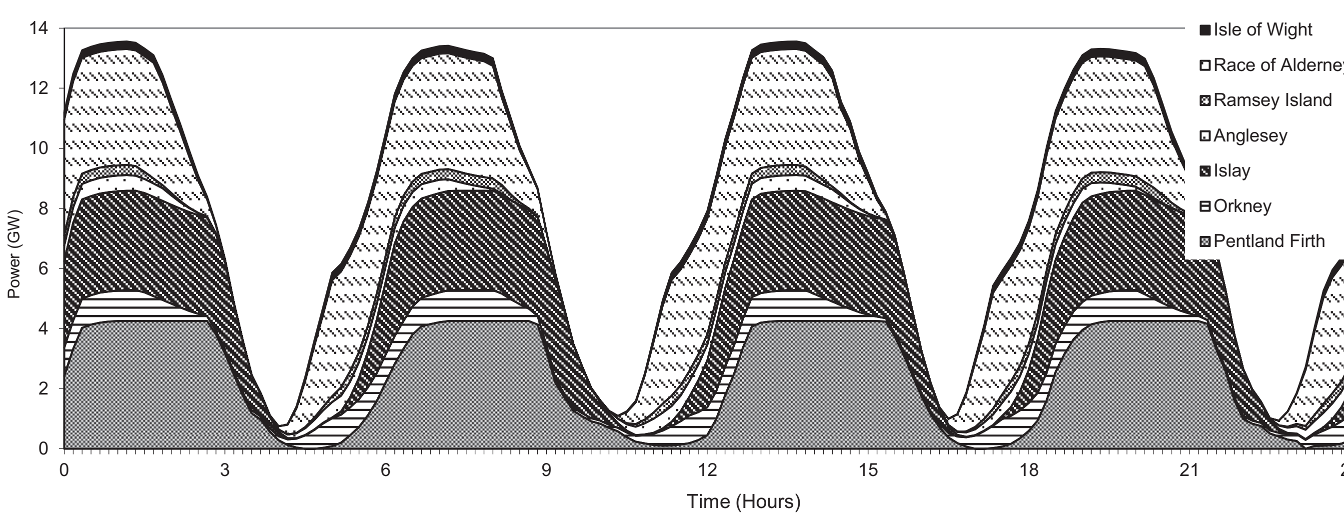

Fig. 10. Stacked time series of all sites showing aggregate production at spring peak with environmental constraints ignored.

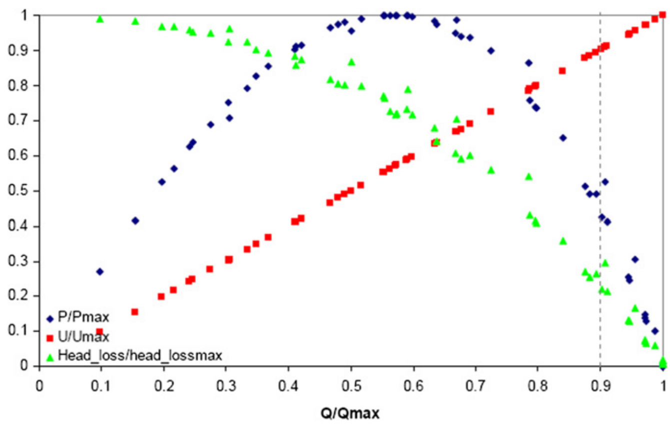

Fig. 11. Key non-dimensional parameters for hydraulic current [9].

the maximum flow rate and a_o the amplitude of the sea level difference between the two ends of the channel in the case of a hydraulic current. For tidal streaming and resonance a_o is the local tidal elevation amplitude. To evaluate the level of power that can be harvested from each of the sites, their respective hydrodynamic mechanism is identified and a TAP value defined. Regions with multiple sites are treated in one of two ways: the sites at Orkney, Islay and Anglesey are considered to be sufficiently geographically and hydraulically dispersed to be evaluated separately while for the Pentland Firth, sites are considered interdependent and are handled jointly by a single set of limits. For many sites the high flow velocities experienced are a result of a combination of mechanisms; Table 4 lists all the sites and identifies the dominant hydrodynamic mechanism experienced. Using the dominant system, the annual 'Environmentally acceptable' power that can be extracted from each of the sites is reported in Table 4 using the extraction limits identified (Table 3).

