Phasing of tidal current energy around the UK and potential contribution to electricity generation

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***Abstract*— Tidal current energy has the potential to play a key role in meeting UK renewable energy targets. Although tides are periodic and predictable, there are times when the current velocity even at high energy sites is too low for power generation. However, it has been proposed that a portfolio of diverse sites located around the UK will deliver 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. Time-series data for sites identified as high energy are obtained using a combination of sources for the year 2009. Scenarios incorporate constraints relating to assessment of the economically harvestable resource, tidal technology potential and practical limits to energy extraction dictated by environmental response. Spatial availability of appropriate bathymetric conditions are assessed which provides an additional limit on the energy harvesting potential. Finally, the variability of power generation from tidal current energy is compared with the existing variability of UK electricity demand using National Grid data.**

***Keywords* – Tidal Current Energy, Marine renewables, Resource assessment, Network integration, Supply and demand matching**

I. INTRODUCTION

The European Union (EU) has ambitious targets to meet future energy demand while reducing carbon emissions. These targets include achieving a 20% reduction in harmful greenhouse gas (GHG) emissions on 1990 levels by 2020, and increasing final energy consumption from renewable sources to 20% on the same timescale [1]. In the UK, more than 30% of electricity generation needs to be supplied through new, clean and carbon free sources in order to meet the EU mandated target, as other parts of the energy sector have less ability to reduce GHG emissions [2]. In order to achieve this, substantial investment in new energy sources such as on- and offshore wind, wave and tidal energy is necessary. Tidal current energy has the potential to play a key role in meeting these targets as around 50% of the economically viable tidal resource in the EU lies in UK coastal waters [3]. Various assessments have equated this tidal current energy resource potential to around 5% of UK electricity demand (e.g. [3]). Ongoing analysis by the authors suggests that assessment may be conservative. Further potential to harvest energy from the tidal resource using barrage and lagoon technologies is also possible [4]. The assessment presented herein is specifically focussed on the potential of tidal current energy solutions.

The marine energy industry is moving towards large scale deployment with regions identified as high energy sites in the Pentland Firth being leased by the Crown Estate for commercial development [5]. However, the introduction of variable sources of energy where supply dependency is related to resource availability as opposed to mechanical availability is a potential cause for concern from an electricity network operator's perspective. Tidal energy resources are driven by the gravitational interaction of the Earth–Sun-Moon system. Therefore, although variable with time, tidal energy production patterns can be reliably predicted on both short and long timescales. However, a challenge with tidal energy is that the peak power at a particular site occurs approximately 50 minutes later each day as the tidal signal around the UK is dominated by the M2 tidal constituent associated with the periodicity of a lunar day (24 hours and 50 minutes). This discontinuity between the solar and lunar day ensures that peak generation and demand are rarely coincident.

Accurate assessment of the output and variability of individual tidal current sites and the impact of aggregation of output from various sites would be highly desirable to facilitate network planning and operation. Such information would also be instructive for scoping the future potential of tidal current energy, and hence planning development and investment in the emerging technology and project development industry.

The research presented in this paper initially quantifies the total available resource in the UK that can be extracted using 'first-generation' technology options. The resource assessment utilises a combination of available datasets. The analysis is based on tidal current characteristics for the calendar year 2009. For the purpose of developing power generation scenarios, representative generic first-generation device characteristics are considered. The overall analysis involves examining aspects of generation, yield, variability, phasing and ultimately the fit with existing UK electricity demand. The potential impacts of introducing tidal generation into the existing electricity mix are thus considered. The work presented uses various methodologies to quantify fluctuations in power generation and makes comparison with day-to-day demand variability. Finally, a preliminary capacity credit calculation is conducted to quantify the contribution of the envisaged future tidal energy generation development scenario towards ensuring demand security.

II. TIDAL RESOURCE DEVELOPMENT SCENARIOS

A number of studies have been conducted to assess the total exploitable tidal energy resource in the UK. It is of value to accurately define the exploitable resource as this quantifies the potential scale of industry development that can be supported. The next section discusses the latest estimates for tidal current energy in the UK and highlights the need for additional analysis of the variability of the resource in an energy context.

A. Resource Assessment

Under the Marine Energy Challenge, Black & Veatch (B&V) [3] estimate the extractable resource to be 18 TWh/yr (±30% uncertainty). This is the most widely referenced assessment at a national scale. The analysis in [3] utilises input data from a combination of sources:

1. The UK Marine Renewable Energy Resource Atlas [6] by the (then) Department of Trade and Industry (DTI),
2. Admiralty chart data from the UK Hydrographic Office [7], and
3. Local port data where available.

A 'Significant Impact Factor' (SIF) is proposed to limit the energy that can be exploited without adversely affecting the environment and the overall resource itself. A constant value of 20% of the total available kinetic energy flux is applied in [3].

Sinden [8] has furthered the work conducted in [3] by extracting power output time series for wave and tidal current energy. The analysis in [8] assumes a scenario where all the available tidal energy resource identified in [3] is developed, after accounting for SIF restrictions. The analysis does not differentiate between shallow and deeper sites where a different generation of technology will need to be deployed. 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, therefore a revision of the 'Extractable Power' considered in [3] and [8] is also necessary.

An interesting aspect that is yet to be fully understood is whether the aggregate output from different tidal sites can represent a form of 'firm' generation by diversifying the phasing of the incoming tidal waves. [9] demonstrates the potential for baseload provision using tidal currents based on analysis of three locations. Nautical Almanacs are used as the input data in [9]. This data is primarily used by yachtsmen for navigation purposes and it has not previously or since been used for tidal current evaluation purposes. Interrogating the BERR Marine Atlas [10], an updated version of the DTI Atlas [6] at the locations used by [9] indicates significant discrepancies. The data in the almanac is likely to refer to high resolution flow features as is necessary for safe navigation. The nearest TotalTide tidal diamond [11] (digitised Admiralty chart data [7]) and the BERR Marine Atlas [9] indicate that these locations would not be suitable for large scale tidal current energy development. Similarly the depths in the regions identified in [9] are not appropriate for even relatively small scale tidal current energy development.

