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Close-proximity tidal phasing for ‘firm’ electricity supply

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Highlights
- There is substantial sub-hourly tidal phasing within Pentland Firth and Orkney Waters
- 5% firm capacity only requires 34 MWh of storage per 100 MW of installed generation
- Firm capacity from phasing is limited to ~10% due to the spring/neap cycle

Abstract
Tidal generation is highly predictable and thus an attractive renewable energy source to develop; however, output varies over short time scales. This can be mitigated through phasing of output between sites, as different locations have different timings of output. Phasing can be increased by geographical diversity; unfortunately areas with tidal resources suitable for generation are few, so the opportunity for this is limited.

The Pentland Firth and Orkney Waters (PFOW) contain the World’s first leased sites for tidal stream generation. This paper focuses on close-proximity phasing between these leases and their ability to provide firm power, i.e. a guaranteed level of output. Results show phasing across individual leases and over the PFOW; combined output from all the lease areas exceeds 1% of nameplate capacity for 97.9% of the study, compared to 83.4%-94.5% for the individual leases. Relatively little storage makes significant levels of firm capacity obtainable; 255 MWh of storage means electricity demand of the two counties the developments fall within would be met ~94% of the time.
The methodology identifies lease suitability, high energy locations within leases, and quantifies the complementary characteristics of different tidal sites. This could inform strategic development of tidal sites, to maximise firm capacity.

**Keywords**

Tidal energy, tidal phasing, firm capacity, electricity supply

### 1. Introduction

Renewable generation has a large potential to displace the production of energy from fossil fuels, thereby helping to mitigate climate change [1]. However, as the share of renewables increases in an electricity system the issue of security of supply becomes increasingly prevalent due to the inherent variability of most renewable electricity sources [1]. Variability is an important issue in Scotland, where the government has set a target of generating the equivalent of 100% of Scotland’s electricity demand from renewables by 2020 [2]. There is political will that a portion of this target will be met by tidal stream energy generation for three reasons: one, Scotland has an estimated tidal resource equating to 25% of the total available across Europe [3]; two, tidal power differs from the other potential sources in Scotland’s future renewable portfolio (wind, hydro, solar and wave) in that it is independent of weather and predictable over decadal timescales; and three to support economic growth with first mover advantage, through supply chain development, employment, and export potential [4]. This provides electricity network operators with a high degree of certainty as to what the tidal power input to the grid will be, making a unit of electricity generated by a tidal turbine a more ‘valuable’ commodity than a unit of electricity generated from wind turbines [5].

Tidal output does, however, vary. Two tidal cycles have a particularly noticeable impact on output: The flood/ebb cycle (approximately twice daily) and the spring/neap cycle (approximately 14.8 days period) e.g. Sinden [6] quantifies this for the UK, showing mean tidal output can be 70% of installed capacity during a spring phase and as little as 6% during neaps. Variation of electricity supplies arising from the flood/ebb cycle could be reduced by development around the UK, exploiting phased tides with slack water occurring at different times at different locations. Several studies explore the potential of this as a means of providing ‘firm capacity’ output [6–10]; i.e. the ability to provide a guaranteed level of output at all
times. It has been suggested that intermittency of supply may be mitigated through wide geographic distribution of tidal energy developments. However as the tidal resource is not evenly spread around the UK (Figure 1) it has been suggested [7] that under-exploiting high-capacity sites may be required in order to increase the benefit of phasing.

**Figure 1.** Potential areas for tidal stream development around the UK. Tidal data is from ABPmer (2008), background map is Crown copyright ©.

The Pentland Firth and Orkney Waters (PFOW) is the UK site with the greatest tidal energy potential, as shown by it having the highest power densities in Figure 1. Lying between the north coast of the Scottish mainland (Caithness) and the Orkney Islands, the area is a narrow sea corridor (~27 km long and ~10-13 km wide) connecting the North Sea to the North Atlantic.
Ocean characterised by strong tidal currents [12]. The constrained nature of the area led Iyer et al. [8] to not consider the separate arrays, instead modelling the output from the area as a whole. Iyer et al. [8] suggest 7.3 GW of tidal stream generation capacity spread around the UK in areas most suitable for development could only achieve 75-150 MW of firm capacity (i.e. the minimum amount of electricity which will be available at any given time). This 7.3 GW covers seven main areas (Orkney, the Pentland Firth, Islay, Anglesey, Ramsey Island, the Isle of Wight, and the Race of Alderney in the Channel Islands), five of which are outside the PFOW region. The presence of phasing within the PFOW was not addressed by Iyer et al. [8] but could extend the achievable level of firm capacity.

