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Variability of UK marine resources

An assessment of the variability characteristics of the UK's wave and tidal current power resources and their implications for large scale development scenarios

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United Kingdom Wave & Tidal Energy Study

Variability of UK Marine Resources

Final Report

Executive Summary

Overview

The development of a viable marine and tidal power programme in the United Kingdom requires a co-ordinated approach – co-ordination between developers and industry, between planners and network operators, between financiers and market policies that support the marine and tidal power sector.

Above all, success in the wave and tidal power sector means generating meaningful and reliable amounts of electricity that help satisfy electricity demand. The ability to supply electricity at times of peak demand in a reliable and predictable manner will be necessary for the sector to truly succeed.

To achieve this aim, the patterns of energy availability from different wave and tidal power regions around the UK need to be understood. This report provides a detailed insight into the regional characteristics of these resources, examines the opportunities available for diversification within marine renewables to reduce supply variability, and assesses the impact of marine renewable electricity generation on the net electricity demand pattern experienced by the network. Strategies to reduce the variability of marine renewables at a national and regional level are examined, and the impact of these strategies quantified.

Planning a diversified renewables strategy will provide a more reliable renewable energy supply – understanding the resource is central to that planning.

United Kingdom Tidal Current Power Resource

The tidal current resource exhibits obvious, repeatable and predictable patterns of availability, and is highly site specific:

- At individual sites, power output rises to a peak and falls to a minimum (generally approaching zero) roughly four times each day. The timing of these maximum and minimum output times is site-dependent and predictable.
- All sites pass through a repeating 14 day cycle of high tidal ranges (Spring tides) and low tidal ranges (Neap tides) – energy output during the Neap tide phase of the cycle is significantly lower than during the Spring tide phase. The characteristics of this cycle are common to all sites.

The overall variability of the UK tidal power supply is highly dependent on both the sites being developed, and the level of development:

- Smaller sites with low development and yield potential tend to be most important in smoothing within-day variability, as maximum and minimum output levels at these sites occur at different times to the larger resource sites.
- Developing around 10% of the UK tidal current resource at a range of sites would result in low daily variability. As development rises above this level, the synchronised output of larger sites becomes progressively more dominant, increasing overall variability.

Despite the inherent variability of the tidal resource, the impact of tidal power variability on net electricity demand patterns is limited:

- Patterns of tidal power availability (daily & Spring-Neap cycles) have a different cycle to demand patterns – at times, peak tidal output matches peak demand, while at other times demand peaks coincide with minimum output levels. This changing relationship tends to balance out some of the variability impacts on net demand.
- Current estimates see a fully developed UK tidal current resource delivering around 5% of electricity demand – at this level of penetration, variability in the tidal current resource is limited in comparison to demand levels.

Executive Summary

United Kingdom Wave Power Resource

The wave power resource of the UK is extensive, with areas of the north, north west and south west exposed to high energy wave environments:

- All regions showed a highly seasonal distribution of energy availability, with average monthly wave power availability up to seven times higher in winter than summer.
- On average, wave power delivers over five times as much energy during periods of peak electricity demand than it does during periods of low electricity demand.

The hour to hour variability of the UK wave power resource is low in comparison to the tidal resource:

- At high energy wave sites, there is a high degree of persistence in the energy delivered by wave power over time - the most likely power output in the next hour is similar to that that being delivered during the current hour.
- Diversification of wave power generating capacity between a range of high energy wave sites is effective at further reducing variability, particularly during winter.
- The pattern of wave power availability shows only minor variation with device type, with the dominant factor being the energy available at the wave face.

The pattern of wave power output is not random, and strategies can be employed to predict future output at varying levels of accuracy

- The annual distribution of wave energy is highly seasonal, with wave power delivering around five times more energy during peak electricity demand periods than during low demand periods.
- Oceanic buoys provide advance warning of waves arriving from distant locations, allowing a significant portion of the hourly variability at nearshore sites to be predicted by the offshore sites some hours in advance.
- Numerical wave models provide wave predictions up to five days in advance (although further work is needed to quantify the accuracy of these models).

Diversified Marine Resources in the United Kingdom

Diversification within the wave and tidal current resource was examined for two scenarios: national level development without external constraints such as transmission, and a regional scenario with transmission constraints:

- At a national level, the combined development of wave and tidal resources smoothes variability when compared to a tidal-only development strategy.
- The optimum development strategy to achieve a low variability electricity supply from marine renewables is dominated by diversified wave power development.
- In a transmission limited region, combining wave and tidal power development will increase transmission utilisation and reduce supply variability, with a minor penalty in electricity being spilt during rare combined peak output events.

Contents

Introduction

Overview

The Carbon Trust commissioned the Environmental Change Institute to carry out the UK Wave and Tidal Energy Project as part of the Marine Energy Challenge. The purpose of this report is to extend current understanding of the UK's marine resource characteristics, particularly in relation to seasonal patterns of marine energy availability and supply, the variability characteristics of the resource, the relationship between supply patterns and electricity demand patterns, and the opportunities and impacts of developing a diversified marine renewables sector.

This report is intended to provide developers, planners and policy makers with details of the issues surrounding the variability of wave and tidal current resources in the UK. In addition to characterising the resource properties, there is a strong emphasis throughout the report of the potential and practicality of reducing the variability of power output from marine resources by combining the power output of different sites and resources. Optimisation modelling is used to identify the approach that would achieve the lowest variability in power output for a wide range of development options.

Approach

To address these issues, long term wave and tidal current data series were used to allow a detailed investigation of marine resource variability, and to carry out modelling of potential electricity generation patterns from UK marine renewables. The limited observed dataset for wave and tidal current conditions around the UK cost made it necessary to rely on extensive model datasets (refer to Annex 1 for a summary of observed marine datasets).

While data were available for individual sites, the results of the work are generally presented on a regional or national basis. This approach reflects an underlying theme to the work – it is likely that a successful marine renewables industry in the UK will see development of both wave and tidal resources occurring at a range of locations. From a long term energy security perspective it is the characteristics of the overall marine energy system, not individual sites, that are important in determining the role of marine renewables in the future UK energy landscape.

Structure

The report firstly examines the characteristics of the UK's tidal current resource, followed by a similar analysis of the wave power resource. Development scenarios are considered in the third section of the report, while the summary of observed marine data sets is presented in Annex 1

Characteristics of the United Kingdom Tidal Current Power Resource

United Kingdom Tidal Current Resource

Overview

Tidal currents (or tidal streams) are the movement of water that is driven by changes in tide height. In deep ocean areas these currents are very slow, however in nearshore locations tidal currents are accelerated around headlands or through constrictions such as channels between islands. As tide height can be predicted with great accuracy, the direction and magnitude of tidal currents can be predicted at better-than hourly resolution.

Electricity generation from tidal currents requires the placement of underwater turbines in locations with high tidal current velocities. The flow of water across the turbine blades causes the blades to rotate, generating electricity in proportion to the velocity of the tidal current and the characteristics of the turbine.

A number of studies have been carried out on the tidal current resource of the United Kingdom (ETSU 1993, Joule-II 1996, Black & Veatch 2004). These studies have identified both the preferred locations for the development of tidal current power systems and the maximum resource available at each site (including factors such as the current velocity, area available, bathymetry, etc). This report uses the maximum development level (or development constraint) at each site as given by Black & Veatch (2004).

Tidal Current Assessment

This report presents an assessment of the pattern of electricity generation that would be expected from the development of tidal current electricity generating systems in the UK. The focus of this report differs from previous studies as it is concerned with the temporal variability of the tidal current resource. By examining the hour-to-hour variability of the tidal current resource, the variability associated with output of a diversified tidal power system can be assessed. Furthermore, differences in the timing of electricity generation between different locations can be determined, and the opportunities and limitations to developing the resource in a manner that reduces system-wide variability, can be identified.

Tidal current characteristics from 36 sites, which together represent 99.5% of the UK's identified tidal current resource (Black & Veatch, 2004), are included in this assessment for the period 1 January 1994 to 31 December 2003. The tidal power sites have been grouped into five regions (Figures 1 & 2), with the results presented on both a regional basis and for the whole of the UK. A complete list of sites and data sources is included in Appendix 1.

Tidal Characteristics

The tide is the regular and predictable change in height of the ocean over time. Tides are driven by the gravitational and rotational forces between the earth, moon and sun that cause water on the earth's surface to move in different directions.

The moon is the single most important factor in forcing tides, however the relative influence of the sun and moon varies over the course of a year. This results in variations in the tide on a number of time scales.

Daily Tides: the change in tide height that occurs each day is the most readily observable tidal pattern. This change in tide height is driven by the gravitational effect of the moon (where water is pulled towards the moon, thus increasing ocean surface height) and the rotation of the combined earth-moon system (where water bulges on the opposite side of the earth to the moon due to the centripetal force of rotation). In many locations around the world, including the UK, these tides occur on a semi-diurnal basis – roughly two high tides and two low tides each day. However, the moon's orbit period of 24hrs 50min means that the timing of subsequent high and low tides advances each day – a location that experienced high tide at 6.00am and 6.25pm on one day would experience high tides at 6.50am and 7.15pm the following day.

Local bathymetry and coastal geography will influence the tidal patterns of individual locations – while the UK has a semi-diurnal tidal cycle, other locations may experience only one tide per day (diurnal), or show a mixture of the two depending on the Spring-Neap tide cycle (see below). The timing of high and low tides is affected by location, particularly in areas where water flow is restricted (such as narrow inlets).

Spring and Neap Tides: The relative position of the moon and sun in relation to each other has a significant effect on the daily tidal range (the difference in height between high and low tides on the same day). The highest tides, or Spring tides, occur when the sun and moon are aligned with the earth (either as a Conjunction (new moon) when the sun and moon are aligned on the same side of the earth, or as an Opposition (full moon) when the sun and moon are aligned but on opposite sides of the earth). The smallest tidal range accompanies Neap tides, which occur during the first and third phases of the moon when the earth-moon axis is at 90 degrees to the earth-sun axis.

The 28 day orbit of the moon around the earth results in Spring and Neap tides occurring twice every 28 days.

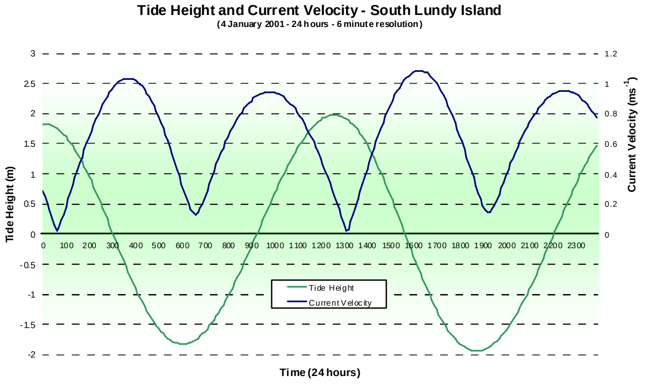
Unlike the daily tide cycle, the timing of Spring and Neap tides is unaffected by geography – thus, the Spring and Neap tide pattern is experienced throughout the world at the same time.

Seasonal Patterns: As the latitudinal position of the sun and moon vary during the year, they exert a further influence on the observed tidal range. In the UK, Spring tides occurring during the spring and autumn equinoxes are larger, whilst those occurring during the summer and winter solstice are smaller. In terms of magnitude, this is a subtle change compared to the daily and Spring-Neap tidal cycles.

Tidal Currents

Tidal currents occur when the tide forces water movement, particularly if that water movement is constrained by headlands, islands or channels. As tidal currents are a direct result of the action of tides, the pattern of variation is controlled by the pattern of the tides.

In most cases, tidal currents reach a maximum at mid tide conditions, half way between high and low tide, as this is the time of maximum water movement. Combined with the semi-diurnal tidal regime of the UK, this results in four peaks in tidal current velocity each day, twice on the ebb tide (between high and low tide) and twice on the flood tide (from low to high tide) – the figure below provides an example of this relationship. Around the time of high and low tide there is very little water movement; as a consequence the tidal current velocity drops (often to near zero).



While this general relationship is shown at many sites, other patterns occur – Casquets in the Channel Isles shows the opposite relationship, with peaks in current velocity coinciding with high and low tide. However, at all UK sites this relationship results in four predictable peaks in current velocities, and four lows, every 24hrs 50mins.

Modelling Approach

A fundamental aspect of this project was the modelling of hourly electricity generation levels at each of the sites – this modelling process is described below.

Step 1 – Tidal Current Velocity Time Series

Tidal current data was obtained from the Proudman Oceanographic Laboratory's CS20 model of tides and tidal currents for the UK. This model covered 30 of the 36 sites (representing 97% of the identified development potential of the UK), with data for the remaining six sites being derived from Admiralty Tidal Current Atlases.

The CS20 model allows site-specific tidal current data to be generated, however it was found that in some cases the model output was highly sensitive to minor changes in location (this is a characteristic of the model in complex coastal areas and not representative of the actual change in velocity across a site). Where this was observed, the peak tidal current velocity determined in other studies (eg Black & Veatch 2004) was used as a check to ensure the CS20 model output was close to the expected result. Tidal current velocities at the CS20 sites were determined at a six minute resolution, and averaged to hourly resolution.

The Admiralty Tidal Atlas provides hourly tidal current velocities at six sites – given the coarser resolution of these data, together with the complexity of the tidal currents at some sites, the accuracy of the tidal current data for these sites is considered to be lower than that for the CS20 model sites. Whilst the timing of the tidal currents modelled using this method is considered reliable, the magnitude of the velocities is considered questionable, and reference to previous studies was again used to ensure consistency with previous work (notes on any changes are included in Appendix 1). Given that the sites modelled using this method account for less than 3% of the available resource, the impact of any inconsistencies is considered minimal.

Step 2 – Conversion to Hourly Power Output

The annual electricity yield of each site was taken from the Tidal Stream Study – Phase II report (Black & Veatch, 2005). With the maximum annual yield at each site known, the hourly power output of the site was determined from tidal current velocity time series data. This combined approach allowed the energy yield estimates derived from 3D flow modelling to be incorporated into the model, while retaining the timing of hourly tidal power availability at the different sites.