The technically unconstrained values listed in Table 4 are used to place limits on the development at each site – defined as the TAP yield. In order to incorporate this, the capacity factor for each cell was used to define the 'least economic', and these cells are prioritised for removal from the analysis when limitation of the site output is necessary to meet TAP constraints. This was achieved either by removing the cell entirely or by reducing the number of devices deployed in the identified cell to meet TAP constraints. The energy yield reductions imposed by TAP constraints range from 5% for the Pentland Firth to 80% for the Race of Alderney, with an overall reduction of 52% (from 35.2 TWh/yr to 17 TWh/yr). In some cases, there is no reduction in capacity and yield (N. Ronaldsay Firth, Sound of Islay, Anglesey North and Isle of Wight) as the original unconstrained energy yield is less than those implied by the TAP limits. This is because the power that can be extracted using first generation devices is less than the identified TAP and hence these locations do not require further constraint beyond the initial spatial availability for device deployment.

Fig. 10 presents the time series of aggregate unconstrained production from the sites from a day coincident with a Spring tide. In contrast Fig. 12 shows the same time series with the TAP limits applied and indicates the significant overall reduction in aggregate energy generation. Most significant is the impact on the Race of Alderney, reduction on the aggregate generation potential is obvious. This is of particular significance from a phasing perspective, as the Race of Alderney is the only site that made any significant out of phase contribution. Fig. 12 represents the final scenario that is used for further assessment, representing a realistic scenario of tidal current energy development that can be undertaken with first generation depth limited devices. Over a 3 h period during a typical Spring tide, the power output varies from 7 GW to 1 GW or less and this variation occurs four times daily. During the Neap cycle (not shown) the peak power generation will be of the order of 4 GW and falls to near zero four times a day (Fig. 12).

4.5. Limitations

Although a TAP value is obtained using an environmentally acceptable limit to the energy extraction, a full physical response of the system is not considered. While establishing the TAP value, it is assumed that the power output of the sites and their kinetic energy density is unchanged. Ideally a feedback method should be considered where the velocity reduction is used to recalculate the installed capacity and AEP. However, this feedback effect is a non-linear response and cannot be achieved without the use of an appropriate numerical model. Further work in this area should use the model developed by [27] to include this physical response. Additional factors such as array interaction and wake effects should also be considered.

5. Discussion

The method described here suggests that first generation tidal current devices installed at suitable UK sites could produce up to 17 TWh/yr. This method accounts for the limits of available technology and tolerable environmental impacts on a regional scale. It does not, however, include the reduction in kinetic resource intensity that will occur as a consequence of power generation and, therefore, overstates that power generation potential that could be practically achieved. Approximately 7.8 GW of installed capacity is necessary to meet this scenario of generation. While the analysis presented here lacks the very high temporal and spatial resolution data necessary to inform individual project development detailed design, it offers a credible and broad resource analysis suitable for understanding the nature of the UK tidal resource and its phasing. A true understanding with a high level of accuracy of the resource will only be gained by extensive site measurements combined with new generations of hydrodynamic tidal models incorporating the complex interaction of device operation alongside the evolving hydrodynamics.

In terms of answering the original question as to whether first generation tidal current devices can offer a significant degree of firm power supply in the UK, the results suggest that it is not possible. Continuous output can be achieved for a number of days around Spring peak. However the level of continuous generation is only a small fraction of peak generation. This can be confirmed by

Table 3
Summary of technically acceptable power (TAP) extraction limits for the three identified tidal flow driving mechanisms.