An additional benefit of phasing is that it reduces the likelihood of transmission bottlenecks. The PFOW are on the extremity of the national transmission grid: this makes congestion a potentially significant issue for large scale renewable development [5]. If peak output is experienced simultaneously across all tidal sites the resulting load may be too great for the grid connection to cope with, so some generation may need to be curtailed or dumped. Any smoothing due to phasing will reduce the stress on the grid and therefore the need for curtailment, making the developments more beneficial.

Initially concentrating tidal Scottish and UK tidal in the PFOW offers substantial benefits beyond the area’s high value resource. The proximity to EMEC offers access to the trained staff and supply chain which has built up both around the site and the tidal resource and leases. Studies have already been carried out and companies formed for the collaboration of vessels with the tidal sector [1,2]. Beyond a specialised tidal supply chain the PFOW would also benefit from the infrastructure (including grid) and supply chain of the nearby large scale offshore wind developments in the Moray Firth [3,4] (Beatrice Offshore Wind Ltd and Moray Offshore Renewables Ltd). In addition, site characterisation and environmental data collection remain high cost and risk for developers, these risks and cost are reduced in the PFOW by the extensive work in regard to this already carried out in the area [5]. There have been coordinated efforts to understand the environmental implication of developing tidal power in the PFOW, highlighted by the publication by the Scottish Government of a Marine Spatial Plan for the area [6]; which should assist with the consenting process.

The benefit of remotely located sites in Scotland and the UK as a whole is limited due to the nature of co-tidal lines and these correspond to areas with a large tidal resource, this is explored
and quantified in detail by [7]. In other countries this will not always be the case so the benefit of remotely located sites in terms of tidal phasing will be enhanced.

In March 2010 the Crown Estate leased 1000 MW of tidal stream development sites in the PFOW; these were the first such leases in the World. The PFOW leases, being some of the most economic and advanced in terms of development, are likely to be constructed before there are other tidal farms of a scale which can contribute to smoothing overall tidal power output. Consequently, the objective of this work was to establish and quantify the extent to which ‘close proximity’ phasing of tidal output within the PFOW can be expected to contribute to ‘firm capacity’.

2. Methodology

The Crown Estate 2010 PFOW leasing round contained five tidal stream sites: 100 MW at the Ness of Duncansby, 200 MW at Cantick Head, 200 MW at Westray South, 100 MW at Brough Ness, and 400 MW at the Inner Sound of Stroma. The locations of these are shown in Figure 2. Most of the arrays are closely grouped; Brough Ness, the Ness of Duncansby, the Inner Sound and Cantick Head arrays cover an area of only 17 km by 18 km.
Figure 2. Leased tidal generation sites within the PFOW. Water bodies are given in the bold and italic; land masses in bold; and tidal lease sites in plain text. Crown copyright ©.

Tidal sites were defined according to the coordinates for the leased areas from The Crown Estate [13]. A grid was draped over the development areas in ArcGIS and centroid co-ordinates of each grid square (‘nodes’) extracted, 856 nodes in total.

The spatially smaller development areas of the Inner Sound, Ness of Duncansby and Brough Ness were assigned 150 x 150 m grid squares, whilst the Cantick Head and Westray South sites were assigned 200 x 200 m and 250 x 250 m squares respectively. This gave a balance between size of data sets and resolution. The resolution is fine compared with, for example, Clarke et al. [9] who used just one point from the UK Admiralty tidal charts for their three study sites, and Iyer et al. [8] who used 1.8 km² grid cells.

Tidal current velocities were obtained at ten minute intervals for one year (2009), for each of the 856 nodes, from the POLPRED Orkney model (ORKM). POLPRED is a suite of tidal
prediction software, developed by the Proudman Oceanographic Laboratory [14]. The ORKM uses 26 tidal harmonics, derived from a high-resolution numerical circulation model, to provide two-dimensional depth-averaged current for a desired location.

There is no mature tidal turbine in use, and thus no definitive power curve for modelling applications [15]. A review of existing devices was conducted and the Atlantis AR1000 selected. The power rating of the device was regarded as ‘typical’ of that proposed across the leases in the PFOW and a detailed power curve was available (Figure 3). In addition the turbine manufacturer is working with the developer of the Inner Sound lease and the device is likely to be deployed at the site [16].

Figure 3. Power curve for Atlantic AR1000 tidal turbine (from data in [17]). The cut-in speed is 0.65 m/s; the rated speed 2.65 m/s; and the cut-out speed 4.5 m/s.

The power curve of the AR1000 1 MW device was applied to the POLPRED derived tidal velocities for each of the 856 nodes at 10 minute intervals. The term 10 minutely is used to describe these data, as each datum is only true for a specific point in time. This term is used rather than 10 minute, which implies it is an average figure.

