Impact of Tidal Stream Site Interconnectivity on Resource Assessments

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***Abstract*—To reduce the uncertainty in resource assessments, the physical presence of the turbine arrays must be accounted for. Using a 3-D Regional Ocean Model with tidal stream energy extraction, we show that in regions where tidal stream energy sites have been leased in close proximity to each other there is some degree of inter-connectivity. In this paper a methodology is presented to identify the levels of connectivity between adjacent tidal energy developments to aid resource assessments and marine spatial planning.**

***Index Terms*—Tidal, Energy, Extraction, Hydrodynamics, Environmental Impact**

I. INTRODUCTION

Tidal energy is a growing area in both industry and research, from exploitation of high tidal ranges (in the form of barrage and lagoon technologies [1], [2]) to fast tidal streams, using arrays of tidal turbines [3]–[5]. Globally, there are a large number of sites that have been identified as suitable for tidal stream energy extraction, including locations around north-west Spain [5], the Bay of Fundy, Canada [6], the Alas Strait, Indonesia [7] and the Pentland Firth, UK [8]. The energetic UK shelf seas, with shallow waters, well mixed tidal regimes, many coastal ports and grid connections, are home to the Pentland Firth with its world leading tidal stream resource [9] and hence, are a prime location for the development of tidal stream energy [10].

First generation tidal stream sites are located where tidal currents exceed 2.5m/s [11], a result of coastal topography and bathymetry constraining the propagating tidal wave. With this definition, it has been determined that first generation tidal energy sites only cover 0.5% of the entire north-west European shelf seas [12]. For this reason, in some parts of the UK shelf, a number of sites for tidal stream development have been leased within a relatively confined area, for example, in Wales: the Skerries, Holyhead Deep and West Anglesey Development Zones are located within 20km of each other [13], in the Pentland Firth, Scotland: four sites have been identified for tidal stream energy development, these sites lie within $10-20$km of their neighbouring sites [14]. Previous research by Neill et al., [15], found that wake effects from a 300MW tidal energy array could be felt over a distance of 100km^2. This research didn't include the turbulent effects of turbines, which would undoubtedly reduce the wake effects of the array [16]. Nevertheless, tidal stream device installations will interact with the unconstrained tidal resource [17], and in some cases, the resource of neighbouring sites [18].

Using a $3-$D modeling technique, Fairley et al. [14], investigated the environmental impacts of multiple tidal stream sites on sediment dynamics, and determined that the cumulative impact of the four planned arrays in the Pentland Firth is equal to the sum of the impacts of each individual array. However, the authors acknowledge that larger scale developments could lead to increasingly complex neighbouring interactions. Hence, whilst accounting for inter-site interactions is important for resource assessments, it may not be necessary for all stages of environmental impact analysis, except to acknowledge that neighbouring sites will add to any impacts seen.

The analysis presented here aims to quantify the site interactions within the Pentland Firth using a $3-$D ROMS (Regional Ocean Modelling System) model of the Orkney region at a high resolution ($\sim$100m) with the inclusion of $3-$D tidal stream arrays. This area has four tidal stream arrays in development (Table I, Fig 1(inset)) and is described in more detail in Section II. Previously, academic research has focussed on the unconstrained resource, particularly within the Inner Sound [8], [9], [19], [20] and the environmental impact of complex energy extraction scenarios [14], [21], [22]. However, to obtain accurate resource estimations, it is vital to understand how multipule tidal stream arrays interact with the available tidal stream resource.

II. STUDY AREA: PENTLAND FIRTH

The Pentland Firth (PF) is a narrow channel ($\sim$10km $\times$ 20km) which separates the Scottish mainland from the southern group of Orkney Islands and links the North Atlantic with the North Sea. The tides here are predominantly semi-diurnal however, the amplitude of the vertical tide at either end of the channel only differs by 30cm ($\sim$1m at Wick, 1.35m at Scrabster); It is the combination of topographical and bathymetric constrictions and the 2 hour phase difference between the North Atlantic and the North Sea which results in peak spring currents in excess of 5m/s [14], [20].