Tidal mechanisms	Theoretical limit of tidal current energy harvesting	'Technically acceptable' limit of tidal current energy harvesting	Hydrodynamic response limiting energy harvesting
Hydraulic current	$P_{\text{Theoretical}} = 0.2\rho g Q_{\max} a_o$	$P_{\text{acceptable}} = 0.086\rho g Q_{\max} a_o$	Velocity reduction
Resonant basin	$P_{\text{Theoretical}} = 0.2\rho g Q_{\max} a_o$	$P_{\text{acceptable}} = 0.033\rho g Q_{\max} a_o$	Downstream tidal range
Tidal streaming	$P_{\text{Theoretical}} = 0.16\rho g Q_{\max} a_o$	$P_{\text{acceptable}} = 0.020\rho g Q_{\max} a_o$	Downstream tidal range

Table 4
Technically acceptable power that can be extracted from each of the sites and the final annual energy yield including TAP constraints.

	Site name	Tidal site system	Annual yield TWh/yr				Capacity MW		
			Technically unconstrained	Flux TAP	Actual	% reduced	Technically unconstrained	Flux TAP	% reduced
Pentland Firth	Pentland Skerries	HC	1.8	Calculated	1.8		708	708	
	S. Ronaldsay P.Firth	HC	0.4	as one system	0.4		194	194	
	S. Ronaldsay/P.Skerries	HC	1.7		1.7		759	759	
	Duncansby Head	HC	0.6		0.6		205	205	
	Inner Sound	HC	1.4		1.4		813	813	
	Stroma P.Firth	HC	3.9		3.4		1673	*1526*	
	Regional Total		**9.7**	**9.2**	**9.2**	−5%	**4352**	**4205**	−3%
Orkney	Westray Firth	HC	2.6	0.7	0.7		620	*259*	
	N. Ronaldsay Firth	TS	0.2	0.2	0.2		180	180	
	Regional Total		**2.9**	**1.0**	**1.0**	−67%	**800**	**439**	−45%
Islay	Islay North	TS	2.5	0.5	0.5		875	*167*	
	Islay Centre	TS	4.5	0.6	0.6		1526	*192*	
	Islay South	TS	2.6	1.2	1.2		879	*393*	
	Sound of Islay	HC	0.1	0.7	0.1		23	23	
	Regional Total		**9.6**	**2.9**	**2.3**	−76%	**3303**	**775**	−77%
Anglesey	Anglesey North	TS	1.0	0.8	0.8		418	*363*	
	Anglesey South	TS	0.3	0.4	0.3		105	105	
	Regional Total		**1.3**	**1.2**	**1.1**	−10%	**523**	**468**	−11%
	Ramsey Island	TS	**0.7**	**0.6**	**0.6**	−16%	**340**	**285**	−16%
	Race of Alderney	TS	**10.4**	**2.1**	**2.1**	−80%	**3855**	**747**	−81%
	Isle of Wight	HC	**0.7**	**1.2**	**0.7**	–	**255**	**255**	–
	Total		**35.2**	**18.2**	**17.0**	−52%	**13428**	**7174**	−42%

HC = Hydraulic current, TS = Tidal streaming.
Text in bold highlights the Regional total.
The number in bold are values where the flux TAP is greater than the technically unconstrained resource.

aggregating the time series output of all the sites and presenting them as a power exceedance curve over a period of a year (showing the percentage of time the aggregate power output is exceeded). Fig. 13 shows curves for aggregate tidal current generation with and without the TAP limit enforced. In both cases aggregate output at or near 100% exceedance is zero, meaning that there is no true capability for firm power generation with first generation tidal current devices. Other definitions of 'firm' output exist with, for example, the hydropower sector often adopting the 95% exceedance figure as firm output. Adopting this definition for the tidal current case, represents a firm capacity of around 75–150 MW with and without TAP constraints respectively – still negligible in comparison with the peak generation potential, or as a percentage of the installed capacity.