As the AR1000 has the ability to yaw 180° [17] its output is independent of current direction. Down-time for maintenance and breakdowns is not accounted for in this study as due to lack of device maturity and data availability. It can be expected that for ease of access, maintenance would preferentially take place at times of lowest current velocity and output. Furthermore, assuming maintenance schedules will be uniform across all sites, there should be no impact on phasing characteristics.
2.1. The POLPRED model

POLPRED’s ORKM uses a 1/120° latitude by 1/60° longitude grid (equating to approximately 1 × 1 km). The spacing of nodes means that within an array several will be in the same grid square. Model output for these closely grouped locations will vary as ORKM predicts general flows but not features at a sub 1 km scale; predictions for a particular location are derived within POLPRED from the harmonic constants which have been interpolated from the surrounding four cells.

Using Acoustic Doppler Current Profiler (ADCP) survey Goddijn-Murphy et al. [18] showed, that flows in the Pentland Firth vary greatly on scales smaller than the 1 km of the ORKM. Goddijn-Murphy et al. [18] conclude that the ORKM predictions generally agree with measurements but its spatial resolution is not high enough to assess small scale phenomena including: cross-currents, eddies, and the narrowness of tidal streams. This is likely to cause a slight under-prediction of phasing, as the increased complexity at this finer scale will further decouple the output profile of turbines in close proximity.

In arrays, turbines will impact upon the energy available for other turbines, due to both energy extraction by the tidal device and drag from the structure. Vennel [19] indicates that the losses due to this array effect will result in smaller arrays to maximise the economics of generation. However, the presence of other turbines will not necessarily result in a reduction of output for a turbine. Others [20,21] suggest the presence of additional turbines can, in some situations, increase current velocity and thus turbine output. How turbines interact is highly complex and unfortunately cannot be accounted for in POLPRED.

3. Results and site selection

Using 2009 as an example year, the methodology described creates output figures at 10 minute intervals for each of the 856 nodes within the arrays, at a spatial resolution of 150 - 250 m. Annual capacity factors (i.e. the mean power generated as a percentage of the installed capacity) for each location for 2009 are displayed in Figure 4.
Figure 4. Theoretical capacity factors for locations within PFOW leases. a. Inner Sound; b. Westray South; c. Cantick Head; d. Brough Ness; and e. Ness of Duncansby. Figure legend is provided in f. Figure legend. Arrays are given a latitude and longitude grid on the same scale as the POLPRED ORKM.

Cantick Head (Figure 4c) exhibits the lowest capacity factors of the PFOW sites (Figure 4); the mean capacity factor for all the nodes is 9.5%. The next lowest being Westray South with a 18.9% mean capacity factor. Most of the Cantick Head site experiences capacity factors under 12.5% for 73.6% of the nodes, a higher proportion than all the other arrays.

The 12.5% capacity factor is considered a critical value. At this point, if a 15 year life cycle is assumed, it will cost more to install and operate a tidal stream device than the income it will generate. This is based on the 305 £/MWh guaranteed for tidal generation under the current UK subsidy system, installation costs of 3100 £/kW and 143,300 £/MW/yr in operation and maintenance [22,23].
For these reasons the Cantick Head site was considered to be significantly less economically viable than the other sites and therefore, for the purposes of this study, unlikely to be developed. It should be noted that since undertaking this study negotiations between the developer and the Crown Estate led to the lease being moved to west of the original area [24] to take advantage of higher current speeds, Figure 4 suggests this is likely to cause significant improvement to the site’s tenability as the South Western corner has the highest capacity factors across the site; capacity factors on this extremity of the site exceed 20% which is substantially higher than the mean of 9.5% for the whole array.

For the remaining four sites the number of turbines required to achieve their respective leased capacities was assessed. It was assumed that each turbine would, as a minimum, comply with the tidal farm spacing standard recommended from the European Marine Energy Test Centre (EMEC) of 2.5 turbine diameters lateral spacing across the current by 10 diameters downstream [25]. For a single AR1000 1 MW turbine, with a diameter of 18 m [17] this equates to 8100 m². Applied to the arrays, Westray South, Ness of Duncansby and Brough Ness had large enough leased areas to limit development to locations where current speeds would result in capacity factors >22.5%, thereby increasing profit. Locations within these sites with capacity factors <22.5% were consequently excluded from further analysis.

The area of the Inner Sound array was found to be too small to fit the 400 turbines required to meet leasing requirements whilst meeting EMEC spacing figure and the site was limited to 350 MW of development. To allow this installed capacity to be achieved locations within the array with a capacity factor <20% were excluded from further analysis rather than the <22.5% of other arrays. Estimated deployment costs provided by [23] suggest the economic viability of sites with capacity factors below 20% will become increasingly questionable, hence this limit being put in place.