There is a high level of uncertainty between resource assessments for the Pentland Firth, with predicted values lying between 1 and 18 GW [8], nevertheless it is arguably one of the most promising sites in the world for tidal stream development [24]. The proof of this lies in the four leased tidal stream sites with a combined leased capacity, at the time of

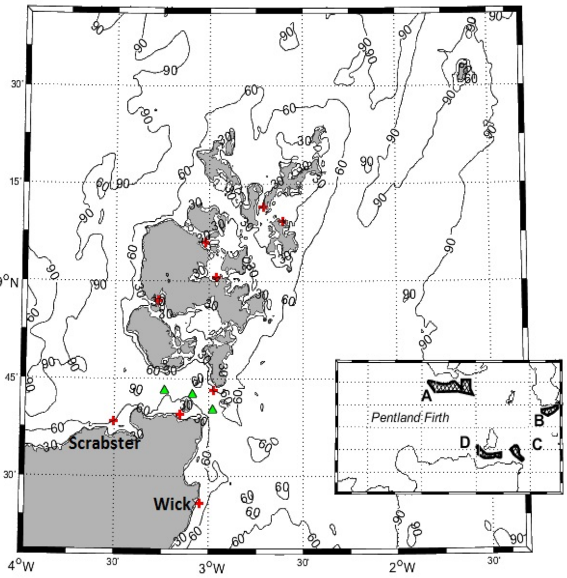

Fig. 1. Orkney model domain showing ADCP locations (green triangles) and tide gauge locations (red crosses). Inset is the Pentland Firth with polygons displaying the regions allocated by the crown estate for tidal energy development. Bathymetry contours show spatial distribution of water depth over the model grid. From Goward Brown et al. [23]

writing, of 800MW (See: http://www.gov.scot/Topics/marine/Licensing/marine/scoping/, Table I) [23].

TABLE I
PENTLAND FIRTH: LEASED TIDAL STREAM SITES

Column1	Brims	Brough Ness	Ness of Duncansby	Inner Sound
Identifiers				
Map Reference	A	B	C	D
Developer	Open Hydro	Atlantis	Atlantis	Atlantis (MeyGen)
Location				
Latitude	58.76	58.65	58.66	58.72
Longitude	-3.17	-2.93	-3.04	-3.13
Parameters				
Rated Velocity (m/s)	2.5	2.5	2.5	3
Total Capacity (MW)	200	100	100	400
Device Rating (MW)	1	1-1.5	1-1.5	1-1.5
Diameter (m)	20	18-20	18-20	18-20

The Inner Sound (IS; Site D), located between the Isle of Stroma and the Scottish mainland, is currently under development by Atlantis Resources and has the largest leased capacity of the four at 400MW. North and east of the IS site are sites B and C, respectively. Brough Ness (BN; Site B) and Ness of Duncansby (ND; Site C), are also leased by Atlantis and each have a leased capacity of 100MW. West of site B is Brims (BM; Site A) which has a leased capacity of 200MW and is leased by OpenHydro (Figure 1).

III. METHODS

This research uses the Regional Ocean Modeling System (ROMS; www.myroms.org), to investigate the resource of the Pentland Firth. ROMS is an open-source model which undergoes continuous development by its user group - led by Rutgers University and the University of California, LA. It solves the hydrostatic Navier-Stokes equations using a Boussinesq approximation on a structured horizontal grid with terrain following sigma layers [25]. ROMS includes a variety of sub-models including four different turbulence closure schemes for selection by the user, and can therefore be applied to numerous applications from analytical studies [26] to coastal and regional domains [27], [28]. ROMS has been used for a number of tidal resource characterisations from regional assessments [29] to site scale assessments [30]. Tidal energy extraction is paramaterised as a mid-depth force term within the ROMS source code, using an adaptation of the method devised by Roc et al., [16], described in full detail in Section 2.2 of Goward Brown et al., [23].

A. Nested Model: Pentland Firth

The Pentland Firth model, with a spatial resolution of ∼100m, was one-way nested within a wider model of Orkney with a spatial resolution of 500m). Bathymetry was provided from the GEBCO and Digimap datasets, available at 900m and 30m respectively (gridded to mean sea level (MSL) using MATLAB). The boundaries of the outer Orkney model were forced by the FES2012 dataset, available at 1/16.

TABLE II
OBSERVED AND MODELLED AMPLITUDES (H, IN METERS) AND PHASES (g, IN DEGREES) OF THE M_2 AND S_2 TIDAL CONSTITUENTS FOR THE 9 TIDE GAUGES REPRESENTED BY RED CROSSES IN FIGURE 1. THE AMPLITUDES AND PHASES OF THE INDIVIDUAL CONSTITUENTS ARE DERIVED USING 'T_TIDE' [31] FROM WHICH THE RMSE IS CALCULATED. THE PRINCIPLE TIDE GAUGE IS IDENTIFIED IN BOLD FONT.