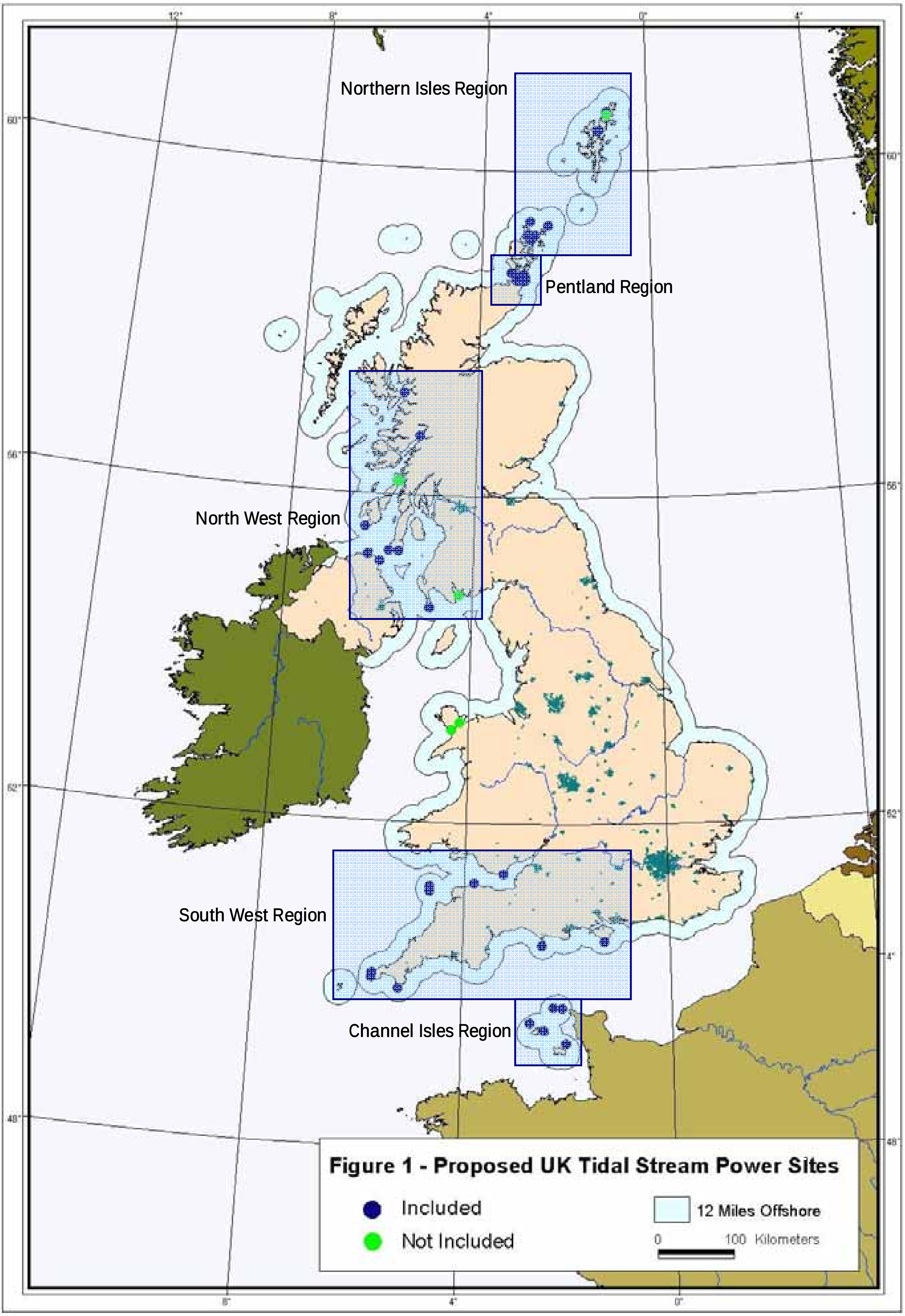
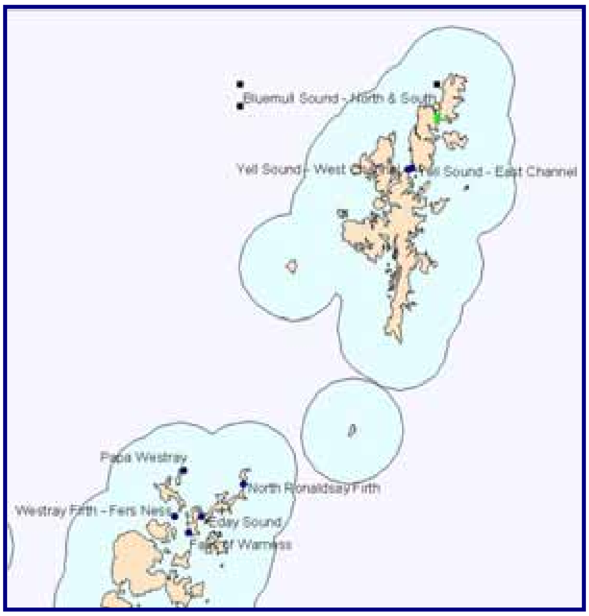


Figure 1 - Proposed UK Tidal Stream Power Sites

Figure 2 – Tidal Current Power Development Regions

Northern Isles Region

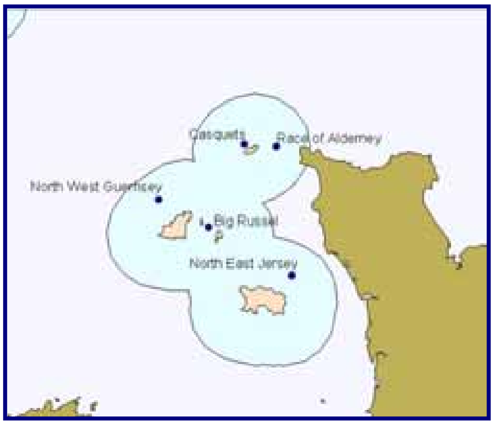


North West Region

Pentland Region

South West Region

Channel Isles Region



A power transform function at each site was used to represent the timing of power output from a turbine located at each site. The power (in kW) of a tidal current passing through a given area can be approximated by:

Power = Area x Density x (Current Velocity)^3 x 0.5/1000 kW

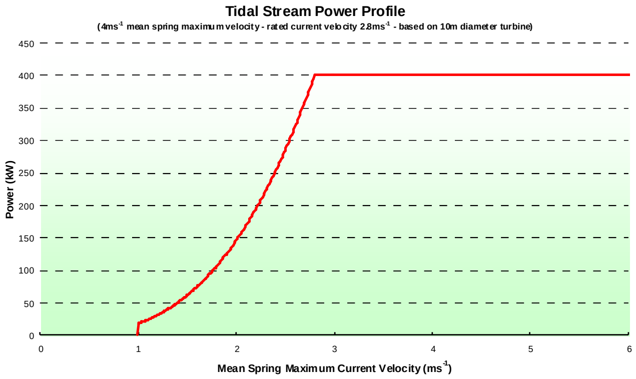
Area = the swept area of the rotor in m^2
Density = 1023kg/m^3
Velocity=instantaneous current velocity in ms^{-1}

With the annual site yield known from the flow modelling, this equation was used to determine the proportion of the annual yield being delivered during each hour. Following the advice of Peter Fraenkel from Marine Current Turbines Ltd, a range of site specific power transform functions were developed, with the key parameters being:

1. Cut-in velocity of 1ms^{-1};
2. Efficiency at rated velocity of around 45%;
3. Rated velocity (velocity at which maximum power output is achieved) typically set to around 70% of mean Spring maximum tide velocity, and

The resulting profile appears similar to a wind turbine power profile, except that there is no high-speed shutdown due to the limited velocity range of tidal currents.

From this information, site-specific power transform functions have been developed, an example of which is shown below. Finally, the six minute power output data was then grouped to give the average output at each site for each hour in the 10 year period.



Step 3 – Regional Characteristics and Optimisation

Analyses were carried out on a regional basis (Figure 2), including an assessment of the variability in the aggregate electricity supply for each region. Where the total development level was less than the regional or UK maximum development potential (as given by Black & Veatch 2005), optimisation analyses were carried out to identify the optimal mix of site contribution to electricity generation. For this study, the optimal solution was the mix of sites that resulted in the lowest average hourly change in energy output, expressed as a percentage of maximum system output. Diversification of capacity between different sites was catered for by the model, up to the site capacity limit.

Additional Analyses

In addition to the modelling work described above, a range of additional analyses were carried out, including:

- UK diversification and optimisation
- Tidal power installed capacity and variability
- Tidal power variability and electricity demand
- Current velocity distribution

The background to each of these analyses is included in the relevant section.

Interpreting the Results

This text relates predominantly to the following regional summaries – whole of UK results are treated separately.

For each region, a description of the findings is accompanied by four graphs, each depicting a different aspect of electricity output from the region, and one table:

Graph 1 – shows the variation in tidal current velocity at each site in the region over time. The important feature of this graph is the similarity in timing of the high current velocities. In general less correlated sites offer a greater opportunity for smoothing the aggregate output.

Graph 2 – shows a typical 48 hour period of tidal power output from the region for both Spring and Neap tide conditions. Hourly electricity output data are averaged from six minute tidal current velocity data.

Graph 3 – shows a typical 28 day cycle of two Spring and two Neap tides. Energy output is relative to the maximum hourly output.

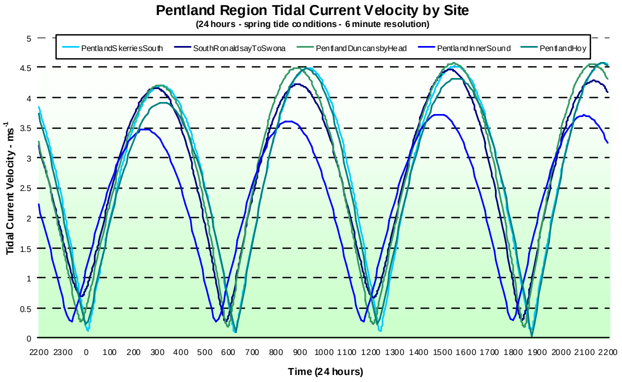
Graph 4 – shows the annual variation in electricity generated from the regional tidal system, assuming maximum development occurs at each site. Hourly data are shown in light blue, however there is too much data for this to be distinct – to aid interpretation, a running 24hr mean energy output line has been added (dark blue).

Table 1 – shows the change in average variability from a region based on the level of development in the region (as a percent of maximum development). The variability results reflect the optimal allocation of generating capacity between sites at the given development level.

Tidal Power Properties – Pentland Region

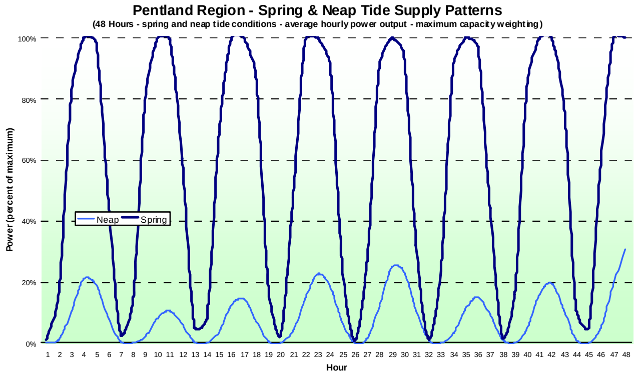
Overview

The Pentland Region is a significant tidal resource for the UK, representing around 61% of total electricity generating potential. The region includes five high velocity sites where development could take place, however the highly correlated nature of the tidal current velocities at these sites limits the opportunity for diversification to meaningfully impact on the aggregate pattern of electricity supply. For this reason, the Pentland Region exhibits a high degree of hourly variability.

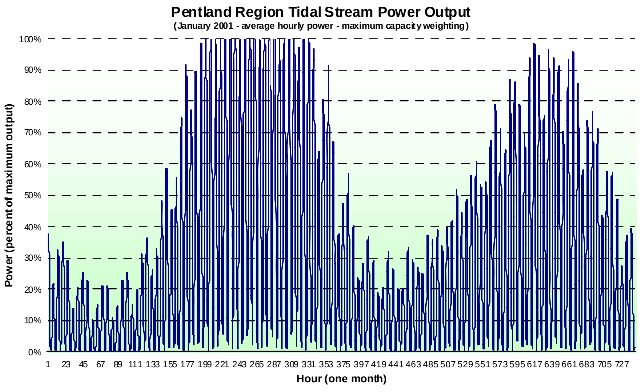


Power Output Distribution

While the Pentland Region has the potential to produce significant amounts of electricity over the long term, there is high variability in aggregate supply from the region. This is a result of two main drivers– firstly, the Pentland Region exhibits high tidal current velocities, with turbine rated velocities exceeding 4ms^{-1} at five of the seven sites. While providing significant power output, these velocities tend to accentuate the change in power output over time. Secondly, the highly correlated timing of velocity at the different sites minimises the opportunity for smoothing the aggregate power output from the region.



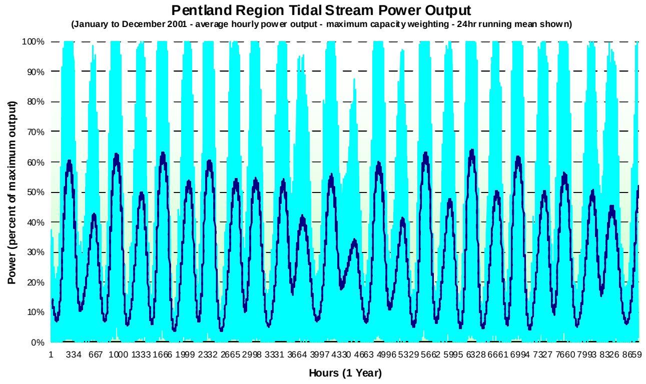
There is significant variation in the average power output levels during both Spring and Neap tide conditions. During peak Spring tide conditions, typical output ranges from less than 10% to 100% of maximum output during each 6 hour period, while neap tide conditions can see minimum output levels at 0% and peak outputs between 10 to 30% of maximum output.