Another attempt to assess potential for firm aggregate generation is presented by [12] where it is proposed that a careful selection of sites can generate a steady output. Back-testing this analysis, the authors have found significant discrepancies. For instance, [12] purports to use data relating to tidal diamond SN040A and suggests that it has a spring peak velocity of 2.1 m/s. Interrogating the same tidal diamond using UKHO TotalTide software [11] indicates that SN040A only reaches a spring peak of 0.57 m/s – this would be inappropriate for tidal current energy development. Other discrepancies with reported tidal diamond data were also observed. Hence the outcomes of the analysis presented in [12] are considered to be flawed.

For the analysis presented herein, only first generation devices are considered, where first generation technology is defined as prototype devices already undergoing pre-commercial demonstration. These devices are typically deployable in water depths of 25 to 50 meters. An additional concern with operating in deeper water is the implication of being further from shore – this would suggest a substantial increase in project cost due to the need for extended undersea cabling. Other limitation imposed within this analysis is site selection based on regions where tidal current velocity is above 2.5 m/s at the time of spring peak. Such a stipulation is a simple means of ensuring that there is potential for economic development of the site due to the energy density that will be available for capture by tidal current devices.

B. Tidal Resource Phasing

The timing of local tidal conditions stems from the fundamental concept of tidal wave propagation. In the deep ocean, tides predominantly propagate as progressive waves. However, as they approach nearshore regions on the northern European continental shelf, their behaviour tend towards a standing wave characteristic where high and low water coincides with slack tide. Hence nearshore tidal velocities tend to peak when the gradient of the surface elevation is at a maximum. Figure 1 illustrates the current velocity and tidal heights for a random 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. Holyhead data is used here as being generically representative of large swathes of UK coastal waters.

What Figure 1 represents is the tidal wave characteristics throughout UK waters. Slight time lead/lag may be experienced at specific sites but the current will typically change direction at the time of highest gradient of local surface elevation. Figure 2 presents co-tidal lines around the UK that represent the time of high water – the propagation of the tidal wave is easily observed. Assuming that the relationship between tidal height and current is similar as indicated in Figure 1, then Figure 2 also broadly illustrates the relative timing of tidal current propagation.

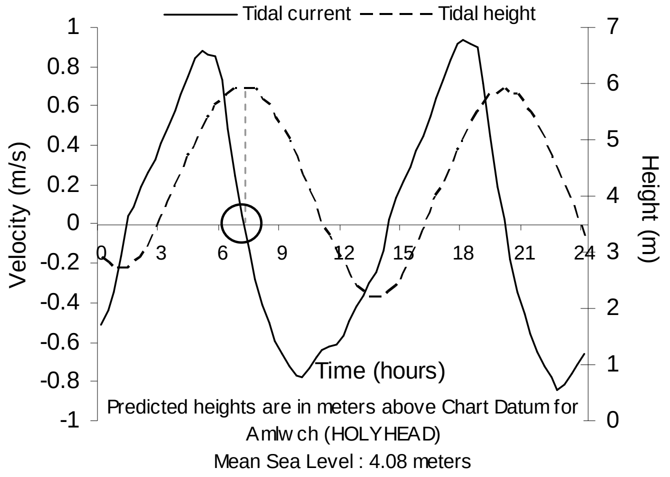


FIG. 1 Tidal currents (solid line) and height data (dotted line) at Holyhead indicating relative phasing of current and surface elevation (source data [10]).

The locations circled in Figure 2 have been identified by Black & Veatch [3] as being sites of major interest for tidal current energy extraction. Ideally a phase difference of 90° or 270°, relating to a time variation of three or nine hours would be optimal for tidal sites to formulate a combined output for firm power generation. However, the sites highlighted in Figure 2 experience high water at approximately the same time (some sites show a variation of up to an hour). If these identified sites are characterised by similar tidal height and current relationships as in Figure 1, then all these sites can be expected to experience ebb and flood in phase with each other.

Coincidence between two of the biggest sites can have a significant negative impact in terms of tidal current energy's contribution towards firm power. The Pentland Firth and Channel Islands have been identified as locations that embody about 70% of the technically extractable resource [13]. As these two sites are potentially in phase, the aggregated power output will also be in phase. From an electricity network perspective this is the worst case scenario, as the system will have to absorb surges of power over relatively short periods assuming large-scale tidal current energy development. This potentially in-phase characteristic of the most important sites is entirely coincidental and specific to the UK context due to its unique shape and size. The above theory relating potential 'locking' of tidal phase around the UK at major tidal current energy development sites will now be examined further.

III. METHODOLOGY FOR RESOURCE ASSESSMENT

Resource assessment analysis in this section follows the methodologies demonstrated in [14]. Only first generation sites are considered as mentioned earlier.

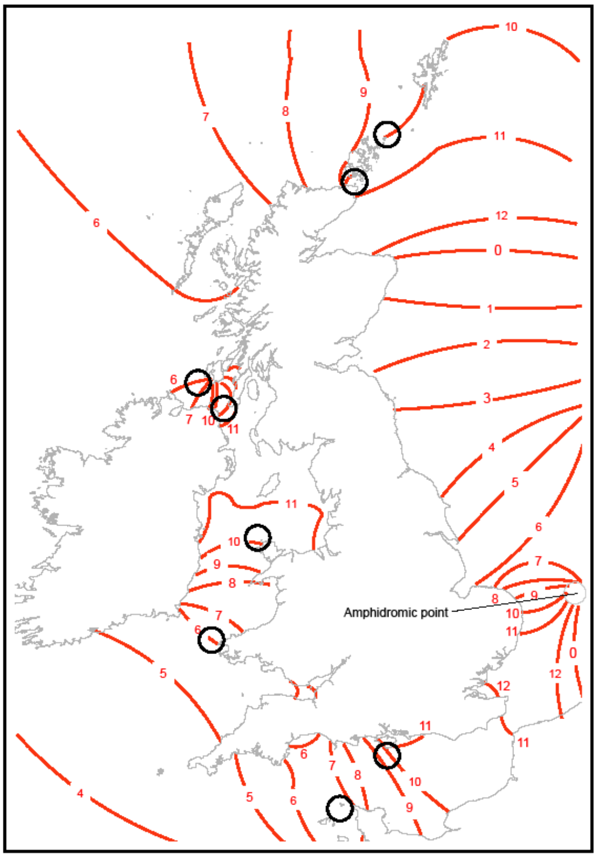


FIG. 2 Co-tidal lines for the coast of the UK. Areas marked in the circle show regions of interest for tidal current energy development.