Tide Gauge Validation for 500m Orkney Model								
Station	Observed				Modelled			
	M2		**S2**		**M2**		**S2**	
	H (m)	g(°)	H (m)	g(°)	H (m)	g(°)	H (m)	g(°)
Wick	**1.02**	**322**	**0.35**	**0**	**1.02**	**312.31**	**0.37**	**353.51**
Burwick	0.88	287	0.35	322	0.81	289.39	0.30	326.77
Gills Bay	1.12	268	0.41	300	1.09	263.14	0.41	297.77
Scrabster	1.35	247	0.51	280	1.26	241.25	0.49	276.01
Kirkwall	0.84	301	0.29	339	0.91	278.26	0.34	315.64
Loth	0.74	300	0.26	336	0.85	279.67	0.32	316.96
Kettletoft Pier	0.92	312	0.33	347	0.85	301.24	0.32	339.69
Tingwall	0.86	276	0.31	310	0.90	271.16	0.33	308.22
Stromness	0.89	270	0.35	303	0.87	252.43	0.34	288.56
	RMSE				**0.07**	**13.06**	**0.03**	**11.83**
	SI(%)				**6.39**	**12.13**	**9.11**	**8.24**
Tide Gauge Validation for 100m Pentland Firth Model								
Station	Observed				Modelled			
	M2		**S2**		**M2**		**S2**	
	h (m)	g	h (m)	g	h (m)	g	h (m)	g
Wick	**1.02**	**322**	**0.35**	**0**	**1.01**	**314**	**0.38**	**0**
Burwick	0.88	287	0.35	322	0.77	287	0.29	322
Gills Bay	1.12	268	0.41	300	1.00	268	0.38	300
Scrabster	1.35	247	0.51	280	1.01	247	0.38	280
Kirkwall	0.84	301	0.29	339	0.77	301	0.27	339
Loth	0.74	300	0.26	336	0.30	310	0.09	345
Kettletoft Pier	0.92	312	0.33	347	0.53	300	0.18	336
Tingwall	0.86	276	0.31	310	0.80	276	0.29	310
Stromness	0.89	270	0.35	303	0.70	270	0.26	303
	RMSE				**0.24**	**14**	**0.09**	**13**
	SI (%)				**26**	**13**	**27**	**9**

Modelled elevations and velocities were validated against nine tide gauge stations (Table II) and three ADCP moorings within the model domain (Figures 1 & 2).

B. Tidal Energy Extraction Model

Tidal stream energy extraction is applied as mid-depth force term, within the regions leased by the Crown Estate for tidal stream development within the Pentland Firth. Each of the tidal

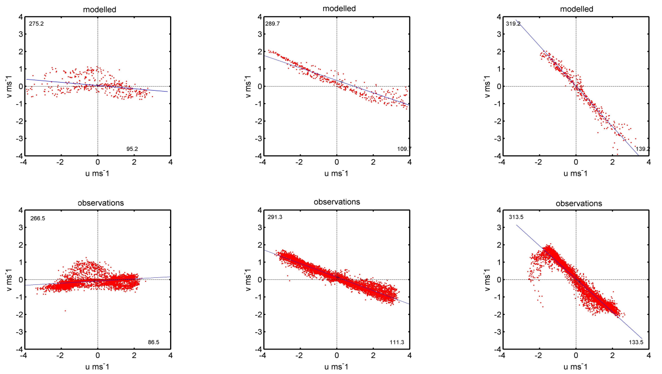

Fig. 2. Pentland Firth model current validation: Tidal ellipses for the observed and modelled tidal currents at each ADCP location. The RMSE was 0.13m/s and 0.05m/s for M_2 and S_2 respectively. Both had a RMSE for phase of 11°.

stream sites was parametrised by the information available to the authors at the time of conducting this research (Table III). The diameter of 10m was chosen to reflect $1/3$ of the average site water depth (30m), to simulate realistic blockage effects and prevent surface and bottom boundary layer interactions. The method used is an adaptation of that described by Roc et al., [16]. Each array was designed to be sited at the mid-depth of the water column, with the force spread evenly over the area covered by the diameter of the device. The energy extraction term is applied to each grid cell within the leased array area which is calculated by taking into account the leased capacity of the array and dividing it by the total area covered by the turbines.

The model was run without any turbines for the control run and validation as described in section III-A above. Then the model was run four times for two daily tidal cycles with tidal energy extraction switched on and off at each of the four sites successively (See polygons; Figure 3). The results presented show the impact of tidal stream energy extraction at peak flood and peak ebb tides.