To further investigate this phasing aspect, the correlation between power generation at individual sites is presented in Table 5 to indicate the relationship between their various timings; all combinations showing a correlation in excess of 0.5 are shown in bold. This analysis does not take any consideration of the relative magnitudes of each site, only the relative phasing. The majority of the locations in the study show either some or strong positive correlation. Maximum correlation is observed

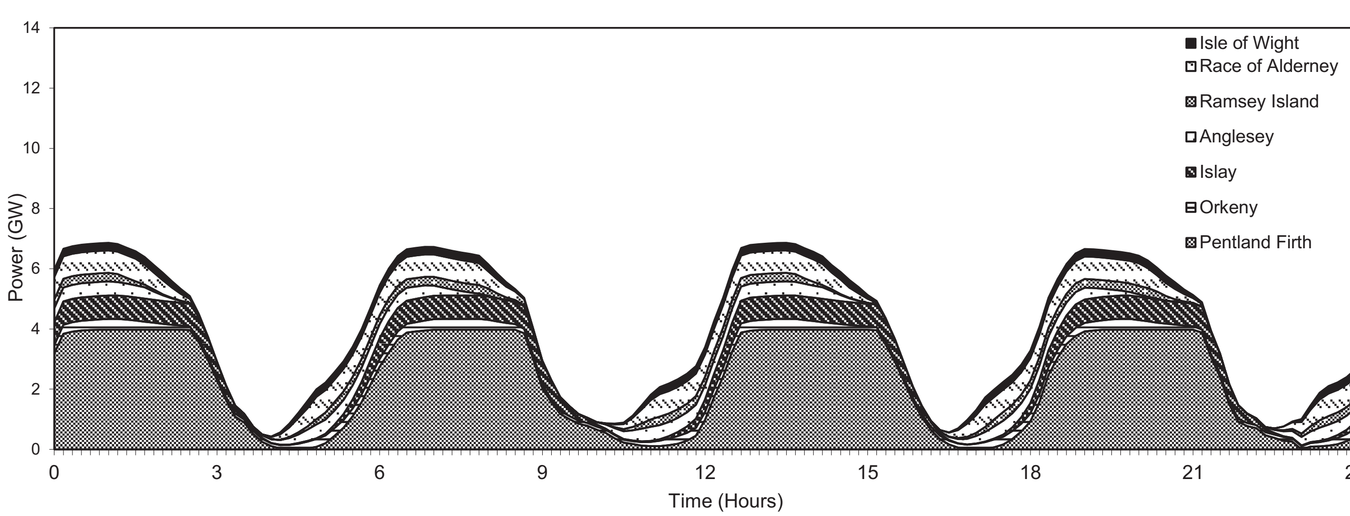

Fig. 12. Stacked time series of all sites showing aggregate production at spring peak with environmental constraints included.

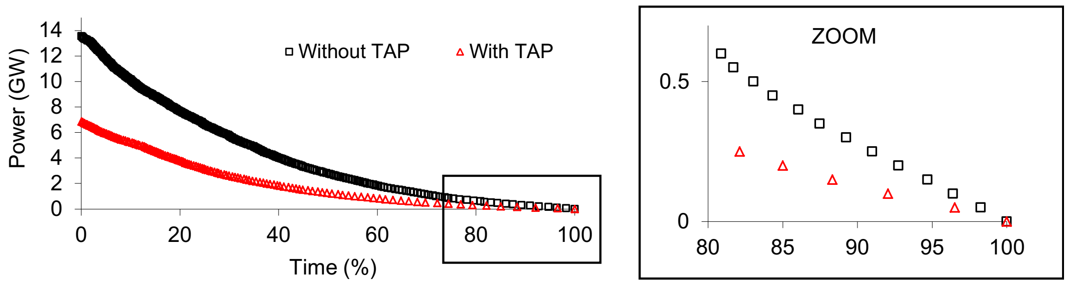

Fig. 13. Power exceedance curve from instantaneous tidal generation with and without TAP over a year.