A. Site Selection

A Geographical Information System (GIS) was used to interrogate the BERR Marine Atlas [10]. The Marine Atlas dataset provides mean spring and neap tide velocity values and water depths for the UK continental shelf (UKCS) at a spatial resolution of approximately 1.8 km^2. The Marine Atlas provides wide spatial coverage but lacks temporal resolution. Therefore the Atlas was used to identify cells meeting certain criteria: cells were only considered appropriate for economic development where the spring peak velocity exceeded 2.5 m/s. This criterion is based on the findings of [3] which suggests that sites that do not experience speak peak velocity of this magnitude are considered uneconomic.

A number of sites included in [3] are not identified in this study as they do not meet the criteria outlined for site selection for first generation development. Narrow channels such as Strangford Narrows are not included in this study as the Marine Atlas is unable to resolve these regions, although the location has been identified as an energetic site for economic development [15]. Hence, insufficient data exists in the public domain to effectively generate reliable time series. All the sites identified using the above criteria are listed in Table 1 with data synthesised from [10].

The UK Hydrographic Office software (TotalTide) [11] is used to determine time series spanning the calendar year 2009 by accessing tidal diamond current velocity data. A limitation is that the tidal diamonds do not necessarily coincide with the location of the specific cells. Therefore ‘pseudo diamonds’ have been created using interpolation techniques outlined in [16]. The authors have already utilised this approach for application to tidal diamond data as identified in [14] where more detail is provided.

TABLE I
LIST OF SITES IDENTIFIED FOR THIS STUDY

Site name	**No. of Cells**	**Region**	**Avg. Depth (m)**	**Avg. Spring Peak (m/s)**
Pentland Skerries	2	Scotland	35.50	3.60
S. Ronaldsay P. Firth	1	Scotland	39.00	3.19
S. Ronaldsay/ P. Skerries	5	Scotland	43.20	2.93
Duncansby Head	1	Scotland	36.00	3.25
Inner Sound	3	Scotland	28.67	3.27
Stroma P. Firth	7	Scotland	39.29	3.44
Westray Firth	2	Scotland	29.00	3.81
N. Ronaldsay Firth	1	Scotland	34.00	2.57
Islay North	7	Scotland	29.00	2.75
Islay Centre	12	Scotland	27.75	2.76
Islay South	8	Scotland	38.88	2.63
Sound of Islay	2	Scotland	50.00	2.95
Anglesey North	4	Wales	30.00	2.59
Anglesey South	1	Wales	31.00	2.60
Ramsey Island	3	Wales	35.00	2.66
Race of Alderney	19	England	31.68	3.38
Isle of Wight	2	England	27.50	2.76

The combination of applying the velocity magnitude from one source and temporal variation from another is sub-optimal. However given the lack of more effective and robust data coverage across the UK, this is deemed an appropriate method; combining two source datasets to provide appropriate spatial and temporal resolution.

More robust in-situ Acoustic Doppler Current Profiler (ADCP) data was obtained for sites where possible. For example in the Orkney region, data was purchased from EMEC for Westray Firth. The ADCP measurements were taken over a month long period in 2005 and did not coincide with the selected tidal diamond time series for the other locations. Therefore harmonic constituents were derived from the ADCP data using the NOAA least–squared analysis approach [17]. 23 principal constituents were obtained using this methodology and were then used to recreate the time series coincident in spatial and temporal resolution to the rest of the datasets (i.e. spanning 2009). Additional ADCP data for Sound of Islay was kindly provided by ScottishPower Renewables [18]. The final additional dataset covers the area around Anglesey. This data was accessed via the British Oceanographic Data Centre (BODC) [19]. Datasets spanning periods above 29 days were once again used in conjunction with harmonic analysis and reconstruction for the common time series via harmonic prediction. A detailed discussion of this analysis and the methodology applied can be found in [20].

IV. SCENARIO DEVELOPMENT AND ANALYSIS

The device characteristics in this study are based on the assumption of a generic horizontal axis device. Previous analysis [14] has utilised a rated velocity determined for each device by taking 70% of the spring peak velocity as suggested by [3]. However, during the analysis in [14] it was thought that the capacity factors of some of the sites that are otherwise known to be high-energy sites were lower than expected. In this context, capacity factor is defined as a ratio of actual power output over the nameplate capacity of the plant over a period of time.

Discussion with the authors of [3] highlighted that this method does not fully consider the site economics and they have since moved on to an in house cost optimisation model that chooses a device rated velocity accordingly. Unfortunately this cost model is not available in the public domain. Therefore, in order to strike the right balance between maximum power generation and economic capacity factor an alternative simplified method of assigning the rated velocity has been identified.

Figure 3 is a velocity exceedance curve for all the cells of interest identified in Table 1. All the sites experience spring peak velocity above 2.5 m/s, but examining the exceedance curves it becomes clear that for some sites this occurrence is very low. Therefore to choose a rated velocity based on the spring peak characteristics for a site could mean that the device would spend only a small proportion of its time operating at rated power and hence have a low capacity factor.