Taking these factors into account in total 750 MW of tidal stream capacity is considered in this study. The ten minute outputs for this capacity are summarised in Table 1.
Table 1. Summary of 10 minutely array outputs for 2009 (percentage of nameplate capacity i.e. equivalent to an instantaneous capacity factor, calculated for each time step).

<table>
<thead>
<tr>
<th>Array</th>
<th>Mean</th>
<th>Median</th>
<th>StDev</th>
<th>1%</th>
<th>10%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brough Ness</td>
<td>31.7</td>
<td>19.9</td>
<td>32.4</td>
<td>82.8</td>
<td>62.6</td>
<td>44.7</td>
<td>26.5</td>
<td>15.6</td>
<td>10.0</td>
</tr>
<tr>
<td>Inner Sound</td>
<td>31.1</td>
<td>20.4</td>
<td>30.8</td>
<td>83.7</td>
<td>64.1</td>
<td>45.1</td>
<td>25.8</td>
<td>14.3</td>
<td>7.2</td>
</tr>
<tr>
<td>Ness of Duncansby</td>
<td>27.8</td>
<td>19.4</td>
<td>26.5</td>
<td>88.4</td>
<td>64.7</td>
<td>42.7</td>
<td>21.5</td>
<td>9.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Westray South</td>
<td>24.6</td>
<td>15.1</td>
<td>26.7</td>
<td>80.5</td>
<td>58.8</td>
<td>36.6</td>
<td>17.4</td>
<td>7.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Combined arrays</td>
<td>29.0</td>
<td>19.8</td>
<td>28.3</td>
<td>85.3</td>
<td>64.4</td>
<td>43.7</td>
<td>23.6</td>
<td>10.3</td>
<td>3.9</td>
</tr>
</tbody>
</table>

The mean values equate to the capacity factors for each site. These figures are comparable with those of Iyer et al.’s [8] study which gives capacity factors for the different areas in the PFOW of between 23.3% and 32.6%. Unsurprisingly, given tidal power’s rapidly changing inputs (current speeds) and thus outputs, the standard deviations (StDev) in Table 1 are large, explaining the disparity between the mean and median values.

4. Analysis and discussion

Although examining the overall capacity factor of sites is of value, the focus of this work is on phasing and whether it will enable the tidal stream leases of the PFOW to provide firm capacity. For this to be undertaken the 10 minutely data need to be interpreted to answer three interlinked questions: (a) Is there noticeable tidal phasing in the PFOW? (b) If there is phasing, does it mean that tidal development in the PFOW area will create firm capacity? (c) If tidal sites are unable to produce firm capacity, how much storage is necessary for various levels of firm capacity to be achieved?

Tidal stream lends itself well to storage, with reserves foreseeably being drawn upon and replenished four times a day, in keeping with the flood/ebb cycle. Quantifying the storage needed to achieve firm capacity provides a means to better understand the challenges and potential of integrating tidal stream into the Scottish electricity system. Firm capacity in this study is often given as a percentage figure of the installed capacity which would constantly be producing electricity; this quantifies the extent to which tidal power can be relied upon.
4.1. Within array phasing

Prior to investigating pan-array phasing the presence of phasing within individual arrays is examined. The potential for phasing is determined by comparing the length of zero output occurrences for the individual locations with the total array output. If there is phasing within an array it will result in shorter periods of zero output in the combined area than in the individual locations.

Figure 5 illustrates the differences in zero output length. It was constructed by first analysing zero output for each individual array. This was done by binning the varying lengths of zero output for individual locations and calculating how frequently each length of zero output occurs (as a percentage of total time). The same process was repeated for the array as a whole.

![Figure 5](image)

**Figure 5.** Length of zero output incidences (minutes) from individual locations and for the arrays as a whole. a. Brough Ness; b. Inner Sound; c. Ness of Duncansby; d. Westray South.

There is within array output phasing displayed in Figure 5, with the arrays having shorter periods of zero output than the individual sites e.g. for the whole arrays 71.2% of the zero output incidents are calculated to be 10-40 minutes duration, compared to 14.9% for the individual locations within the arrays. Furthermore, when the mean length of zero output events for individual locations and whole arrays are compared it may be seen that the mean length of zero output incidents are 25, 31, 38, and 18 minutes shorter for the whole arrays than the
individual locations at Brough Ness, the Inner Sound, the Ness of Duncansby and Westray South respectively. This suggests it is advantageous to examine arrays in a high resolution, i.e. the 0.0225 - 0.0625 km$^2$ grid cells in this study compared the 1.8 km$^2$ cells used by [8].

4.2. Pan-array phasing

Having established that there is phasing within the individual arrays the potential for phasing between arrays is assessed. The 10 minutely outputs for each array over the course of a day provide an indicator of the potential of phasing within the PFOW (Figure 6).