TABLE III
MODELLED TURBINE PARAMETERS

Site	Brims	Brough Ness	Ness of Duncansby	Inner Sound
	A	B	C	D
Number of turbines in array	200	100	100	400
Turbine Diameter	10	10	10	10
Thrust Coefficient	0.87	0.87	0.87	0.88
Power Coefficient	0.59	0.59	0.59	0.59

IV. RESULTS AND DISCUSSION

Initially, the control run was used to identify the spring peak flood tide and spring peak ebb tide. To determine the extent to which neighbouring tidal stream energy sites interact with each other, the difference in current magnitude (m/s) between extraction and control scenarios was calculated by subtracting the peak spring flood (Figure 3) and peak spring ebb (Figure 4) tidal stream energy extraction runs from the control (baseline resource) peak spring flood/ebb tide.

Thus, the results shown in Figures 3 & 4 display the maximum levels of site interconnectivity at each stage of the tide, as opposed to the cumulative zone of influence calculated over the entire model run presented by Haverson et al., for the Irish Sea [18].

In addition, a maximum connectivity matrix (Figure 5) is presented to summarise the magnitude of interaction between leased sites. On the X-axis is the extraction scenario and on the Y-axis is a percentage of change at each of the neighbouring sites. For example, when the Inner Sound site (site D) is extracting the leased capacity (400MW), tidal current magnitude will be reduced at the Brims and Ness of Duncansby sites by more than 10%. Brough Ness (site B) however, will see an increase of $\sim$8%.

To calculate the maximum connectivity the precentage difference of each of the model results presented in Figures 3 and 4 were calculated and combined to create a matrix of peak percentage difference values. The percentage difference values across each site were summed and divided by the number of grid cells in each site to give the mean percentage difference in resource. This was repeated for each of the four runs and the results presented in Figure 5.

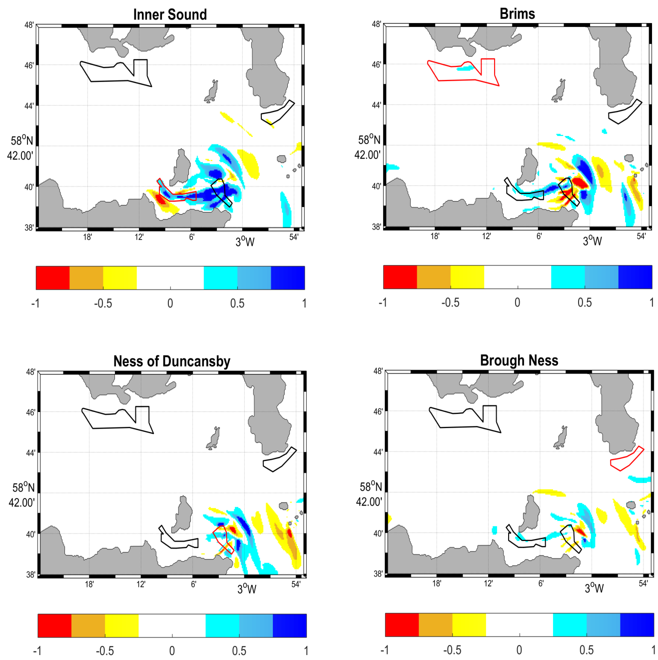

Fig. 3. The impact of individual tidal arrays on current magnitude at neighbouring sites during the peak flood (west to east) tide. Blue colours show a reduction (%) in current speed from the control, red colours show an increase.

During the flood tide (Figure 3), there are few site interactions. The largest change in resource occurs around Duncansby head - site C - in all extraction scenarios. A more complex picture emerges on the ebb tide however (Figure 4). Extraction at sites A, C and D all lead to an increase in resource at Brough Ness (site B). Extraction at site D has the smallest impact on site A which is downstream of all the leased sites and sees a decrease in resource on the ebb tide in all scenarios.