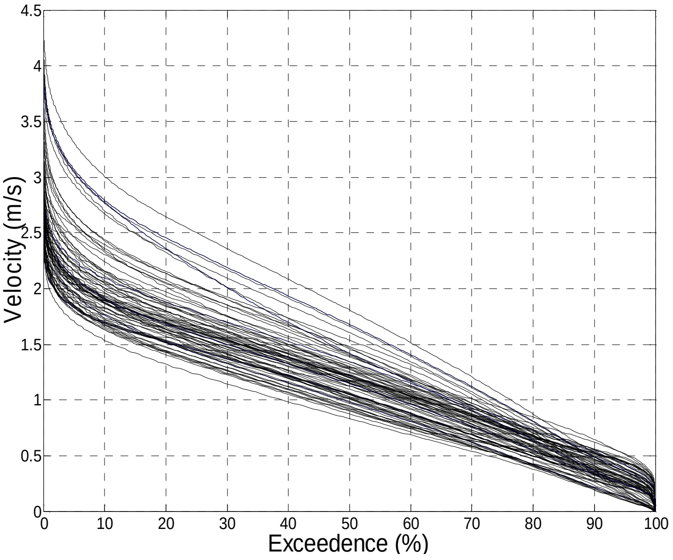


FIG. 3 Velocity exceedance curve from all the selected cells.

The interpretation of capacity factor statistics is complicated by the fact that increasing the rated power of a turbine increases the energy harvested but decreases the overall capacity factor. A compromise needs to be made between maximising generation at the expense of engineering the device to withstand the forces at higher rated velocity. It is considered uneconomic to engineer a device that will only be operating at its rated value for a small percentage of the time. Therefore, in order to reach an effective balance, the approach adopted herein specified the rated velocity as the velocity value associated with 10% velocity exceedance. The idea behind choosing the rated velocity this way is that using the 10th percentile value forces the device specified in each cell to operate at rated power for 10% of the operational time (assuming no downtime). Examining the exceedance curve in Figure 3 indicates that for roughly 20% of the time, the majority of sites experience velocity below 0.7 m/s. This equates to the cut in velocity expected of first-generation tidal current technologies; below 0.7 m/s the device will not generate. For the remaining 70% of the time the device will be generating but will be operating somewhere between cut-in and rated velocity.

Capacity factor is used here as a simplified indicator of how ‘economic’ a site is (assuming common turbine design). A low capacity factor indicates low economic performance. This method of using the exceedance plot therefore provides a sensible way of understanding the power generation distribution over tidal cycles and assists in identifying a rated velocity appropriate for each cell location that will lead to a capacity factor of around 30% (deemed a likely economic balance for first generation tidal devices in light of wind energy developmental experience).

Having established the rated velocity, the power generated from a device can be characterised using the equation:

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

where C_p is the device efficiency, assumed to be a constant value of 40% based on [21], the water density, ρ = 1025 kg/m^3, A (m^2) is the rotor swept area and v (m/s) is the depth-averaged current velocity. Two energy capture device models are utilised in the analysis to reflect the difference required for operating across a range of water depths: in cells of depth between 25 to 30 meters, a device diameter of 15 meters is used to provide appropriate surface and seabed clearance and avoid conflict with vessel navigation. In water depths of 30 meters or more (up to 50 meters) a device diameter of 20 meters is specified. Cut-in velocity in all cases is assumed to be 0.7 m/s. The device maintains rated power for velocities higher than rated velocity.

Figure 4 shows the capacity factor for each of the cells already identified in the analysis using the two different approaches for selecting the rated power. From the graph, it can be seen that the updated method of assessing the rated velocity maintains better consistency of capacity factor (around 30% as desired). Hence this new method is carried forward throughout the analysis. This standardised approach is being used to inform a national scale resource assessment. For project scale and site-specific design, much more detailed analysis would be necessary to obtain the desired device rating and other associated user-specified technical specifications of the device.

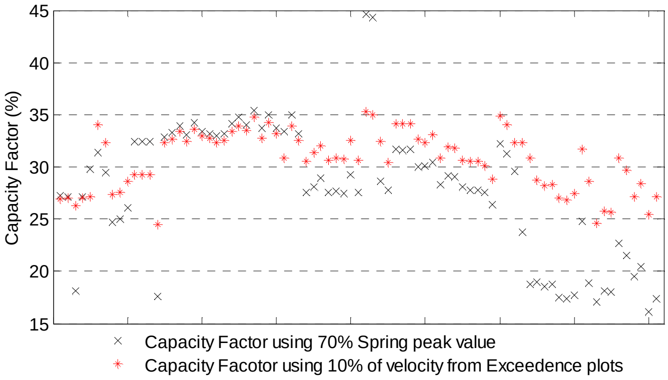


FIG. 4 Summary of Capacity Factor evaluation for all the cells of interest appropriate for first-generation device deployment

V. ACCEPTABLE POWER

The installed capacity for each cell is based on the rated velocity and device spacing as in [14]. Two scenarios are considered, the unconstrained scenario considers all the energy that can be extracted from the site without considering consequences of extraction on the local environment (known as the farm approach).

The second scenario considers constrained power generation, Technically Acceptable Power, (TAP) that can be extracted from the site without significantly impacting the environment based upon current understanding of the engineering potential of the technology.

While the analysis presented here lacks the very high temporal and spatial resolution data necessary to inform individual project development and detailed device design characteristics, 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 tidal hydrodynamic models incorporating the complex interaction of device operation alongside the evolving hydrodynamics.

A. *Total Power*

Aggregating the output from each of the sites, in the unconstrained scenario, there is potential for energy harvesting of 31.22 TWh/yr utilising a total installed capacity of 11.44 GW. Within this scenario there are a range of installed capacities across various locations, the smallest being Isle of Wight at 0.23 GW. The largest installed capacity of 3.4 GW is at Race of Alderney. The productivity of each site broadly reflects the installed capacity as the scenario developed achieved a good consistent capacity factor of 30.17% nationally.