![Figure 6](image.png)

Figure 6. 10 minutely output for Westray South, Ness of Duncansby, Inner Sound and Brough Ness and the four sites combined at different stages of the spring (a) and neap (b) cycles.

Both the Inner Sound and Brough Ness have differing outputs depending whether the tide is in its flood or ebb phase, this is most noticeable during neap tides (Figure 6b); with the Inner Sound performing better on the flood and Brough Ness on the ebb, thereby helping to compensate, through phasing, for the other site’s variability. So even a 10 km spread of tidal leases, in the case of the Inner Sound and Brough Ness, may enhance the ability of firm capacity
to be achieved. However, Figure 6 also shows that on some occasions output falls to 0 MW. The amount of time the arrays provide negligible output was quantified in Table 1, in the best case scenario of combining all the arrays 1% of nameplate capacity (7.5 MW) is not reached for 2.1% of the year (7.7 days). The challenge of meeting these shortfalls and achieving various firm capacities is explored in the subsequent discussion.

4.3. Achieving firm capacity

Four levels of firm capacity are considered: 5%, 10%, 15% and 20% of nameplate capacity equating to 37.5 MW, 75 MW, 112.5 MW and 150 MW respectively. The upper value is limited to 20% as for some arrays, during neap tides, maximum generation over the flood/ebb cycle fails to exceed this output (Figure 6a). These four scenarios were chosen to give an indication of how the storage requirement changes with firm capacity. 10% of nameplate capacity equates to approximately the combined winter peak electricity demand for Caithness and Orkney (41.7 MW and 35.7 MW respectively; pers. comm. Scottish and Southern Energy (SSE) and [26]), i.e. the two Scottish counties the tidal sites fall within. Achieving 10% firm capacity therefore infers that all electricity demand within the counties can be met at all times by tidal stream technology. However, this full 10% firm capacity would very rarely need to be utilised within a closed Caithness and Orkney system. Demand data provided by SSE suggests that a 5% firm capacity would provide all the electricity needs of Caithness and Orkney for ~94% of the time. In the remaining ~6% of the year where demand does exceed 37.5 MW tidal power will still fill a large portion of the load (the maximum combined hourly demand for the two counties in the data provided was 82.42 MWh). As such, the 5% firm capacity is analysed in the greatest depth.

The data presented in Table 2 shows that, for any level of firm capacity to be achieved from tidal power in the PFOW, electricity will need to be stored.

Table 2. A summary of the ability of combined Westray South, Inner Sound, Ness of Duncansby and Brough Ness arrays to achieve four different levels of firm capacity. The total annual shortfall of under generation does not include the 80% efficiency, being primarily a
measure of array performance not storage requirement.

<table>
<thead>
<tr>
<th>Firm capacity (%)</th>
<th>Proportion of the year firm capacity not reached (%)</th>
<th>Annual shortfall of under generation incidents (MWh)</th>
<th>Storage needed to reach this firm capacity (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>26.4</td>
<td>62523</td>
<td>255</td>
</tr>
<tr>
<td>10</td>
<td>35.8</td>
<td>165084</td>
<td>3100</td>
</tr>
<tr>
<td>15</td>
<td>43.6</td>
<td>295734</td>
<td>7508</td>
</tr>
<tr>
<td>20</td>
<td>50.4</td>
<td>450372</td>
<td>13121</td>
</tr>
</tbody>
</table>

Tidal power is a desirable source of electricity to store as the extent and timing of storage capacity needed can be modelled. Given the nature of tidal cycles storage would be utilised frequently and predictably, reducing risk for those operating the storage technology as payback times can be very accurately forecast.

In order for electricity to be stored the desired firm capacity has to be exceeded, as otherwise the electricity will be utilised to meet demand. In this analysis it was assumed any excess could be stored with no limit placed on charging rate. The storage system was assumed to have a round trip efficiency of 80%, in line with storage options such as pumped hydro and large scale batteries [27].