From Figure 5, it can be summised that the resource at

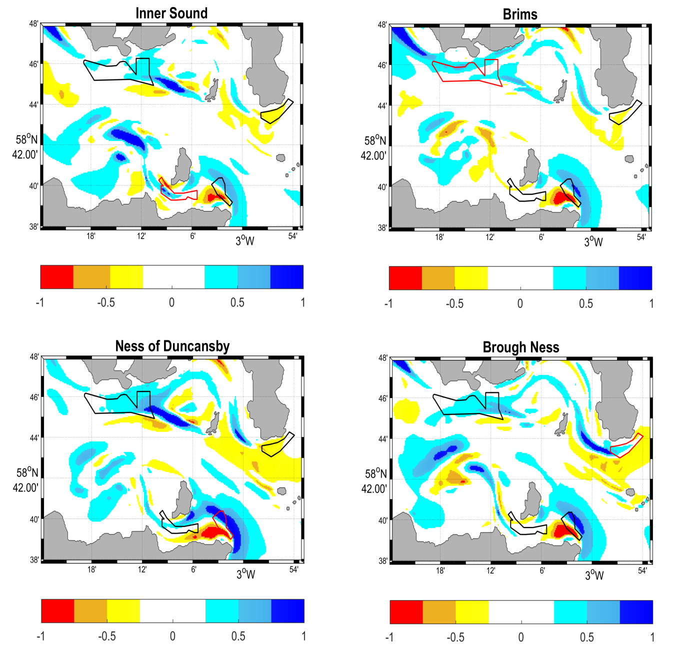

Fig. 4. The impact of individual tidal arrays on current magnitude at neighbouring sites during the peak ebb (east to west) tide. Blue colours show a reduction (%) in current speed from the control, red colours show an increase.

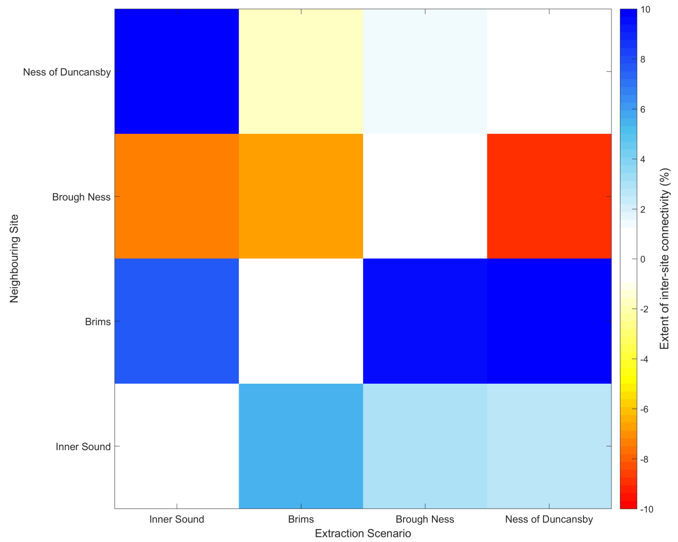

Fig. 5. Maximum change to velocity magnitude (m/s) across each leased area as a result of energy extraction. Red suggests an increase in velocity and blue colours suggest a reduction in available resource

Brims will not benefit from extraction at any of its neighboring sites, however we know from Figure 3 that the flood tide resource will not be influenced. Similarly the resource at Brough Ness will not be altered by its neighbouring tidal stream sites on the flood tide, but in contrast to the Brims site, it will see an increase in its available resource on the ebb tide with extraction at Ness of Duncansby having the largest influence. The resource of the Inner Sound will be reduced on both stages of the tide by it's neighbouring sites with extraction at Brims having the greatest impact on the available resource with a 6% reduction in current magnitude across the site. The available resource at the Ness of Duncansby site, which sits directly downstream of the Inner Sound array, is unsurprisingly greatly reduced by tidal stream extraction within the Inner Sound during flood tides (Figure 3), but also sees a marginal increase in resource as a result of extraction at Brims and a similar magnitude decrease in resource as a result of extraction at Brough Ness.

V. Summary and Conclusions

Asymmetry and misalignment of tidal flow will have a large role in the spatial variability of the resource [32], [33], and the interconnectivity between sites is largely up to the fate of geographical location. However, using this methodology it is possible to infer the inter-connectivity between sites and engineer the best strategy for inter-connected site development. For example it may work out more profitable for the turbines at Brims to only operate during flood tides, to determine this the next step of analysis would be to investigate the impact of inter-connectivity on annual power yields since, due to the cubic relationship between power and resource, an uncertainty in the resource assessment of 10% can translate into a 50% uncertainty in the power potential at the site.

Acknowledgement

This is a preliminary study part of a wider research project supported by the SEACAMSII project, which is part-funded by the European Union's Convergence European Regional Development Fund, administered by the Welsh Government and a HPC Wales (now SuperComputing Wales) studentship funded by Fujitsu (2012-2016). ADCP data was kindly provided by the University of Highlands and Islands for model validation.

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