B. *Technically Acceptable Power*

The national resource assessment presented in the preceding section has been conducted without considering the effect energy extraction may have on the underlying tidal system. The SIF approach utilised by [3] and [8] is now outdated and needs to be revised to update and reflect enhanced understanding of the resource. Numerical modelling in [22] suggests that tidal hydrodynamic mechanisms can be grouped into hydrodynamic mechanisms – tidal streaming, resonance and hydraulic current. These flow phenomena are necessary to generate tidal current flow conditions extreme enough to warrant considering the location appropriate for economic development. [22] identifies that there is a limit to the amount of energy that can be extracted before the energy extraction process starts affecting the local hydrodynamic mechanism. [23] has already identified that beyond a theoretical harvesting limit, any more energy extraction would in fact reduce the cumulative energy harvested as a result of reduction in kinetic energy flux.

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 as a result of a combination of mechanisms

Where a site needs to be constrained, the capacity factor of each cell is considered. Cells with the lowest capacity factor are sequentially removed until the restricted TAP generation conditions are met. 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. Details of the limitations for the sites considered in this scenario can be found in [14]. For the UK wide constrained scenario using the locations identified in this analysis, a TAP of 14.25 TWh/yr is extractable utilising an optimised total installed capacity of 5.4 GW. The limit imposed by the constraint reduces the total power output by more than half from the unconstrained to the constrained scenario. A breakdown of unconstrained and constrained generation for all the sites is listed in Table II.

Figure 5 shows the combined power output from all the sites for the constrained and the unconstrained scenario. Only the peak value far each 12 hour period is plotted so an envelope of the generation can be seen representative of the variation of the spring-neap cycle. What is not shown in the graph is the daily cycle with two peaks and two troughs in generation every 12.4 hour period. Hence, the power output varies every three hours, ranging from 12 GW to 0 GW in the unconstrained scenarios and a range of 6 GW to 0 GW in the constrained scenario during Spring tide conditions. Since the output from all the sites are predominantly in-phase, the potential for tidal current to provide significant firm generation is limited. Continuous output can be achieved for a number of days around Spring peak, however the continuous output is sustained as a small fraction of the peak generation potential. An informative way of summarising the data is using an exceedance curve as shown in Figure 6. Time over the year is presented as a percentage, it can be seen that for the constrained and unconstrained case, the power output drops to zero near 100% exceedance indicating that tidal current energy cannot generate firm power, at least not within this scenario considering the major tidal current energy locations around the UK coastline.

As the unconstrained scenario is likely to be deemed unacceptable due to the associated environmental impact (e.g. extracting 9.76 TWh/yr from Race of Alderney as developed

TABLE II
POWER GENERATION POTENTIAL FOR ALL THE SITES CONSTRAINED AND UNCONSTRAINED

Site name	Generation Unconstrained (TWh/yr)	Generation Constrained (TWh/yr)
Pentland Skerries	1.173	1.173
S. Ronaldsay P. Firth	0.287	0.287
S. Ronaldsay/ P. Skerries	1.085	1.085
Duncansby Head	0.410	0.410
Inner Sound	0.886	0.886
Stroma P. Firth	2.658	2.658
Westray Firth	2.877	0.746
N. Ronaldsay Firth	0.144	0.144
Islay North	2.580	0.493
Islay Centre	4.614	0.580
Islay South	2.099	1.173
Sound of Islay	0.104	0.104
Anglesey North	0.871	0.832
Anglesey South	0.288	0.288
Ramsey Island	0.726	0.625
Race of Alderney	9.766	2.115
Isle of Wight	0.664	0.664
Total (TWh/yr)	**31.23**	**14.26**

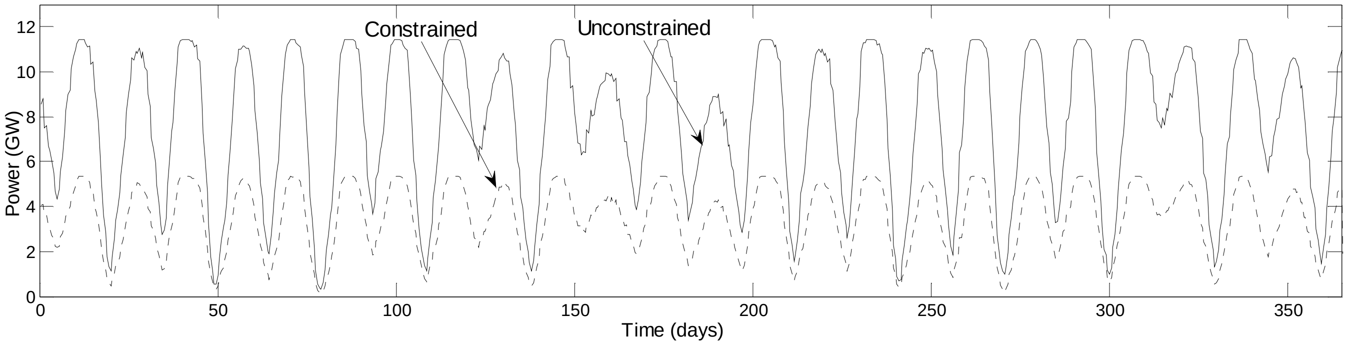


FIG. 5 Power output for 2009 in the constrained and unconstrained scenario.

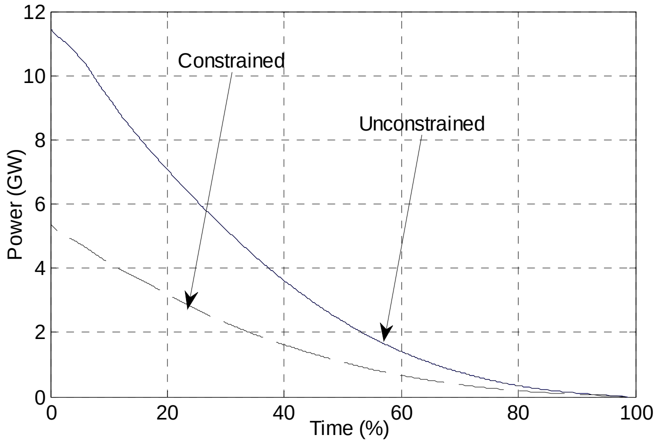


FIG. 6 Power exceedance for the constrained and unconstrained scenario.