To calculate the quantity of storage needed the output data was converted to MWh for each 10 minute time step in the array (by dividing the output figure by six). The required generation (MWh) needed to reach a given firm capacity for a 10 minute period is then subtracted to give the input from those 10 minutes to the storage reservoir. For example, in the case of the combined arrays 75 MWh is needed in one hour to achieve 10% firm capacity (Table 2), so in 10 minutes 75 MWh/6 or 12.5 MWh needs to be generated. This first stage of calculating storage is assigning an input to the storage reservoir (ir) in MWh for each time step. Two values are needed for this, gen which is the electricity generated (MWh) by the array for the 10 minute period, and fc is the generation needed (MWh) in a 10 minute time step to achieve a given firm capacity. The calculating of ir varies depending on whether gen is greater than fc and is expressed as:

\[(gen - fc) > 0 = (gen - fc) \times 0.8\]

\[(gen - fc) \leq 0 = gen - fc\]

0.8 being used in times where the storage reservoir is charging to represent an overall 80% efficiency of the storage system.
The final stage is to calculate storage reservoir state \((rs)\), this is expressed as:

\[
prs + ir \geq 0 = 0
\]

\[
prs + ir < 0 =prs + ir
\]

with \(prs\) being the storage reservoir state for the previous time step (for the initial time step this is taken as 0). The lowest \(ir\) value is the negative of the size the storage reservoir should be to achieve the prescribed \(fc\), although in a real world situation some additional storage capacity as a safety buffer would be necessary. The storage reservoir is effectively limited to 0 to prevent it being charged to increasingly high levels as the year progresses.

Pumped hydro potential is given by:

\[
\text{Pumped hydro potential Wh} = (\text{Head m} \times (\text{Volume l ÷ 3600}) \times \text{Gravitational acceleration m/s}) \times \text{Turbine efficiency}
\]

with 3600 being the number of seconds in an hour. Therefore, a 5% firm capacity system, needing 255 MWh of storage (Table 2), could have its requirements met by a pumped hydro storage system with a reservoir of 100000 m\(^2\) surface area and 5 m depth, a 207 m head between the upper and lower reservoirs, and a 91% turbine efficiency [28]. To put this in context Cruachan and Foyers, the two large pumped hydro plants currently operating in Scotland, have reservoir sizes of 10 GWh and 6.3 GWh respectively [29].

The PFOW are unable to achieve a firm capacity without storage for a significant portion of time (Table 2) e.g. 26.4% of the year where 5% of nameplate output is not reached. The 10 minute occurrences which make up this 26.4% are always grouped in clusters of at least 60 minutes, with the longest being 230 minutes with a mean of 98 minutes. These show the shortfalls do not last long, certainly compared to wind power i.e. it is rare, but not unknown, for the current UK wind fleet to fail to achieve 5% of nameplate capacity over extended periods exceeding 10 consecutive hours [30].

Times when no power is being generated, by the four arrays combined, make up only 1.4% of the year – a figure markedly better than for individual arrays i.e. Brough Ness 11.2%, Inner Sound 9.1%, Ness of Duncansby 4.2%, and Westray South 14.5%. This is a clear demonstration of the presence of pan-array phasing within the PFOW.
Although the tidal sites of the PFOW are unable to provide firm capacity, very little storage is necessary in a hybrid tidal and storage system to achieve a firm capacity figure of 5% of installed capacity (Table 2). Calculated storage required for 5%, 10%, 15% and 20% firm capacity is presented further in Figure 7.

**Figure 7.** Storage capacity (MWh) required for the PFOW arrays to achieve 5-20% of firm nameplate capacity.

The 255 MWh of storage needed for the combined arrays to achieve a firm capacity of 5% of nameplate capacity equates to 34 MWh of storage required per 100 MW of installed capacity. This is only 60% of the storage required when all sites are considered individually, demonstrating that there is a benefit to considering these separate sites as a whole.

If generation is low for extended periods it necessitates far more storage. For a 5% firm capacity to be achieved at Westray South a standalone system requires 116 MWh of storage per 100 MW of capacity. This is a result of the storage reservoir being unable to fully recharge over successive flood/ebb cycles during neap periods, where current speeds are particularly low. This is clear when a comparison is made between the longest period 5% of nameplate capacity is not reached (Table 3) and the maximum time the storage reservoir is not full (Table 4). The longest instance Westray South’s storage reservoir is not full is nearly 25 times longer than the longest period 5% of nameplate capacity is not realised (6680 minutes as opposed to 270 minutes).

The capacity of a storage reservoir necessary to achieve a given firm capacity is determined by the longest extended period of low generation. There are ways to explore this: first, quantifying
the longest period a given firm capacity is not achieved (Table 3) and second by determining the lengths of time the storage reservoir is not full (Table 4).

Table 3. Periods of generation below 5% of nameplate capacity during 2009.