Impact of Diversity & Development

The average hourly change in aggregate electricity output from the region remained relatively stable across a range of development scenarios, as shown in the table below. The primary cause of both the magnitude of the hourly variability and insensitivity of the results to changes in development level is the correlated nature of the output from the seven sites. Given this feature of the region, there is no development strategy available amongst these sites that would significantly reduce hourly variation in electricity output levels.

Installed Capacity (% of Regional Maximum)	Average Hourly Variability (as % of Maximum Output)
10%	18.6%
25%	18.7%
50%	18.8%
100%	19.3%
2 Main Sites (77%)	19.5%

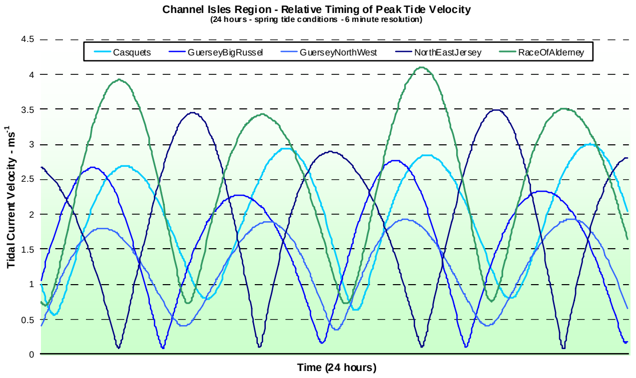


Tidal Power Properties – Channel Isles Region

Overview

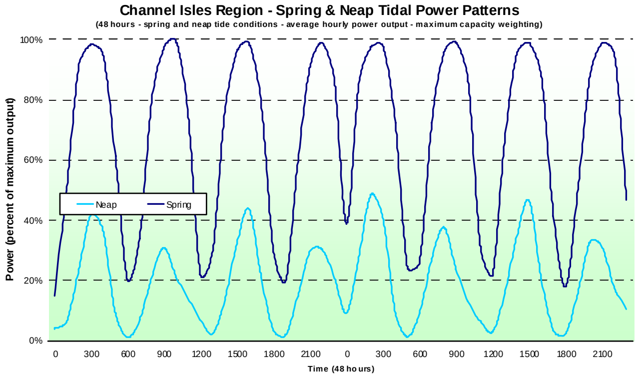
The Channel Isles Region has the second-largest tidal current resource in the UK, with 13.6% of potential electricity generation. The region includes a total of five sites identified for development, with three of these being moderate to high velocity sites.

There is a high degree of variation in the timing of peak tide velocities in this region – this implies an excellent opportunity to smooth the aggregate output of the site, however resource development constraints at three of the sites severely limits this in practice.



Power Output Distribution

With the maximum capacity of turbines installed at all sites, there is significant variation in the average power output levels during both Spring and Neap tide conditions During peak Spring tide conditions, typical output ranges from 10% to 20% to around 100% of maximum output. Power output during Neap tide conditions is highly variable, with a minimum output of around 0%, and peak outputs rising to between 30% to 50%, of maximum output.

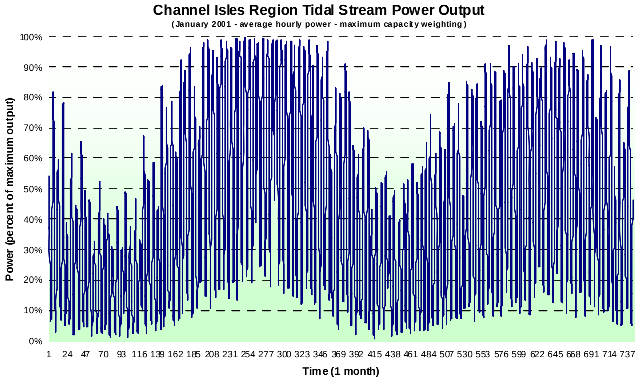


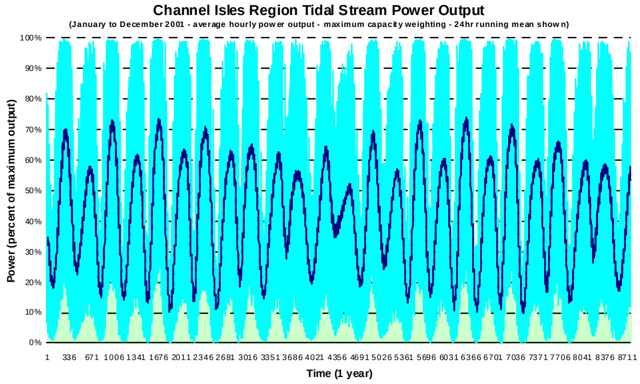
Impact of Diversity & Development

The variation in velocity patterns at different sites in this region suggests an ideal opportunity to minimise hourly variability through diversification. However, to achieve the minimum variability scenario, development of the regions tidal resource would be limited to 10% or less. This is because the output from the North East Jersey site is essential for smoothing daily variability in the region, however the development potential of this site is very limited (4% of the region's development potential).

At low regional development levels, output from North East Jersey can make up a significant proportion of total output, however development beyond the 10% level sees hourly variability rise rapidly as the output from North East Jersey is quickly swamped by the (highly correlated) output from the surrounding sites. Restricting development to Casquets and Race of Alderney, which together account for over three quarters of the resource, further accentuates the hourly variability of the aggregate output (see table).

Installed Capacity (% of Regional Maximum)	Average Hourly Variability (as % of Maximum Output)
10%	7.8%
25%	8.0%
50%	12.4%
100%	18.9%
3 Main Sites (71%)	22.7%





Tidal Power Properties – South West Region

Overview

The South West Region represents 9% of the UK's tidal current resource, with capacity being spread across nine locations. Foreland Point, Portland Bill and the Isle of Wight are the highest velocity sites in the region, with Foreland Point and Portland Bill making up 80% of the region's development potential.

There is a high degree of variation in the timing of peak tide velocities in this region. The benefit of this is reflected in the generally low hourly variability figures for this region – the South West Region shows the lowest level of hourly variability of any UK region.

Power Output Distribution

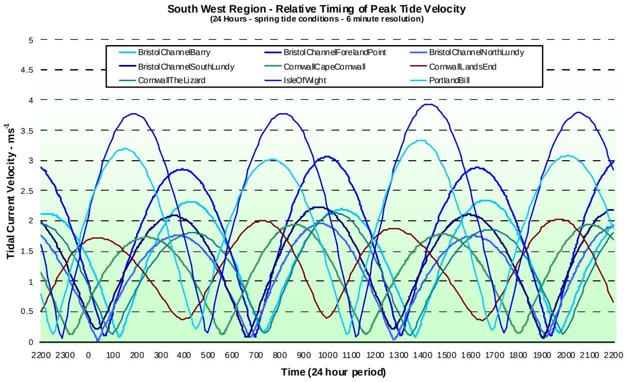
Variation in output levels during Spring tide cycles is significantly lower in this region than in other UK regions, ranging from 40% to highs of 90% to 100% of maximum output. During Neap tide conditions, output ranges from around 5% to around 30% of maximum output – it is rare that output drops to zero.

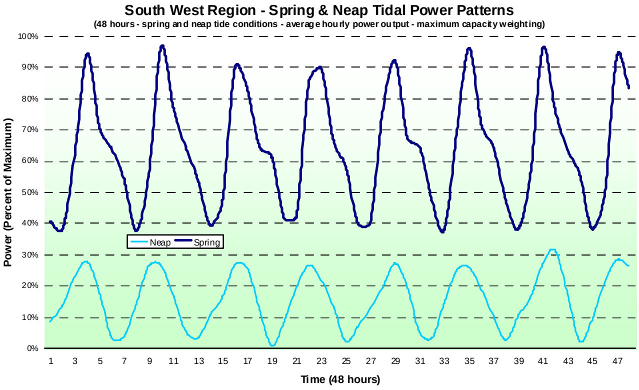
Impact of Diversity & Development

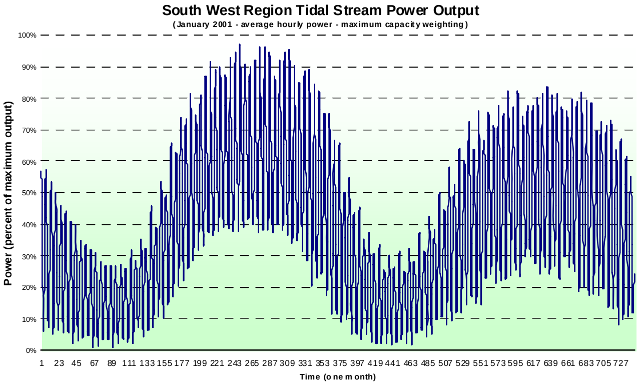
The sites of Lands End, The Lizard and Barry are important for the variety they bring to the timing of power output in the region, however they account for only 11.6% of available capacity. There is variation in power output patterns of the remaining sites which acts to lower the hourly variability of this region (particularly at high development levels).

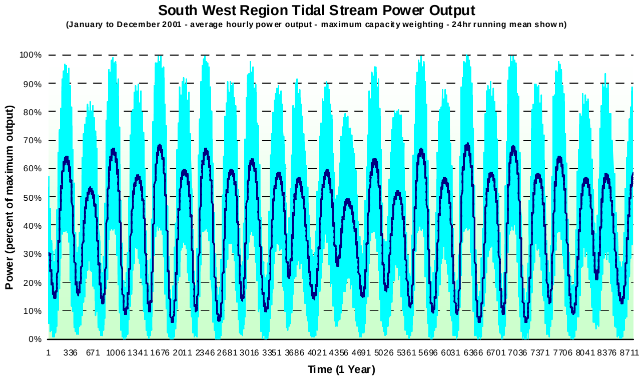
By restricting development of the resource to the two main sites of Foreland Point and Portland Bill, there would be a small increase in hourly variability. However, given the difficulty of developing the resource at some of the more remote sites, such as North and South Lundy where transmission costs would be high, it may be appropriate to focus development in the region around key sites such as Foreland Point and Portland Bill. Measures of average hourly variability under a range of development scenarios are given in the table below.

Installed Capacity (% of Regional Maximum)	Average Hourly Variability (as % of Maximum Output)
10%	6.7%
25%	8.4%
50%	10.9%
100%	13.7%
2 Main Sites (80%)	14.9%







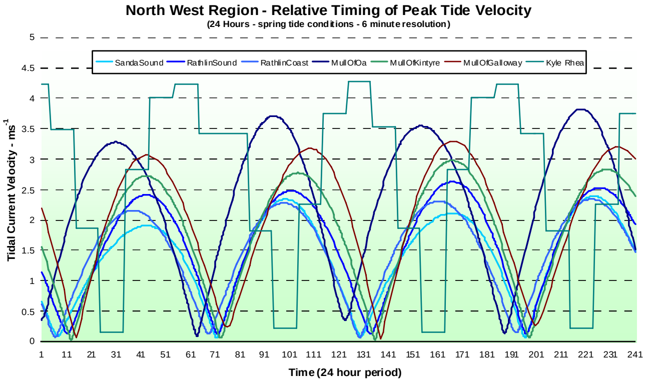


Tidal Power Properties – North West Region

Overview

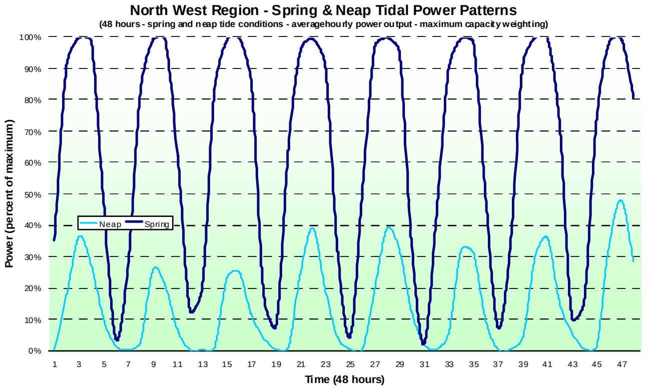
The North West Region accounts for just over 8% of tidal current development potential in the UK. This analysis is restricted to seven of the eleven sites in the region due to poor tidal current data availability, however the four sites not included (Dorus Mor, Gulf of Corryvreckan, Loch Linne and Wigtown Bay) together represent only 5% of the region's resource (0.4% of the UK resource).

With the exception of Kyle Rhea (2.4% of the assessed regional resource), the remaining six sites have highly correlated outputs, limiting the opportunity to smooth the hourly fluctuations in power output from the region.



Power Output Distribution

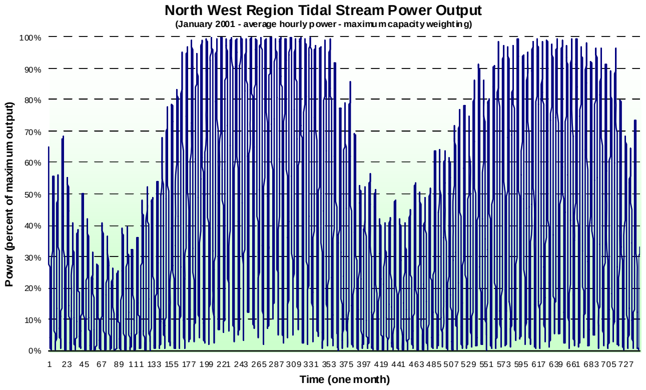
The correlated nature of energy production in this region results in large variations in hourly power output, particularly during Spring tide conditions. Electricity generation typically peaks at around 100% of maximum during Spring tides, with minimum output commonly less than 10%. During Neap tide conditions, the output range is from 0% to around 20% to 50% of output.