for the unconstrained case would reduce the free stream velocity by 25% and alter tidal height variation by more than 35%), only the constrained scenario will be considered hereafter. The analysis indicates that for most of the identified key sites, the limit to how much energy can be extracted is determined by the TAP constraint limiting energy harvesting due to excessive environmental impact. In the constrained scenario presented here, most of the sites meet or exceed the TAP limitations imposed. The only exceptions are Pentland Firth (consisting of Pentland Skerries, S. Ronaldsay P. Firth, S.Ronaldsay/P.Skerries, Duncansby Head, Inner Sound and Stroma P. Firth), N. Ronaldsay Firth, Sound of Islay, Anglesey South and Isle of Wight. At these locations if suitable depth conditions are available, further development potential would be possible when second and third generation tidal energy devices become available. However at locations where the TAP constraint has already been reached, further development with newer generations of technology will be constrained by the existing first generation deployments.

VI. MATCHING TIDAL GENERATION AND DEMAND

Demand for electricity is characterised by variation at different time scales. Northern European countries, including the UK experience winter periods that are dominated by cold weather and short daylight periods. Peak electricity demand is therefore concentrated in the winter period with the increase in consumption of electricity associated with the need for domestic heat and lighting along with the usual underlying load. Electricity consumption patterns are well understood and the extent of the variability can be estimated with a high degree of certainty. Detailed weather forecasting systems can help prepare for cold spells and provide early warning for the system to secure more reserve. For this study, half hourly demand data is obtained from National Grid, the Transmission System Operator in Great Britain. IO14_DEM demand values are used for this analysis, which takes into account station load but no pump storage activity [24].

A. *Tidal Variability*

The addition of renewable generation to the existing electricity network will further complicate the operation of the system, particularly during periods of high demand expectation. Although the inherent predictability of tidal generation is beneficial, there is no obvious casual relationship to expect that strong periods of generation will coincide with high demand. Figure 7 shows tidal generation fluctuation potential simulated every half hour using the constrained development scenario data for 2009 already detailed. This graph presents the aggregated output of the complete tidal generation scenario. Extreme fluctuations of -2 to +2 GW are observed. Considering the total installed tidal capacity under the constrained scenario is 5.4 GW, the maximum indicated half-hourly swing is a significant proportion of installed capacity. However smaller swings are generally the norm. The modular approach to tidal current generation installation ensures that intermittency is avoided. Key distinction to be made here is that near–zero output from an entire fleet of conventional generation units does not occur, while for tidal generation the output is constantly variable dependent upon the forcing of the resource. However an unexpected shutdown is highly unlikely.

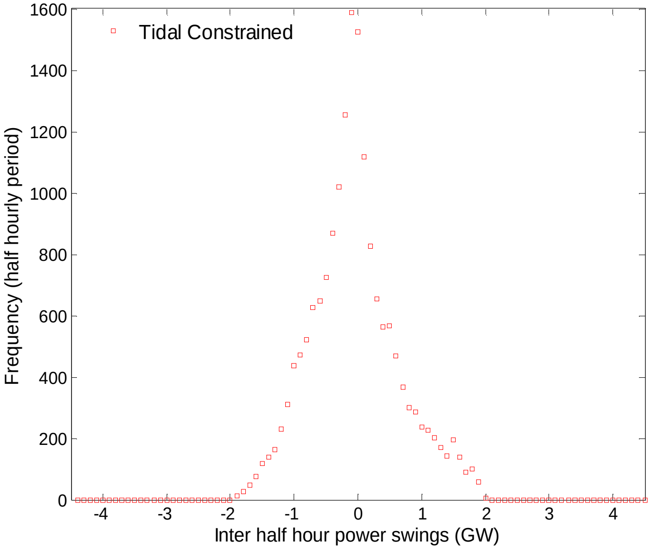


FIG. 7 Inter half hourly power output fluctuations from constrained scenario.

An advantage tidal generation has over wind and wave power is the absence of extremities of operation. For example, a standard wind turbine may be rated at 12 m/s and cut out at 25 m/s. This is necessary as gust speeds of 50 m/s are not uncommon across the UK [25]. A cut-out velocity or survival strategy is therefore necessary for these technologies as sites can experience extreme gust speeds (wind) or wave heights (wave) that are far beyond the operating region of the energy extraction device. For tidal current this is not a major issue as the operating conditions are not that far removed from the extreme conditions as shown in Figure 3; most tidal devices are therefore not designed to cut out and can operate at rated power during extremes by pitching the blades to alter the angle of attack and hence shed load.

B. *Demand Variability*

The UK electricity system has an average demand of 36.4 GW, with a standard deviation of 7.7 GW. In 2009 electricity demand peaked at 59.1 GW (6th January, 17:30) and is expected to grow at a 1.2% growth rate per year [26]. Figure 8 shows the mean demand for each half hour period in a standard day determined from the complete 2009 data record. Although the average demand for the entire year is 36.4 GW, it can fall as low as 20.15 GW (2nd August), 34% of the peak value.

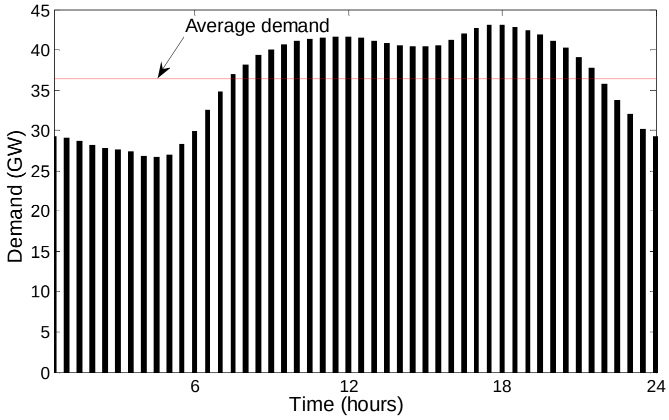


FIG. 8 Mean demand for each half hour period in the day (2009).