Table 5
Correlation coefficient for production between each site.

Site name	Pentland Firth	Orkney	Islay	Anglesey	Race of Alderney	Ramsey Island	Isle of Wight
Pentland Firth	1	**0.69**	**0.96**	0.21	0.37	0.35	0.49
Orkney	**0.69**	1	**0.70**	0.48	**0.75**	**0.73**	**0.79**
Islay	**0.96**	**0.70**	1	0.26	0.38	0.35	0.49
Anglesey	0.21	0.48	0.26	1	**0.82**	**0.72**	**0.76**
Race of Alderney	0.37	**0.75**	0.38	**0.82**	1	**0.95**	**0.97**
Ramsey Island	0.35	**0.73**	0.35	**0.72**	**0.95**	1	**0.93**
Isle of Wight	0.49	**0.79**	0.49	**0.76**	**0.97**	**0.93**	1

between Pentland Firth, Orkney and Islay and between Anglesey, Race of Alderney, Ramsey Island and Isle of Wight. It is also interesting to observe the high correlation between Orkney and Race of Alderney, Ramsey Island and Isle of Wight, particularly as they are geographically distant. It would be preferable from the point of view of generating continuous base load profile if the sites indicated a wide spread of both positive and negative correlations.

Despite the apparent lack of a firm production capability, tidal current energy is periodic and can be predicted over a long period which is a huge advantage when compared to stochastic resources such as wind and wave. As such, it provides an opportunity for network operators to schedule generation and reserve to meet demand and coupled with some form of storage could even contribute towards firm generation. In addition like all variable renewable sources, tidal current devices possess a ‘capacity credit’ or capacity value that describes the degree of conventional generation mix that can be substituted by tidal current energy generation. Assessment of the capacity credit of tidal current energy generation building upon the scenarios presented in this work is an area for future work.

Overall this study highlights that tidal current energy production is highly variable and site specific, but this variability can be predicted fairly accurately using the harmonic constituents, although meteorological factors can add a certain percentage of uncertainty. A credible high level analysis of the aggregate potential of tidal current energy production from first generation tidal current devices sited in locations with high current velocities and relatively shallow water has been presented. The analysis presented lacks the high (temporal and spatial) resolution data necessary to conduct a rigorous detailed resource analysis on a site-by-site basis as would be appropriate for detailed project design and financing. However, the approach utilised is tractable within the framework of the research and, on a site-by-site basis is analogous to preliminary site assessment in a project development context. To provide a more detailed understanding with a high degree of accuracy, extensive in-situ measurements would be necessary. Such detailed data would enable reliable assessment of additional aspects such as short–term variability for system balancing.

6. Conclusions

This study presents a high level analysis of the aggregate behaviour of the tidal current energy resource in the UK and credible scenarios for exploiting the resource using first generation tidal current technology. With due consideration to the environmentally acceptable limits to energy extraction identified, although not considering the physical response, the resource available at first generation sites was estimated to be 17 TWh/year for an installed capacity of 7.8 GW.

Although this work aims to offer an improvement in further understanding the UK’s tidal current resource, each stage of this analysis has considerable uncertainties and inaccuracy:

- The datasets used to generate the time series
- The metrics used to identify site suitable for this analysis
- The site-and device characteristics
- The accuracy of the technically unconstrained and TAP value

Due to this uncertainty and lack of a feedback re-evaluation it is thought that first generation development will be less that 17 TWh/yr. Despite these uncertainties, the analysis is rigorous about the phase assessment of the different tidal sites. Unfortunately, the nature of tidal wave propagation around the west coast of the UK means that most tidal energy hot spots suitable for first generation technologies are largely in phase, with only the Race of Alderney in the Channel Isles differing significantly. It is concluded that there is insufficient diversity between the sites identified for first generation tidal current schemes to be considered as a firm power source.

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