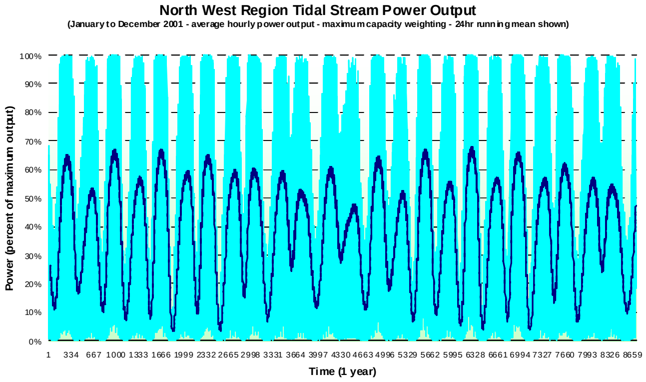


Impact of Diversity & Development

There is little opportunity for site diversity to smooth the hourly electricity output from this region, as the major generating sites exhibit highly correlated production patterns. While Kyle Rhea provides a production pattern that is out of phase with the major sites, the small development potential of this site quickly limits its impact on overall production patterns at significant development levels.

The two sites of Mull of Galloway and Rathlin Island together account for 84% of generating capacity in the region, and their production patterns dominate the regional output pattern. With development occurring at just these two sites, there is only a small increase in the hourly variability in the region - therefore, it may be appropriate to focus development on these two sites, rather than developing the full range of sites in this region.





Installed Capacity (% of Regional Maximum)	Average Hourly Variability (as % of Maximum Output)
10%	15.6%
25%	20.6%
50%	22.3%
100%	23.5%
2 Main Sites (71%)	23.9%

Tidal Power Properties – Northern Isles Region

NOTE: The island and channel systems in the Orkney and Shetland Islands complicate the analysis of temporal patterns of tidal energy in these regions. Assessment of four of the eight sites in this region (55% of regional development potential) was carried out with Tidal Atlas data. While the findings given for this region are considered reliable, the accuracy of data from the Tidal Atlas for this region is considered lower than that available for other sites included in this report.

Overview

The Northern Isles Region includes eight sites located in the northern Orkney and Shetland islands (the North and South Bluemull Sound sites have been grouped as one), which together account for almost 8% of UK development potential.

The majority of sites in this region show correlated velocity patterns, however Bluemull Sound (14% of regional potential) does exhibit some variation from this pattern.

Power Output Distribution

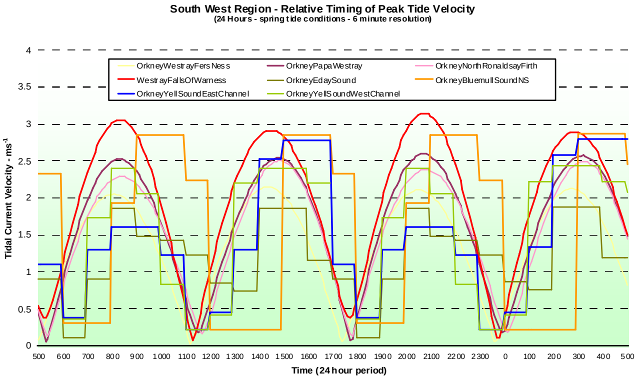
Spring tide electricity generation levels vary significantly, both between high and low tide and between successive high tides, with maximum output levels alternating between 100% and 70% to 80% of maximum for successive high tides. Minimum output levels are typically in the 0% to 20% range. Neap tide generation levels typically range from 0% to 30% of maximum.

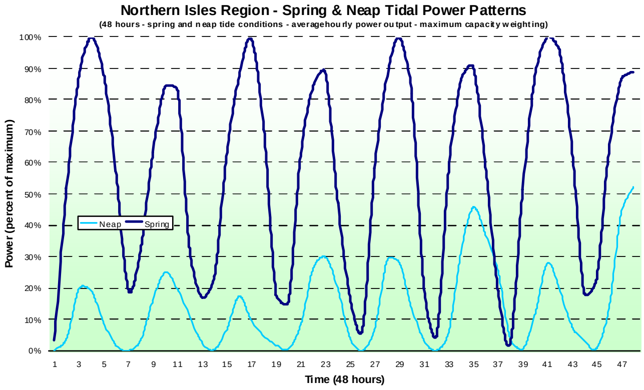
Impact of Diversity & Development

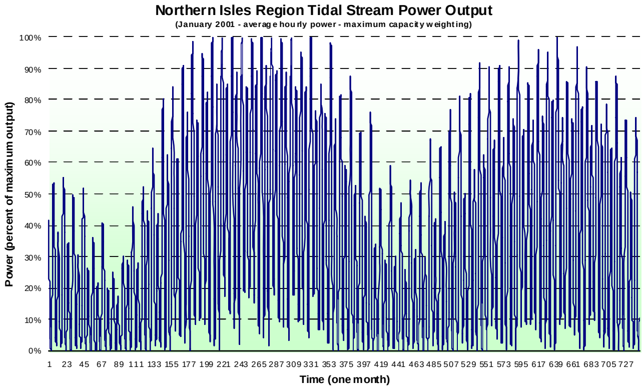
Hourly variability levels are relatively insensitive to development levels in this region. The diversity of generating locations would be expected to smooth hourly variation and limit the impact of different development levels on hourly variability; however, the correlated nature of electricity production at many of the sites restricts the impact of this diversification.

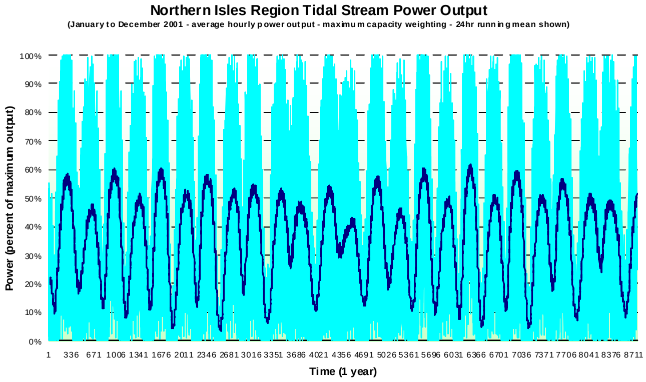
Four of the eight sites in the region represent 75% of development potential – were development to be restricted to these sites, the impact on hourly variability levels would be minor.

Installed Capacity (% of Regional Maximum)	Average Hourly Variability (as % of Maximum Output)
10%	17.9%
25%	18.1%
50%	18.9%
100%	20.6%
4 Main Sites (75%)	21.8%









Tidal Power Properties – United Kingdom

Overview

The electricity generating potential of the UK tidal current resource is estimated to be 15.6TWh (Black & Veatch, 2005), representing around 4% of UK final consumer demand for electricity of 334TWh (DUKES, 2004). The original 48 UK generating locations identified by Black & Veatch were grouped into 40 sites, 35 of which were included in this study. The tidal power potential of the Isle of Wight was then added to the site list, and each site was assigned to one of five regions (see Appendix 1).

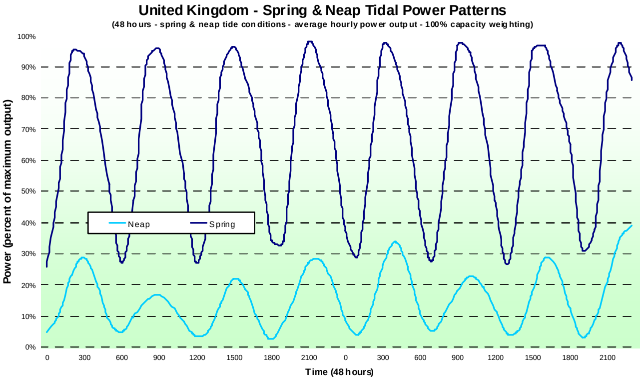
These 36 sites represent 98.7% of the identified tidal current potential of the UK. However it is important to note that 61% of this potential is located in the Pentland Region, with a further 14% located in the Channel Isles Region. The remaining potential capacity is spread across the South West, North West and Northern Isles regions.

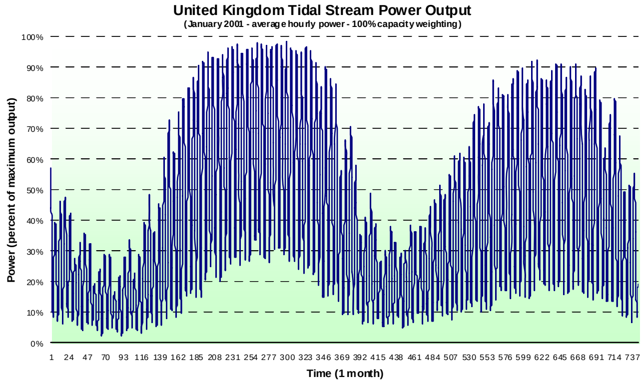
Power Output Distribution

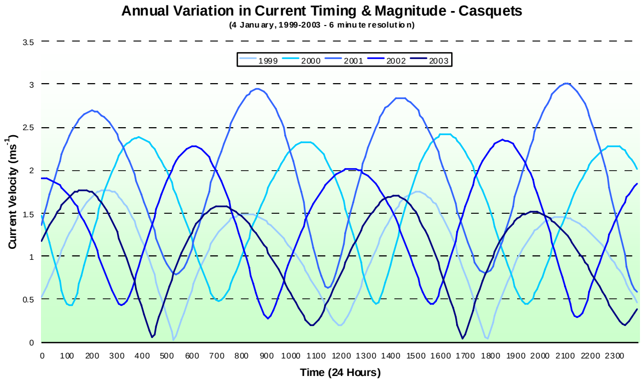
Developed to its maximum potential, the aggregate electricity output from the UK's tidal current resource would exhibit significant variation. There are a number of factors that contribute to this – the semi-diurnal pattern of current velocity at each site, the Spring-Neap tide cycle, the correlation of tidal current velocities at different locations, and the (severe) capacity limitations at many of the sites identified in the UK. These factors are discussed below in relation to a maximum capacity scenario – relevant graphs are presented to the right.

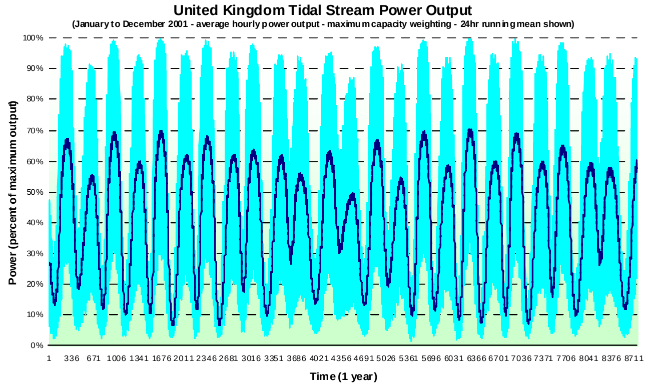
Semi-diurnal: significant diurnal variation in output was apparent over each 24 hour period, with Spring tide peak output around 90% to 100% of installed capacity, and Spring minimums around 15% to 30% of maximum. During Neap tide conditions, maximum output was typically around 15% to 40% of installed capacity, with minimums of less than 10% of peak output (graph 1, this page).

This level of daily variation in output (ignoring the impact of the Spring-Neap tide cycle) appears large, given the range of sites available in the UK and the natural diversity this brings in terms of different generating patterns - there are two interlinked reasons that this is not seen in the results. The first is the dominant role that output from the Pentland Region plays in driving the pattern of production of the whole system – not only does this region provide 52% of total output, but the power output patterns from the sites in this region are highly correlated. It would require all remaining sites in the UK to show different patterns of production for the influence of the Pentland Region to be overcome, and this is not the case.









The second reason is that the sites in other regions with generation patterns that would smooth the variation seen in the Pentland Region all have limited development potential. Thus, at sites where tidal current patterns are poorly correlated to those in the Pentland Region (ie output is at a maximum when output from the Pentland Region is at a minimum), the severe limitation on development at these sites means that their beneficial contribution to total output (in terms of the time of generation) is quickly swamped by other large generating sites. The impact of development capacity is discussed further in following sections.

Spring-Neap Tide Cycle: Longer-term patterns of generation are strongly influenced by the variation in current velocities caused by the Spring-Neap tide cycle. Average output levels during Spring tide conditions can reach 70% of maximum, while average Neap tide output can drop to as little as 6% of installed capacity (see graph 2, previous page).

This change from Spring to Neap tide conditions, and hence the change in average output (and corresponding changes in peak and minimum outputs), occurs every seven days, with the cycle repeating every 14 days. Furthermore, there is no diversification strategy that can be employed to overcome this cycle. Whilst some sites may show slightly less Spring to Neap output variability, the overall trend, and more importantly the timing of the Spring-Neap tide cycle, is controlled by the sun and moon, and the interaction of the gravitational and orbital characteristics of the sun-moon-earth system. As a result, the timing of Spring-Neap tide cycle is identical throughout the world, and cannot be smoothed through diversity amongst tidal current power systems alone.

Whilst the period of the Spring-Neap tide cycle is fixed at around 14 days, the absolute timing of Spring and Neap tides in relation to Gregorian calendar (365.25 days per year) will vary from year to year. This means that the high and low output fluctuations that accompany Spring and Neap tides do not occur on fixed dates each year, but vary from year to year (see graph 3, previous page). The date at which Spring and Neap tides occurs will advance by about 3 days each year.

Seasonal: there is a seasonal variation in the intensity of the Spring-Neap tide cycle, with the tidal range (and hence current velocity) increasing to a maximum and decreasing to a minimum every six months (see graph 4, previous page). This variation in intensity causes a noticeable change in tidal power output across the year – average Spring tide output varies by around 20% (ie from 50% to 70% of maximum), while average Neap tide output varies by about 25% (ie from 5% to 30% of maximum). The difference in average output from successive Spring and Neap tides ranges from 20% of maximum (at the summer solstice) to around 65% of maximum (during the spring and autumn equinoxes).

The driving force for this variability is again the positioning of the sun and moon – Spring tides are highest during the Vernal Equinox (the spring equinox in March) and Autumnal Equinox (the autumn equinox in September), with the corresponding Neap tides and this time being the lowest of the year. Spring and Neap tides are at their least intense during the winter solstice (December) and summer solstice (June) - in the UK, the lowest intensity is during the summer solstice when the sun is closer to the UK, increasing its influence over the tides relative to the moon.