The system is most vulnerable at times of peak demand, so any generation that contributes towards meeting peak demand has a positive influence and reduces the burden on the network. Figure 9 shows two curves, the UK demand profile spanning over the week when peak demand occurred, from the 5th to 11th of January with peak demand occurring on the 6th. The second curve shows net demand with tidal generation imposed as a negative load (demand – tidal generation) utilising 5.4 GW installed capacity (the constrained scenario). The contribution of tidal current energy to the system would only reduce the system peak on the 6th by 0.5 GW. Two days later, on the 8th, maximum demand for the day was 57.3 GW(12th highest for the year). Under the envisaged constrained scenario, this demand would be reduced by 3 GW with the inclusion of tidal in the system. The biggest reduction that can be obtained with the inclusion of tidal in the system will be in the order of 5 GW, which occurs around midnight on the 11th; in this instance, peak generation does not coincide with a significant system demand peak. Examining Figure 8 indicates the importance of timing of demand and tidal generation cycles.

A key question to be addressed is what consequences will the addition of variable generation from tidal current have on the network and the system operator with increasing levels of penetration? In the constrained case, tidal current plays a small role meeting 3.8% of existing UK demand. A method of assessing the variability for the whole year is presented in Figure 10. The two curves show demand with the inclusion of tidal in the system. The reduction in the load duration curve with tidal in the system is an even spread indicating a potential correlation, however the tidal resource is independent of demand due to the lack of any causal relationship.

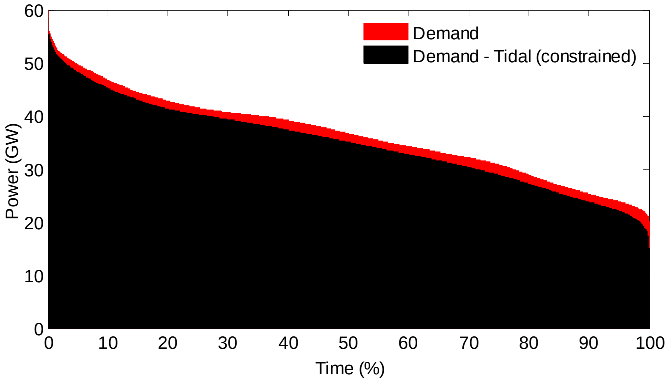


FIG. 10 The half hourly demands and tidal generation presented as Load Duration curve.

Despite its usefulness the load duration curve does not show how demand and generation are responding with respect to time. Therefore, matching of demand and supply is shown in Figure 11. Each column in the bivariate histogram presents the amount of half-hours for which a particular combination of generation is presented as a percentage of the total installed capacity and demand is presented as a percentage of peak demand. The combined frequency of all the columns should add up to 17520 half-hours (8760 hours). The worst-case as defined by [27] is identified as the period when demand is ≥90% and tidal generation is ≤10%, the right-most column in

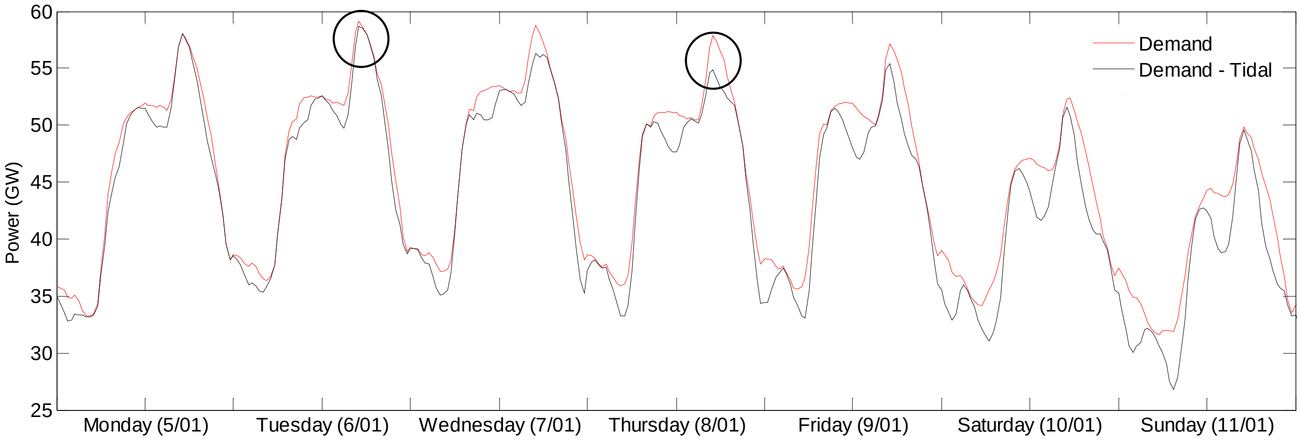
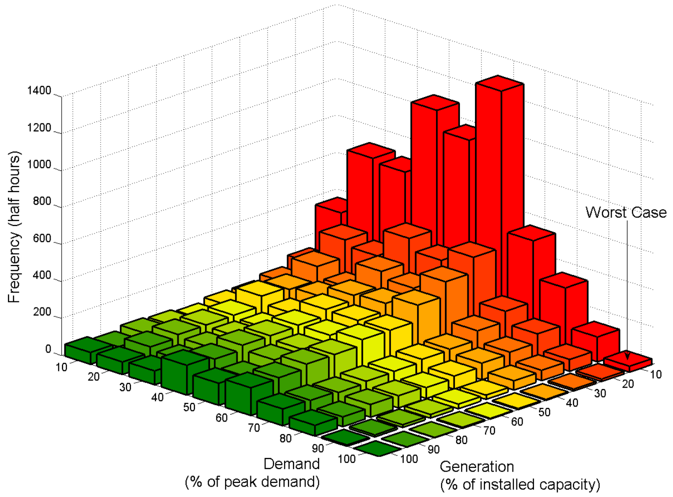


FIG. 9 Demand change with tidal generation in the system.