<table>
<thead>
<tr>
<th>Array name</th>
<th>Longest period 5% of nameplate capacity not reached (minutes)</th>
<th>Mean length of period that 5% of nameplate capacity not reached (minutes)</th>
<th>Median length of period that 5% of nameplate capacity not reached (minutes)</th>
<th>Percentage of the year output falls below 5% of nameplate capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sites</td>
<td>230</td>
<td>98</td>
<td>90</td>
<td>26.4</td>
</tr>
<tr>
<td>Inner Sound</td>
<td>540</td>
<td>100</td>
<td>90</td>
<td>26.8</td>
</tr>
<tr>
<td>Ness of Duncansby</td>
<td>230</td>
<td>95</td>
<td>90</td>
<td>25.4</td>
</tr>
<tr>
<td>Westray South</td>
<td>270</td>
<td>114</td>
<td>100</td>
<td>30.6</td>
</tr>
<tr>
<td>Brough Ness</td>
<td>520</td>
<td>105</td>
<td>100</td>
<td>28.0</td>
</tr>
</tbody>
</table>

Table 4. Occasions the storage reservoirs are needed to achieve a constant output of 5% of nameplate capacity during 2009.

<table>
<thead>
<tr>
<th>Array name and reservoir size (MWh)</th>
<th>Longest period reservoir not full (minutes)</th>
<th>Mean length of period the reservoir not full (minutes)</th>
<th>Median length of period the reservoir not full (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sites (255)</td>
<td>3330</td>
<td>149</td>
<td>130</td>
</tr>
<tr>
<td>Inner Sound (136)</td>
<td>2980</td>
<td>153</td>
<td>130</td>
</tr>
<tr>
<td>Ness of Duncansby (26)</td>
<td>2930</td>
<td>144</td>
<td>130</td>
</tr>
<tr>
<td>Westray South (232)</td>
<td>6680</td>
<td>184</td>
<td>140</td>
</tr>
<tr>
<td>Brough Ness (33)</td>
<td>1410</td>
<td>159</td>
<td>140</td>
</tr>
</tbody>
</table>

For all arrays and the combined PFOW output, the longest period a reservoir does not refill completely far exceeds the maximum period the desired 5% firm capacity is not reached. So although the required generation is exceeded the excess is not sufficient to refill the reservoir. These longest periods the reservoir is not full occur due to a neap tide falling close to the vernal equinox in 2009; this is shown in Figure 8a.
Figure 8. Maximum storage reservoir size required to fulfil various levels of firm capacity on every day of the year in 2009.

The longest periods the PFOW arrays fall below 5% of nameplate output (Table 3) gives a good indication of their generation behaviour, with long periods (>360 minutes) showing a large difference in generation between flood and ebb tides. This demonstrates that the Ness of Duncansby and Westray South have little disparity in output between flood and ebb tide, as 230 and 270 minutes is shorter than the ~360 minute flood/ebb transition.

Both the Inner Sound and Brough Ness have output below 5% of nameplate capacity for periods exceeding 6 hours, demonstrating that they require a flood tide or an ebb tide, respectively, to exceed the 5% firm capacity and refill their storage reservoirs. The two sites combined only require 24 MWh of storage per 100 MW of installed capacity to achieve a 5% firm capacity. Over a third less than the 39 MWh figure for the Inner Sound and just under a third less than the 33 MWh for Brough Ness, showing phasing from the flood to the ebb state (i.e. ~360 minute phasing period).
The Inner Sound array is 3.5 times larger, so its regime may be expected to dominate Brough Ness’ contribution. However, this is not the case because, as shown in Figure 6, the difference in generation between flood and ebb is much more pronounced at Brough Ness than the Inner Sound, helping to make up for the disparity in array size; e.g. in Figure 6b on 04/04/2009 the Inner Sound mid-morning capacity factor peak (09:30) is 25.27% and the afternoon peak (16:00) 47.53%, whilst at Brough Ness the comparable figures are 54.45% (at 9:40) and 23.05% (at 15:50).

4.4. The limits of phasing in the PFOW

Figure 7 indicates that the value of phasing diminishes with larger firm capacity requirements. This is observed in the increasing disparity between the storage required by the combined arrays and the higher capacity factor arrays. This is because the importance of the spring/neap cycle starts to dominate, rather than the changes in current speed due to the flood/ebb cycle; this can be observed in Figure 8. As a result the higher energy sites of the Inner Sound and Brough Ness start to require less storage to cope with spring/neap cycle than the Ness of Duncansby or the combined arrays per 100 MW of installed capacity; i.e. for 20% firm capacity the Inner Sound and Brough Ness require respectively 1672 MWh and 1511 MWh of storage per 100 MW of installed capacity compared to 1722 MWh at the Ness of Duncansby.