Given that control of this seasonal variation is through the positioning of the sun and moon (and the relative positioning of the earth's axis in relation to the sun), it is not possible to diversify generating capacity in the UK to overcome this variability. However, the repeating nature of this pattern does result in the lowest average Spring tide output always coinciding with a period of seasonally low electricity demand in the UK.

Impact of Diversity & Development

Full development of the UK's tidal current power potential leads to a distribution of generating capacity that reflects the development potential of each individual site. With total output dominated by the output patterns from the Pentland Region and other correlated sites, the aggregate pattern of supply from the UK shows significant hourly variability. However, at lower levels of development there is scope for minimising the aggregate hourly variability of the system. The scenarios examined include:

- Limited Development Scenarios: in which the total development level of the UK tidal current resource is restricted to 10%, 25%, 50% or 80% of maximum.
- Restricted Site Scenarios
    - Largest 10 sites (by output) only;
    - Northern, Pentland and Channel Isles only, and
    - All sites except Channel Isles

For each scenario, the optimal contribution to total output was determined for each site included in the scenario.

Limited Development Scenarios: Fully developing the UK's tidal current resource would see each individual site contributing to the total output in proportion to its development potential. Under this development scenario, there is no opportunity to alter the relative contribution of each site, as each site has been developed to the maximum possible level and the individual site limits would set the actual contribution level for each site. However, in a limited development scenario, individual site development limits represent the only the maximum level of contribution, allowing the relative contribution of different sites to the total to be optimised.

Four levels of resource development were investigated – optimisation modelling was used to determine the contribution of each site that resulted in the lowest average hourly variability (expressed as a percent of maximum output) that could be achieved for the given level of resource development (the optimal contribution), The contribution of each site was constrained by the maximum allowable development.

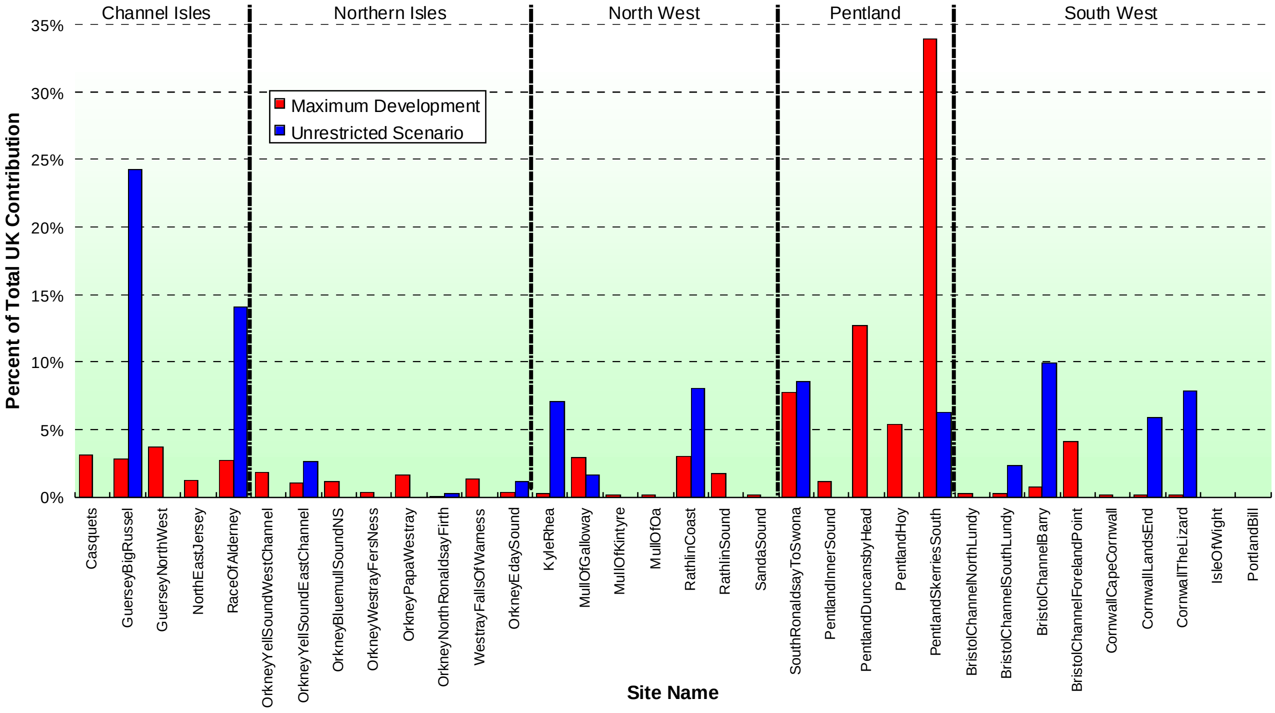
The results of this optimisation process are shown in the table (right), while sample output graphs for the restricted sites are shown on the following page (graphs relating to the maximum capacity scenario are shown on page 16). It is clear from this table, and from the hourly output patterns, that the overall level of development of the UK tidal resource exerts a strong control over the degree of hourly variability seen in the aggregate output. The underlying reason for this impact is that the relative importance of different sites in contributing to total output changes as the development level changes. For example, Race of Alderney (Channel Isles Region) contributes just over 6% of total output under a maximum capacity scenario, however it accounts for 25% of all output in a 10% development scenario, whilst the contribution from Pentland Skerries (Pentland Region) falls from almost 30% of total output to 9.9% under the same scenarios.

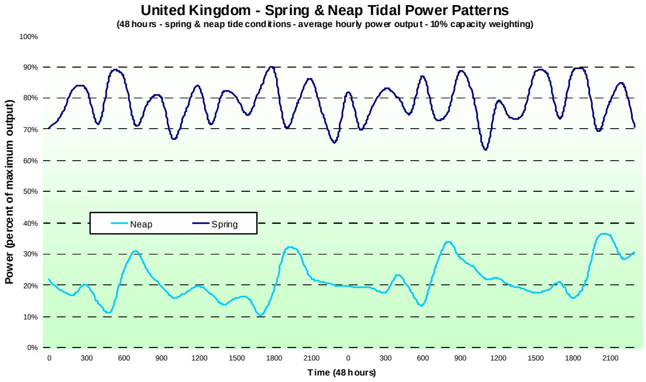
Installed Capacity (% of United Kingdom Maximum)	Average Hourly Variability (as % of Maximum Output)
10%	4.2%
25%	6.3%
50%	11.8%
80%	15.6%
100% (maximum capacity)	17.4%

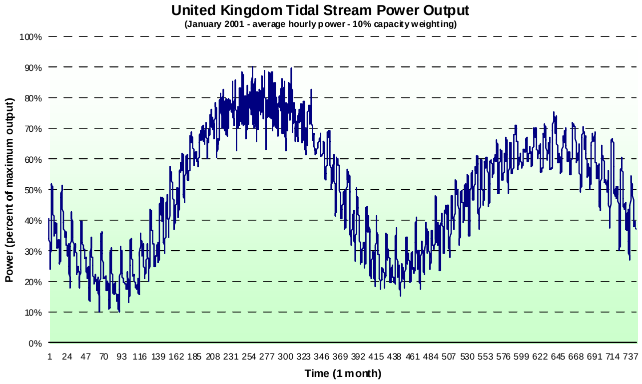
An additional scenario was investigated in which there were assumed to be no capacity limits at any of the sites – an impossible assumption but one that effectively illustrates the importance of site availability. Under this scenario, average hourly variability fell to just 3.5%, however to achieve this result required an enormous change in the contribution of different sites to overall output – the graph below shows the relative site contribution under the maximum capacity and unrestricted scenarios.

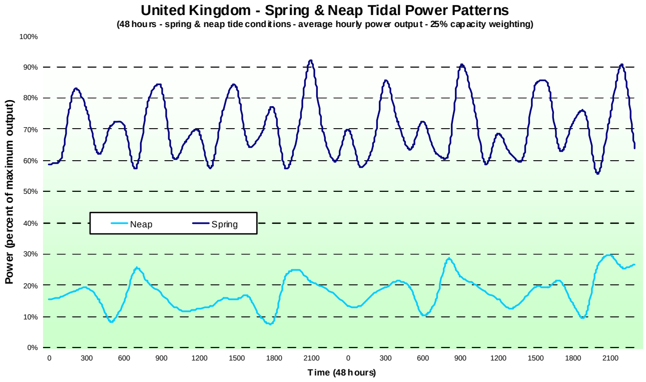
Contribution of Individual Sites to UK Tidal Current Capacity

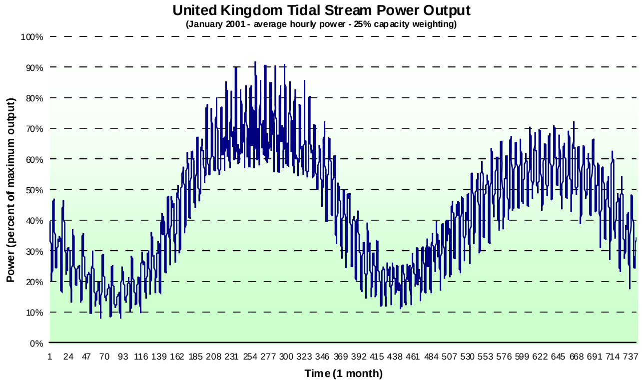
(Maximum development and unrestricted development scenarios)

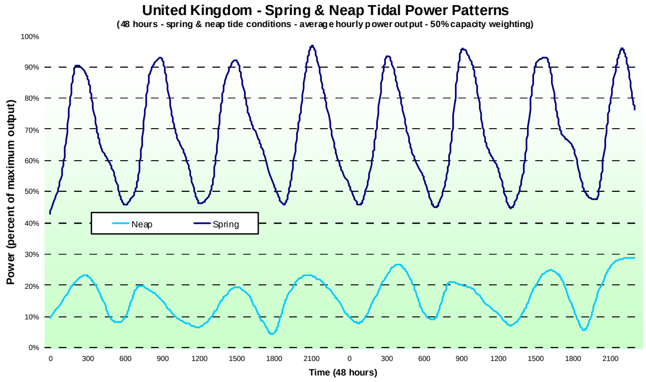


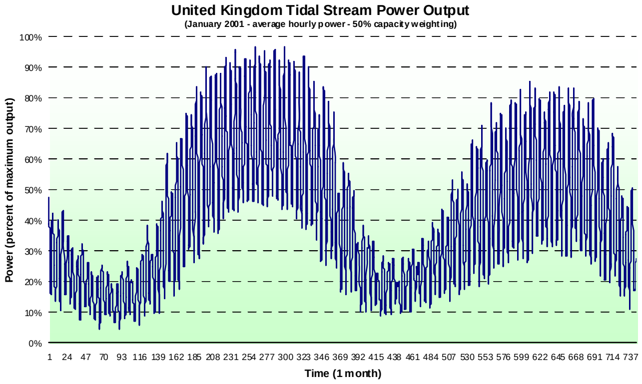

United Kingdom - Spring & Neap Tidal Power Patterns
(48 hours - spring & neap tide conditions - average hourly power output - 10% capacity weighting)

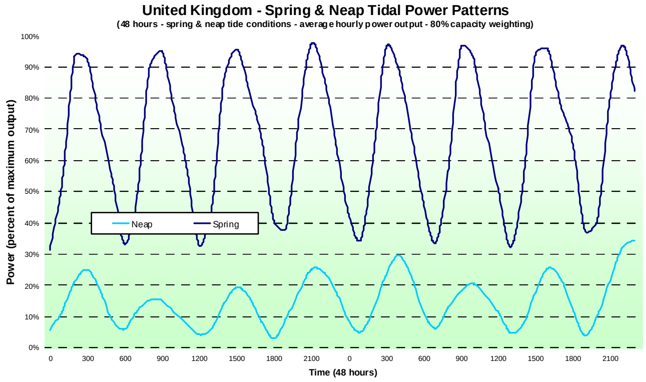

United Kingdom Tidal Stream Power Output
(January 2001 - average hourly power - 10% capacity weighting)

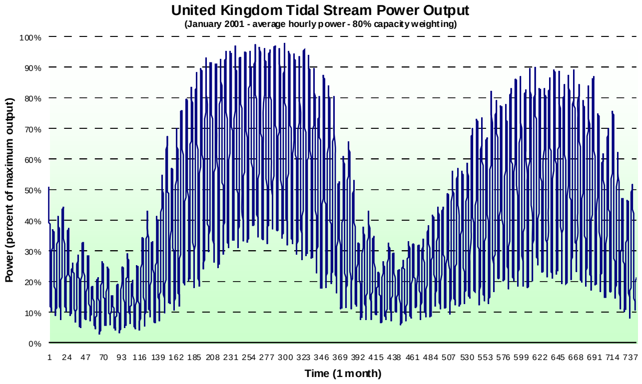

United Kingdom - Spring & Neap Tidal Power Patterns
(48 hours - spring & neap tide conditions - average hourly power output - 25% capacity weighting)


United Kingdom Tidal Stream Power Output
(January 2001 - average hourly power - 25% capacity weighting)


United Kingdom - Spring & Neap Tidal Power Patterns
(48 hours - spring & neap tide conditions - average hourly power output - 50% capacity weighting)


United Kingdom Tidal Stream Power Output
(January 2001 - average hourly power - 50% capacity weighting)


United Kingdom - Spring & Neap Tidal Power Patterns
(48 hours - spring & neap tide conditions - average hourly power output - 80% capacity weighting)


United Kingdom Tidal Stream Power Output
(January 2001 - average hourly power - 80% capacity weighting)

Restricted Site Scenarios: Three scenarios were examined where the range of available sites was limited to a subset of the UK total, with the development level being around 80% of the total available resource in each case. The average hourly variability results (table, right) should be compared to the 80% limited development scenario result (where all sites were available) of 15.6%.