Demand (% of peak demand): 10	20	30	40	50	60	70	80	90	100	Generation (% of installed capacity)
365	714	695	1085	979	1300	545	345	135	32	10
140	323	292	442	379	451	214	147	64	13	20
88	230	171	314	279	369	159	99	56	10	30
63	156	172	235	247	293	110	90	50	5	40
63	171	131	210	206	208	106	71	23	6	50
43	118	104	175	176	208	92	59	25	4	60
57	116	108	169	151	178	89	66	20	6	70
65	115	101	168	144	177	79	69	15	2	80
44	99	82	144	104	154	87	53	11	1	90
64	68	75	161	119	150	91	58	7	0	100

FIG. 11 Coincident half hourly histogram and table.

the histogram. This corner is significant as it defines the time when generation is low and demand is high. The histogram highlights that the largest match occurs when generation is ≤10% and demand is between 60-70%. According to [27] a mix of different resources produces a more even distribution and reduces the number of worst-case hours.

The effect of this variability on the system can be examined by considering the net demand that generation sources other than tidal must provide. Figure 12 shows the frequency of inter-half hourly demand changes before and after tidal is introduced. The impact of inclusion of tidal to the overall system is rather small although there are few occasions with near zero (0 GW) residual demand change. The Y-axis uses a log scale to highlight excursions occurring at the tails of the distribution; an important characteristic of this graph from the perspective of network management. Table III summarises the key changes and highlights that the largest swings are increased and become more frequent with the addition of tidal to the system This outcome obviously relates back to the initial findings of the relative phasing of UK tidal current energy resources – if the resource was more out of phase, the variability felt by the system would be reduced as power generation would vary more smoothly with potential for continuous generation.

Capacity value is another important concept that can help understand the potential contribution made by tidal current energy in supporting demand. The commonly used Effective Load Carrying Capability (ELCC) can be defined as the additional demand which the generation can support without increasing the system risk. The empirical distribution across all days of available tidal capacities at 1700 hours (the time of day at which extreme high demands typically occur in GB) may be used as the distribution of available capacity at time of annual peak. This may be used in an annual peak loss-of-load-probability (LOLP) based generation adequacy risk calculation [28]. LOLP is the probability that generation will be insufficient to meet demand at a particular time. A preliminary calculation has been performed using a Gaussian distribution of available conventional capacity with mean 65 GW and standard deviation 2 GW; this is representative of a sustainable long-term level of adequacy risk. The ELCC is then 1.15 GW (10.05% of the unconstrained scenario installed capacity) and 0.82 GW (15.19% of the constrained scenario installed capacity). The small difference between the two cases arises because, in the unconstrained case the possibility of very low percentage output is more significant than the substantial mean of 3.39 GW (the mean in the constrained case is 1.55 GW). A more detailed study of adequacy risk will be presented in future.

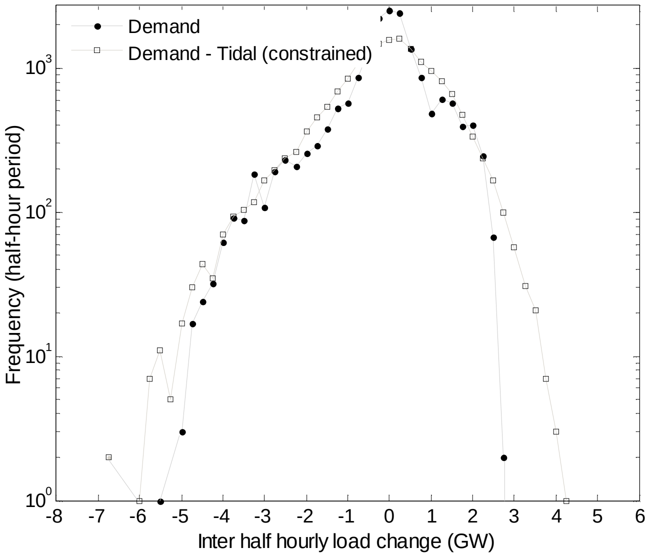


FIG. 12 Inter half hourly demand change with and without tidal current in the system.

TABLE III

KEY DATA FOR HALF HOURLY POWER EXCURSIONS WITH THE INCLUSION OF TIDAL IN THE SYSTEM.

	Tidal Penetration	
	None	**Constrained**
Maximum decrease: GW	5.47	6.65
Number of decreases of 5.25 GW and above	1	21
Maximum increase: GW	2.77	4.36
Number of increases of 2.5 GW and above	2	220

VII. CONCLUSION

This work presents an improved method of assessing the total UK tidal current resource by combining multiple datasets including Marine Atlas, TotalTide tidal diamonds and measured tidal current information where available. First generation device installation is considered in regions where spring peak velocity exceeds 2.5 m/s in water depths of 25 to 50 meters. Based on an economic assessment of the capacity factors for each of the sites considered it is concluded that 14.25 TWh/yr can be extracted without significantly adversely affecting the environment or the resource itself. A new approach to identifying the device rated velocity is introduced to help achieve an overall economic capacity factor.

The nature of tidal wave propagation around the UK coast indicates that all the high energy sites are largely in-phase and that tidal current cannot be seen as ‘base load’ generation. However, generation from this scenario can meet 3.8% of the present UK demand. Two of the largest sites, Pentland Firth and Race of Alderney together contribute 60.4% of the total generation.

The impact of aggregated tidal current generation on the system is considered. Inclusion of tidal in the system increases the number of extreme short-term changes in net demand but they do not appear to be severe and seem manageable as suggested by National Grid [26]. The capacity value of the preferred scenario is 15.19% with an ELCC of 0.82 GW.

The analysis presented here makes specific assumptions about how much resource can be extracted and what type of devices will be used, their efficiency, operating conditions etc. Varying any of these parameters can significantly vary the final output. The intention has been to develop scenarios representative of realistic large-scale uptake of tidal current energy in the UK using conservative assumptions of device characteristics based upon existing prototype devices.

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