The dominance of the spring/neap cycle in driving storage capacity can be determined by examining the length of time a given output is not reached in a system without storage. Theoretically the peak combined output for the four arrays should occur ~720 minutes apart (i.e. a whole flood/ebb cycle). This is due to the large proportion of installed capacity in the Inner Sound array, which will have higher output during flood tides – meaning the peak in output during a flood tide needs to be covered. Thus, if a given output is not reached for over 720 minutes, a portion of the storage is needed purely to increase the peak output, a problem which phasing across a flood/ebb cycle is not able to solve. For the combined arrays phasing is still shown to be beneficial when obtaining a firm capacity of 10% of name plate capacity, as the longest period this isn’t exceeded is 690 minutes. For 15% of nameplate capacity, there is a steep change with a maximum gap between occurrences of 4060 minutes, clearly showing the spring/neap cycle overrides the phasing benefit during the flood/ebb cycle.
4.5. Impact of array assumptions

The turbine type used impacts the study’s findings. The Inner Sound, which is the world’s first multi-turbine tidal stream project, will utilise one Atlantis and three Andritz Hydro Hammerfest turbines in its first development stage [31]. The four turbines are three bladed and horizontal axis, with an 18 m diameter rotor and a 1.5 MW rated capacities [31]. Whilst the rated capacity is higher than the turbine used in this study, the AR1000 represents the most suitable device in terms of manufacturer and device type for which a power curve is available. Changes in turbine size will impact spacing which in turn could have some impact on phasing, due to their relative locations. As turbines designs improve and become more efficient over time they are likely to operate at rated or near rated capacity for a higher proportion of the time. Consequently, during spring tides there may be longer periods within an array or across several arrays that rated or near rated capacity is reached. Similarly, periods of no generation are likely to reduce in length if cut-in speeds are reduced as technology develops – which has been the case in the wind industry.

The turbine densities and array layout will also impact these results and the conclusions of the paper. However this is difficult to quantify because, as noted by [32], relatively few research papers address the issues of tidal turbine configuration. A study by Fallon et al. [33] concluded that water flows and water flows would be affected by turbine layout, including a reduction in tidal range and a delay in high and low tides and slack water. Localised changes in slack water will impact phasing, possibly pronouncing the difference in output timings of turbines within arrays and between different arrays. In terms of output difference between arrays this is most likely to be apparent for the Inner Sound and Ness of Duncansby due to their proximity. Turbine arrangements also impact the power extraction due to factors like wake loss, several studies explore this, for example [21,20,19,34,35]. Changes in power extraction impact generation phasing, as it alters the amount of time turbines will be generating electricity. Consequently, array configurations could have substantial impacts on phasing of tidal generation and should be considered for further research.

5. Conclusions

The methodology utilised in this study demonstrates significant tidal phasing across the leased tidal arrays in the PFOW. This phasing of output is observed both within arrays and across the
area as a whole and occurs at a tens of minutes timescale rather than hours. Consequently, the phasing does not allow for any level of firm capacity to be achieved by the tidal developments of the PFOW alone. However, with the addition of a comparatively small amount of storage significant levels of firm capacity can be obtained.

The methodology can be used to determine which sites have the most beneficial phasing effect upon the tidal portfolio. Firstly, this enables the value of a site to be considered beyond merely capacity factor. If an array has complementary timing of output to other tidal arrays a unit of electricity there will be of high value in terms of electricity system security. With the right market mechanisms in place this security value could then be translated into monetary value. Secondly, if several potential tidal developments are tendered in a small area, a situation which is certainly not unforeseeable given the focused nature of tidal stream energy, cumulative impacts of arrays could become an issue. In this case if two sites are equal, in every other way, the phasing benefit of one of the arrays could, potentially, help to determine which should be granted planning permission. Knowing how different arrays will interact also indicates which order of site development would be best for balancing the grid.

When trying to achieve firm capacity of 10% of nameplate capacity, or lower, the limited phasing within the Pentland Firth and Orkney Waters can be said to be driving force behind the need for storage. To put this 10% (or 75 MW) of firm capacity in context it equates to 1.9% of the generation required to fulfil the forecast annual electricity demand in Scotland in 2020 [30].

Beyond this 10% firm capacity the spring/neap cycle increasingly dominates the need for storage. This has implications for tidal stream generation’s role in the Scottish Government’s intended 100% renewable electricity system; suggesting that even with developments size and location being selected to maximise phasing, the theoretical limit of tidal power to provide consistent base load will not greatly exceed 10% of nameplate capacity, over any given year. Which in turn suggests that within a 100% renewable electricity system, such as is planned in Scotland, the majority of tidal generation will be of greater value due to its predictability and decoupled output from weather, rather than its ability to provide firm base load power.

In addition to assessing the impact of tidal phasing the methodology provides an early means to assess the feasibility for development of a site’s tidal resource. Its usefulness is demonstrated by the case of the Cantick Head lease, which results indicated would not be economically viable – and since the study the lease has been moved to an area which this study indicated would
have higher capacity factors. This aspect of the methodology, combined with its ability to identify sites which enhance phasing and thus firm capacity, make it a useful tool for a cogent tidal stream planning strategy.

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