The Northern, Pentland and Channel Isles scenario is particularly interesting – it showed the lowest hourly variability of the three scenarios, and with a low number of sites concentrated in just three regions there may be associated cost savings (eg transmission development and reinforcement to a limited number of locations).

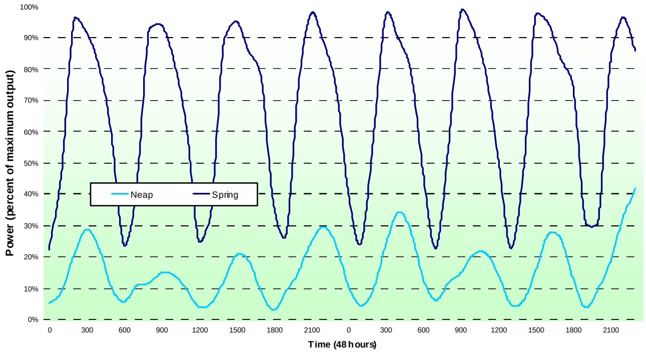
Developing the largest 10 sites is another strategy aimed at concentrating development in a small number of locations. This strategy resulted in developments in the Pentland, Channel Isles & North West regions, as no large individual sites are in the Northern or South West regions.

Development of all sites except those in the Channel Isles was proposed as a strategy for avoiding the transmission costs associated with linking the islands to mainland UK. However, not only did this strategy result in a large hourly variability, but it required the full development of 31 sites in four regions to achieve the 80% development level, compared to 12 sites and 10 sites in the other scenarios.

Installed Capacity (% of United Kingdom Maximum)	Average Hourly Variability (% of Max Output)
82% - Northern, Pentland & Channel	18.0%
80% - Largest 10 Sites	19.5%
86% - All except Channel Isles	21.3%

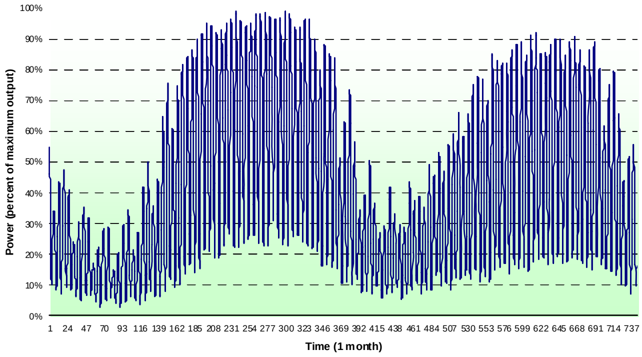
United Kingdom - Spring & Neap Tidal Power Patterns

(48 hours - spring & neap tide conditions - average hourly power output - Northern, Pentland & Channel Isles regions)



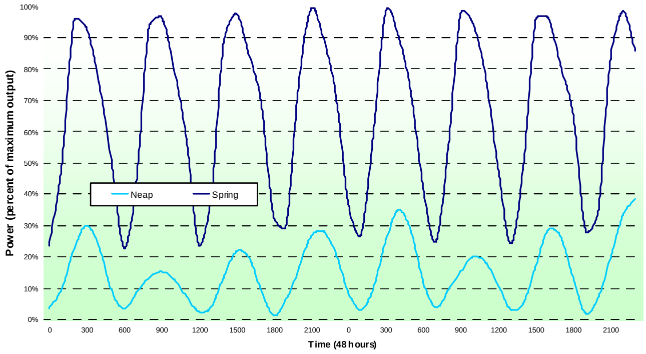
United Kingdom Tidal Stream Power Output

(January 2001 - average hourly power - Northern, Pentland & Channel Isles regions)



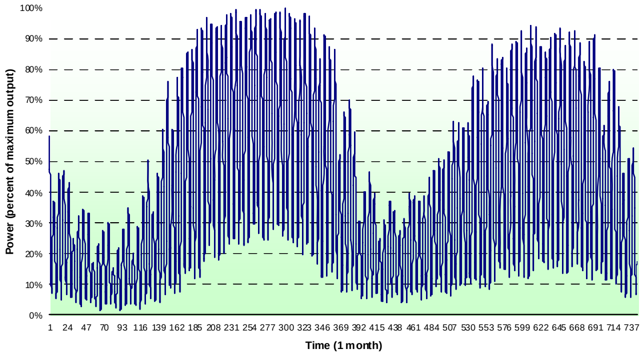
United Kingdom - Spring & Neap Tidal Power Patterns

(48 hours - spring & neap tide conditions - average hourly power output - 10 largest sites)



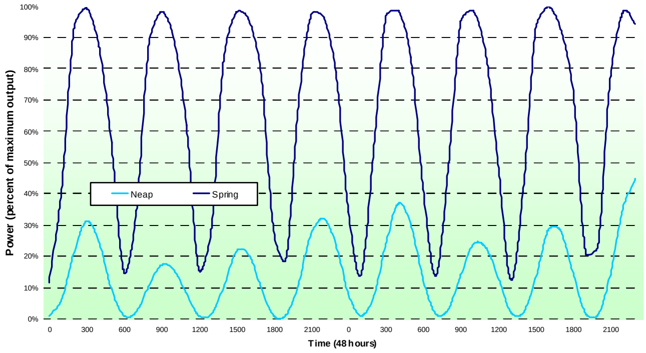
United Kingdom Tidal Stream Power Output

(January 2001 - average hourly power - 10 largest sites)



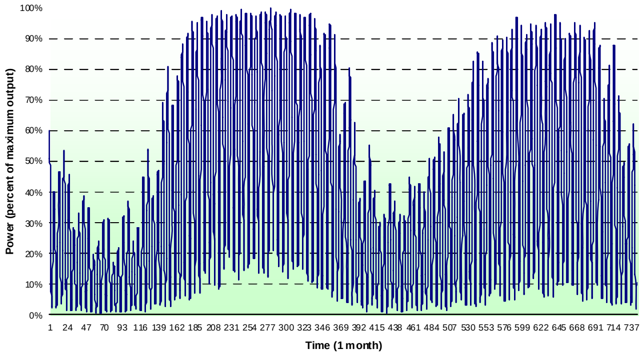
United Kingdom - Spring & Neap Tidal Power Patterns

(48 hours - spring & neap tide conditions - average hourly power output - all sites except Channel Isles region)



United Kingdom Tidal Stream Power Output

(January 2001 - average hourly power - all sites except Channel Isles region)



Tidal Power Installed Capacity and Variability

Installed Capacity by Region

The table below shows the distribution of tidal power yield (in GWh/y) and generating capacity (in MW) across the tidal sites and regions in the UK. These values are based on Table 4-6 from Black & Veatch (2005) – no SIF correction has been included for the smaller sites.

The installed capacity is a function of both the rated current velocity for the turbines at that location (Appendix 1), and the capacity factor (shown below). Also shown is the relative contribution of each site and region to total tidal power output (maximum capacity scenario).

Rate of Change of Power Output

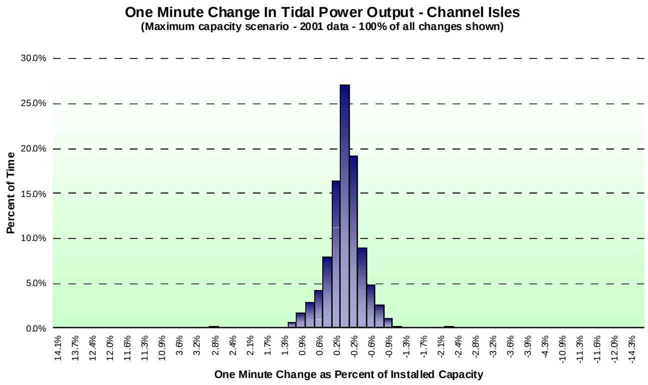
The following two pages provide descriptive statistics and distribution graphs that relate to the change of power output characteristics of tidal current power. Two regions, Channel Isles and Pentland Regions, were selected for this analysis – these two regions represent over 70% of UK tidal current potential, and all sites within these regions have high resolution tidal data available. For both regions, the change in power output has been determined over 1min, 10mins, 30mins and 60mins, and the frequency with which demand supply levels change is shown in the graphs.

	Site	Yield GWh/y	Proportion of Total Tidal Power Output	Installed Capacity MW	Capacity Factor
Channel Isles	Casquets	416	3.12%	110	43%
	Guersey Big Russel	380	2.85%	106	41%
	Guersey North West	492	3.69%	165	34%
	North East Jersey	164	1.23%	55	34%
	Race Of Alderney	365	2.74%	97	43%
Regional Total		**1,817**	**14%**	**533**	
Northern Isles	Orkney Yell Sound East Channel	251	1.88%	58	49%
	Orkney Yell Sound West Channel	132	0.99%	49	31%
	Orkney Bluemull Sound NS	150	1.13%	42	41%
	Orkney Westray Fers Ness	50	0.38%	19	30%
	Orkney Papa Westray	221	1.66%	74	34%
	Orkney North Ronaldsay Firth	8	0.06%	3	34%
	Westray Falls Of Warness	180	1.35%	54	38%
	Orkney Eday Sound	53	0.40%	19	32%
Regional Total		**1,045**	**8%**	**318**	
North West	Kyle Rhea	27	0.20%	7	47%
	Mull Of Galloway	383	2.87%	109	40%
	Mull Of Kintyre	22	0.17%	7	38%
	Mull Of Oa	22	0.17%	6	43%
	Rathlin Coast	408	3.06%	122	38%
	Rathlin Sound	235	1.76%	67	40%
	Sanda Sound	22	0.17%	8	33%
Regional Total		**1,119**	**8%**	**325**	
Pentland	South Ronaldsay To Swona	1,030	7.73%	294	40%
	Pentland Inner Sound	151	1.13%	40	43%
	Pentland Duncansby Head	1,699	12.75%	440	44%
	Pentland Hoy	714	5.36%	194	42%
	Pentland Skerries South	4,526	33.95%	1324	39%
Regional Total		**8,120**	**61%**	**2,292**	
South West	Bristol Channel North Lundy	36	0.27%	15	28%
	Bristol Channel South Lundy	32	0.24%	14	27%
	Bristol Channel Barry	96	0.72%	34	32%
	Bristol Channel Foreland Point	548	4.11%	156	40%
	Cornwall Cape Cornwall	23	0.17%	10	26%
	Cornwall Lands End	23	0.17%	10	26%
	Cornwall The Lizard	23	0.17%	10	27%
	Isle Of Wight	10	0.08%	3	41%
	Portland Bill	438	3.29%	116	43%
Regional Total		**1,229**	**9%**	**368**	
TOTAL		**13,330**	**100%**	**3,836**	

The Channel Isles Region shows a wide distribution in the rate of change of output at different time intervals. This outcome results from the (relatively) low correlation of the different sites forming a complex aggregate output pattern, with a wide range of changes in output from one time period to the next.

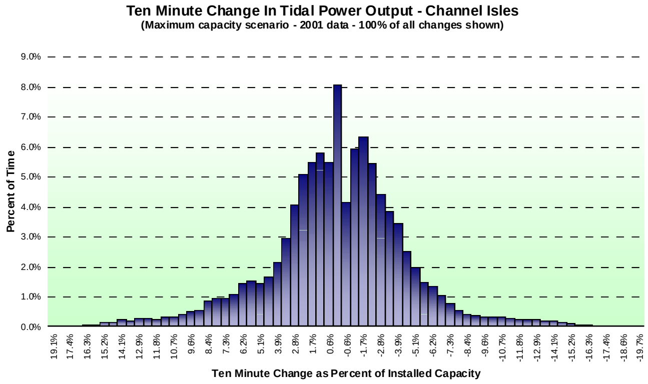
Channel Isles Region – One Minute Power Variation

Parameter	MW	Percent of Installed Capacity
Average Increase	2.7	0.5%
Peak Increase	75	14.1%
No Change	- - -	27.1%
Average Decrease	-2.5	-0.5%
Peak Decrease	-77	-14.4%



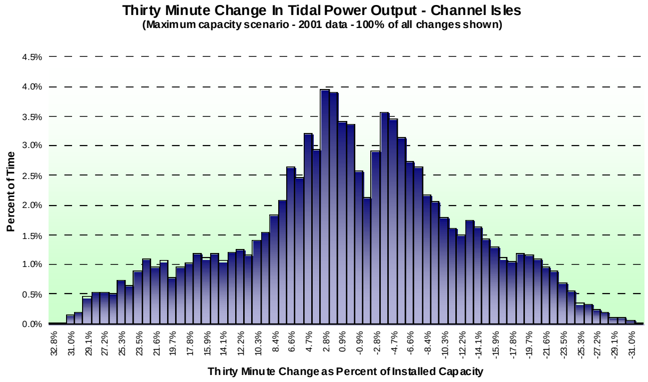
Channel Isles Region – Ten Minute Power Variation

Parameter	MW	Percent of Installed Capacity
Average Increase	19.9	3.7%
Peak Increase	102	19.1%
No Change	- - -	8.1%
Average Decrease	-19.0	-3.6%
Peak Decrease	-105	-19.7%



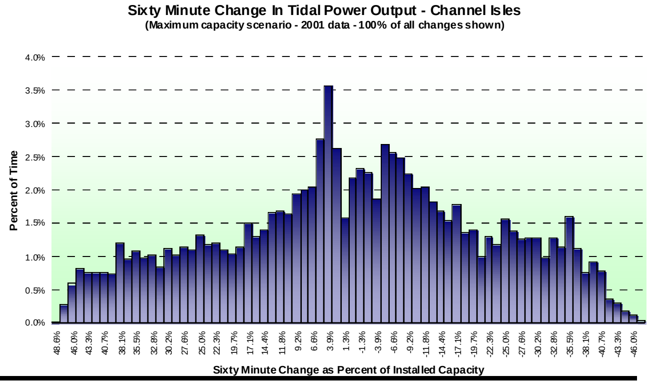
Channel Isles Region – Thirty Minute Power Variation

Parameter	MW	Percent of Installed Capacity
Average Increase	54.9	10.3%
Peak Increase	175	32.8%
No Change	- - -	3.4%
Average Decrease	-54.4	-10.2%
Peak Decrease	-170	-31.9%



Channel Isles Region – Sixty Minute Power Variation

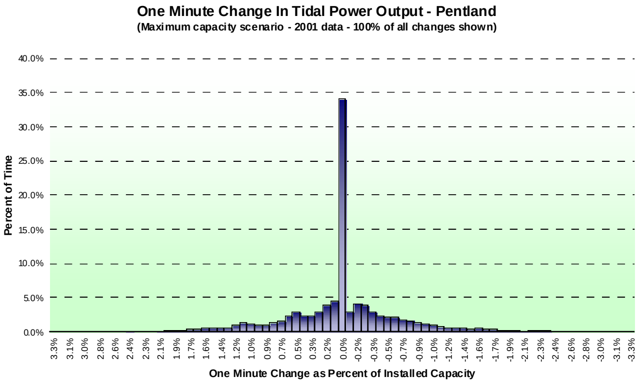
Parameter	MW	Percent of Installed Capacity
Average Increase	100.8	18.8%
Peak Increase	259	48.6%
No Change	- - -	2.2%
Average Decrease	-96.3	-18.1%
Peak Decrease	-252	-47.3%



The Pentland Region shows both greater average output variability and a larger proportion of hours with no change. These characteristics result from the correlated output patterns of the sites in this region, which give rise to many consecutive periods of peak output and of low to zero output.

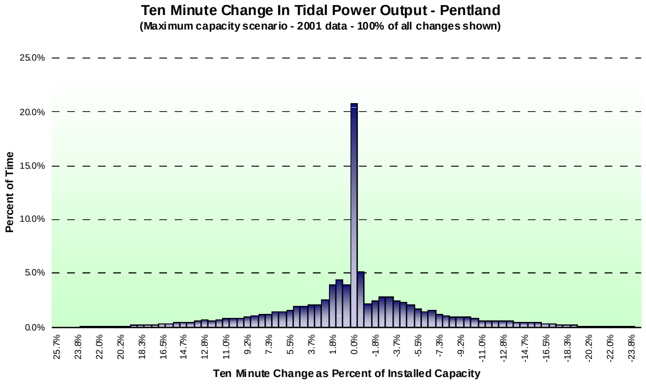
Pentland Region – One Minute Power Variation

Parameter	MW	Percent of Installed Capacity
Average Increase	14.3	0.6%
Peak Increase	76	3.3%
No Change	- - -	34.1%
Average Decrease	-14.5	-0.6%
Peak Decrease	-76	-3.3%


One Minute Change In Tidal Power Output - Pentland
(Maximum capacity scenario - 2001 data - 100% of all changes shown)

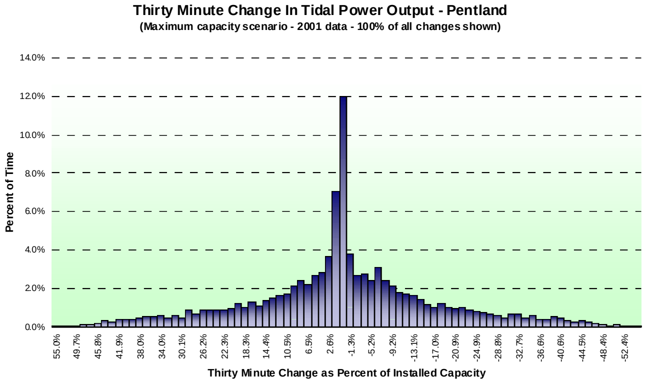
Pentland Region – Ten Minute Power Variation

Parameter	MW	Percent of Installed Capacity
Average Increase	130	5.7%
Peak Increase	588	25.7%
No Change	- - -	20.8%
Average Decrease	-134	-5.8%
Peak Decrease	-560	-24.4%


Ten Minute Change In Tidal Power Output - Pentland
(Maximum capacity scenario - 2001 data - 100% of all changes shown)

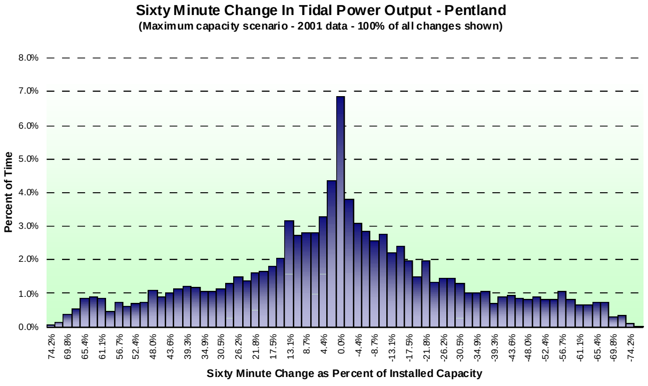
Pentland Region – Thirty Minute Power Variation

Parameter	MW	Percent of Installed Capacity
Average Increase	315	13.7%
Peak Increase	1260	55.0%
No Change	- - -	12.0%
Average Decrease	-341	-14.9%
Peak Decrease	-1260	-55.0%


Thirty Minute Change In Tidal Power Output - Pentland
(Maximum capacity scenario - 2001 data - 100% of all changes shown)

Pentland Region – Sixty Minute Power Variation

Parameter	MW	Percent of Installed Capacity
Average Increase	572	25.0%
Peak Increase	1700	74.2%
No Change	- - -	6.9%
Average Decrease	-591	-25.8%
Peak Decrease	-1750	-76.4%


Sixty Minute Change In Tidal Power Output - Pentland
(Maximum capacity scenario - 2001 data - 100% of all changes shown)

Tidal Power Variability and Electricity Demand

Interaction with Electricity Demand

The analysis of the UK's tidal current resource has so far considered the regional and total resource in isolation from the electricity network. In practice the output of tidal current devices would be integrated into the UK electricity network and would, in part, meet the continuously variable demand experienced by the network.

In this context, it is important to consider the impact that the variable output of tidal power would have on the electricity network. For this analysis, the following assumptions have been made:

- Tidal current power has been developed to the maximum capacity limit at each site (average hourly variability is 16.5% of maximum output);
- There are no transmission constraints (necessary for this analysis, but unrealistic from a cost perspective);
- The contribution of tidal power is seen as a "negative load" on the network;
- The hourly output of the tidal current system is precisely predictable at any time horizon, and
- The hourly electricity demand pattern is that of England & Wales.

Prediction and Seasonal Patterns of Demand

The output of tidal power systems can be predicted many years in advance, allowing future electricity output to be accurately known at hourly or better resolution. In addition, seasonal output variations are extremely low, despite the variation in output from semi-diurnal and fortnightly patterns. Summer shows the lowest seasonal output, 1.5% below the annual average.

At a monthly level variability was similarly limited by the averaging of output across two Spring-Neap tide cycles, smoothing aggregate output between months. August showed the lowest monthly output during 2001 (4% below average), while February showed the highest (3% above average).

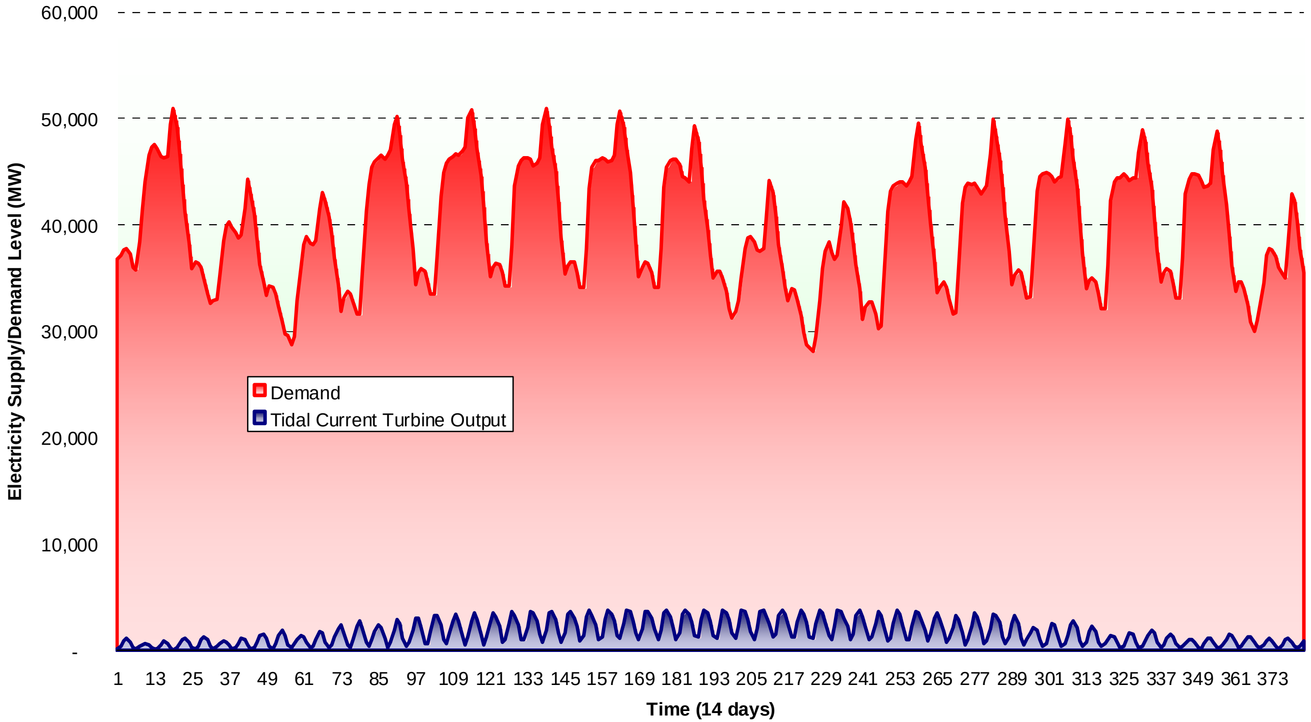
Electricity Supply and Demand Patterns

The graph below shows the typical contribution that tidal current power would make towards meeting winter electricity demand over a two-week period. It is clear from this graph that the semi-diurnal variability in output occurs at a much higher frequency than the daily variability in electricity demand. However, since the general pattern of demand variability occurs on an exact 24 hour cycle, whereas the semidiurnal pattern of tidal power occurs on approximately a 24hr 50min cycle, the relationship between hourly change in demand and tidal supply levels is constantly changing – for some days the morning demand rise will be accompanied by an increase in tidal output, whilst on other days it will be accompanied by a decrease in tidal output.

The second feature illustrated by this graph is the influence of the Spring-Neap tidal cycle, with Neap tide

Tidal Power Contribution to Electricity Demand

(2001 - hourly tidal supply data - hourly England & Wales demand data - typical Neap-Spring-Neap tide cycle)

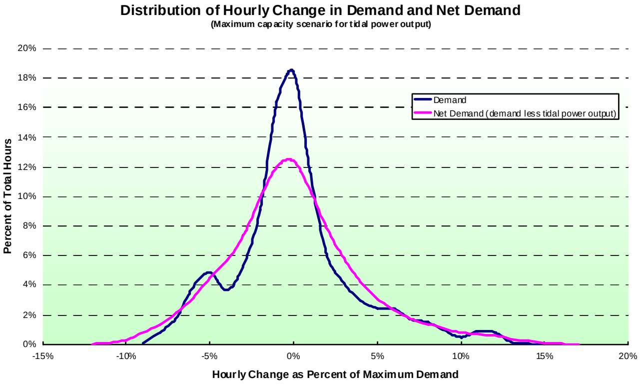


conditions limiting output at the beginning and end of the two week period, and Spring tide conditions contributing to high tidal output during the middle of this period. This Spring-Neap output pattern is more apparent in the graph of annual electricity demand and tidal power supply (below), which matches average daily electricity demand to average daily tidal current output. Less apparent is the annual cycle that accentuates differences in output between Spring and Neap tide outputs in March and September, and reduces them around the new year and in the middle of the year (although this pattern has little impact on seasonal or monthly output levels).

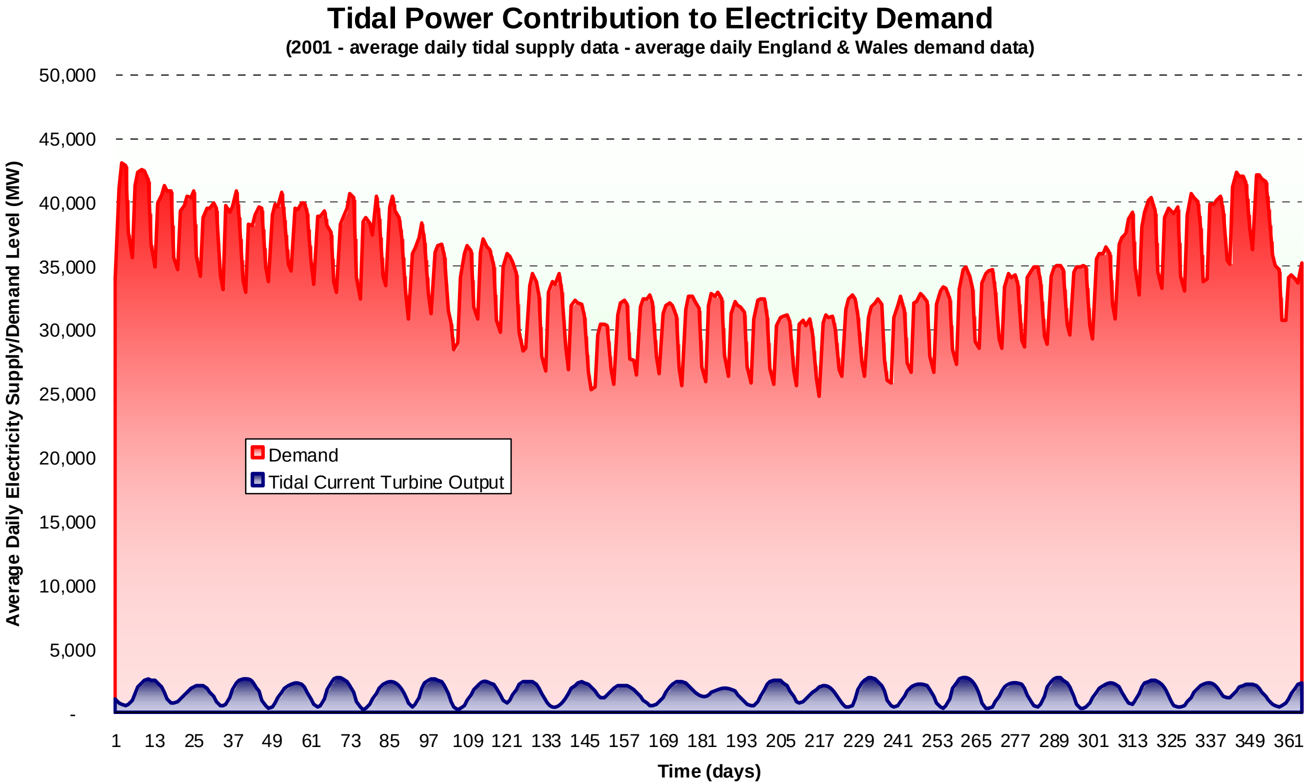
Impact on Hourly Demand Change

Hour-to-hour variation in electricity demand needs to be met, either through the scheduling of additional plant to meet an increase in demand, or by taking operating plant offline in response to a demand reduction. By treating the output of tidal current devices as a negative load on the network, the net demand to be met by conventional capacity is simply calculated by subtracting the hourly tidal output from the hourly demand level. Since tidal power output is predictable to a high degree of accuracy, it does not increase demand-side forecast errors.

The graph to the right shows the impact that tidal power has on the hour-to-hour change in conventional capacity requirement. From this graph it is apparent that the introduction of tidal power to the electricity network would cause a small increase in the load-following requirement of the network – data describing current load-following characteristics (Demand) and the new characteristics (Net Demand) are presented in the following table. From these results it appears that the hourly variability in tidal power would have a limited negative impact on load-following requirements of the network, however further work is required to quantify the cost of this impact.



Parameter	Without Tidal	With Tidal
Hourly Change <±0.5%	18.4%	15.3%
Average Hourly Increase	3.70%	3.80%
Peak Hourly Increase	15%	17%
Average Hourly Decrease	-2.88%	-3.27%
Peak Hourly Decrease	-9%	-12%
St.Dev. of variability as percent of peak (net) demand	3.7%	4.1%



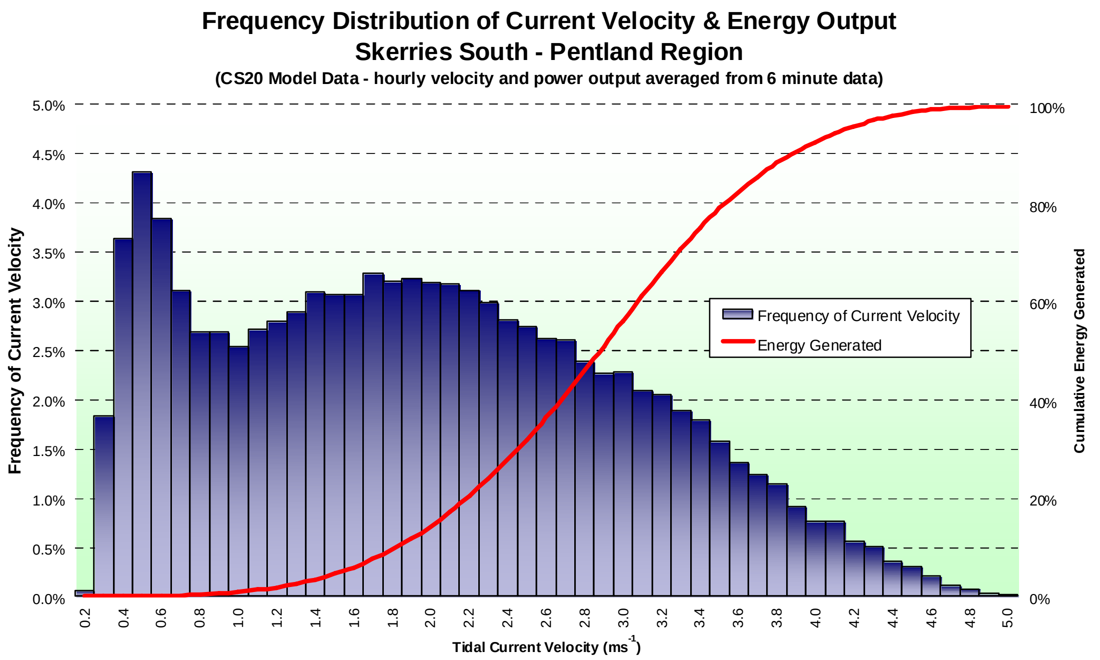
Current Velocity Distribution – Selected Sites

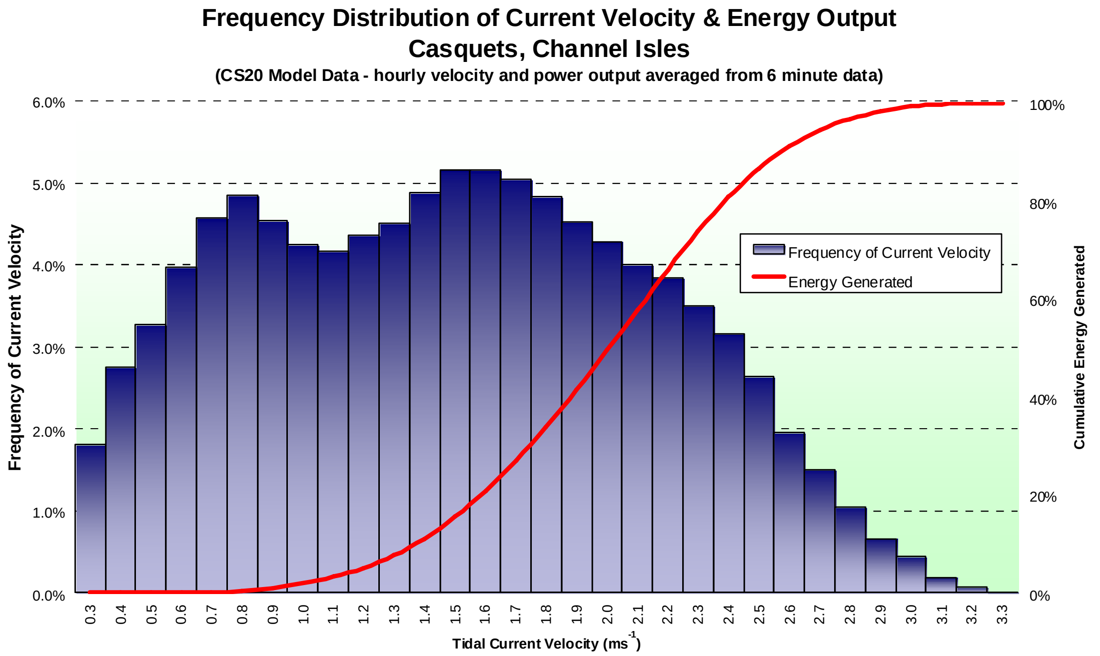
Discussion

Tidal current velocities vary from a minimum to a maximum and back four times a day, with the absolute value of the minimum and maximum dependent on the site and tidal cycle (most importantly, whether it is a Spring or Neap tide).

The two graphs below show the distribution of current velocities for Skerries South in the Pentland Region (top) and Casquets in the Channel Isles Region (bottom). Cumulative energy output from the sites is also shown.

Both sites show twin peaks in the velocity histogram; the first occurs below the cut-in velocity of 1ms^{-1} for the modelled tidal current devices (0.5ms^{-1} for Skerries South and 0.8ms^{-1} for Casquets), while the second occurs at the modal velocity (around 1.9ms^{-1} for Skerries South and around 1.6ms^{-1} for Casquets). Around 80% of all electricity generated at the Pentland site is produced at current velocities less than 3.6ms^{-1}, whilst at the Channel Isles site around 80% of all generation hours occur at current velocities below 2.5ms^{-1}.


Frequency Distribution of Current Velocity & Energy Output
Skerries South - Pentland Region
(CS20 Model Data - hourly velocity and power output averaged from 6 minute data)


Frequency Distribution of Current Velocity & Energy Output
Casquets, Channel Isles
(CS20 Model Data - hourly velocity and power output averaged from 6 minute data)

Characteristics of the United Kingdom Wave Power Resource

United Kingdom Wave Power Resource

Overview

Surface ocean waves allow the movement of kinetic energy through water. Waves can be generated by a number of mechanisms, however it is waves formed by the action of wind on the surface of the water that are potentially useful for generating electricity. This requires the placement of devices that extract some or all of this wave energy.

Waves are a common feature along many coastlines, and it is generally recognised that strong onshore winds will generate waves. However, energy transfer within a wave is extremely efficient – as a result, waves can travel enormous distances before releasing their energy at the coastline. Therefore, the energy in a wave is not necessarily the result of local wind patterns, but can be the result of distant wind systems that never reach land.

The distribution of wave energy around the UK coast is highly variable – continental Europe limits wave generation on the east coast of the UK, while Ireland acts to protect large sections of the UK's western coastline from oceanic swells. However, the Renewable Resource Atlas (DTI, 2004) identifies significant wave power resources in the north-west and south-west of the UK, and this report focuses on these regions.

Wave Power Assessment

This section presents an assessment of the patterns of electricity generation that would be expected from the development of wave power electricity generating systems in the UK. This focus differs from the Renewable Energy Atlas as it is concerned with the patterns of variability of the wave power resource over time and in different locations, rather than the average available wave resource.

By examining the hour-to-hour fluctuations of wave power, the variability associated with this renewable energy source can be assessed. Furthermore, differences in the pattern of electricity generation between different locations can be determined, as well as identifying the opportunities and limitations to developing the resource in a manner that reduces system-wide variability.

Detailed records of wave height and period (the time for successive wave crests to pass a given point) were used to develop time series of wave power availability. Ideally, data from a range of sites would be used for this purpose, with data being collected at frequent intervals over long time periods (typically a number of years). Whilst wave data collection has occurred for a number of decades, the data are limited in both geographic coverage and the record length at any one site.

The analyses presented in this report rely on data for 11 sites from the European Wave Model (EWM) operated by the UK Met Office, together with observed data where available. The data have been grouped into five wave power regions (Figures 3 & 4), and the results are presented on both a regional basis and for the whole of the UK. See Appendix 2 for a complete list of EWM sites and observed sites referred to in this report.

Wave Power Devices

The power of a wave is a function of both the wave height and the period of the wave, and is approximated by the equation:

$$\text{Power (kW/m of wave front)} = 0.49 \times H_{SIG}^2 \times T$$

Wave power devices convert a portion of available wave power into electrical energy, with the efficiency of the energy extraction process dependent on the wave height (H_{SIG}), wave period (T) and device characteristics.

The output characteristics of three different wave power devices were used to convert hourly wave data into hourly power output. These output characteristics broadly describe the following three wave converter devices:

- **Terminator**: involves the interception of the wave by blocking its path. The device modelled here is an overtopping device that intercepts the wave, which then flows up a ramp and into a reservoir from where it drains under gravity through a turbine. Three transform functions have been provided by Wave Dragon ApS, representing the performance of the Wave Dragon device scaled for specific wave climates.
- **Attenuator**: in which some power from the wave is converted into mechanical movement as the wave passes along the device. The transform matrix used in this study represents the Pelamis wave converter device (manufactured by Ocean Power Delivery Ltd).
- **Point**: in which power from the wave is converted into mechanical movement as the wave passes over a specific point. The transform matrix used in this study represents the Archimedes Wave Swing, and was supplied by AWS Ocean Energy Limited.

The transform matrices used in to represent the three converter types are discussed further in the Wave Power Transform Matrices section which follows on page 32.

Wave Data and Modelling

Data Sources

European Wave Model: The EWM is a medium resolution model, which includes the north-western European shelf seas, the Baltic Sea, Mediterranean and Black Sea. Sites are located on a grid measuring 0.25o latitude by 0.4o longitude (approximately 35km resolution), with the grid centred on 0o latitude, 0.06o W longitude. Wave data were obtained at three-hourly resolution for the period July 1988 to June 2004 for each of the 11 sites included in the analysis. There are minor amounts of missing data within the dataset – these missing data periods were excluded from the modelling process.

Observed Wave Data: Observed wave data were available from an array of fixed buoys owned and operated by the UK Met Office. Data is available since 1989 when one buoy (Channel Light Vessel - 62103) was operational. Buoys have since been deployed at 19 sites – in 2004 there were 11 operational buoys in the programme. Data returned by Met Office buoys are at a one-hour resolution and include:

- Recording time (year, month, day, hour)
- Wave height (Hsig) and wave period (Tz)
- Location (latitude & longitude)
- Wind (speed & direction)

The period of data availability varies markedly between different sites - in addition, many of the datasets show significant periods of missing data. This limits their usefulness for long term modelling, however they remain useful for shorter-term, high resolution modelling.

Modelling Approach

The modelling of hourly electricity generation at each potential wave energy site was central to this project; the modelling process is described below.

Step 1 – Wave Power Time Series

Long-term time series for each wave power site were generated from the EWM data, producing an historical record of sea state conditions (wave height and period) at three hour resolution. From these data a time series of raw wave face power (kW/m of wave face) was calculated.

Step 2 – Conversion to Hourly Power Output

Power output levels were modelled from wave height and period time series data. This process required the application of a power transform function at each site to represent the performance of a wave converter device located at the site. Three power transform functions were used, and were applied at each site to generate a time series of device-specific power output levels. Conversion of wave period from Tz to Tpow was carried out where required to match the device power transform function.

Where the wave state conditions were outside the performance characteristics shown in the transform matrix, the conversion process returned a zero power output for that hour. While this may understate the performance of individual devices, the occurrence of these wave conditions are very rare and therefore do not impact on the overall time series result. Additional modification of the AWS time series was carried out to achieve standard capacity factor (see AWS performance analysis, page 58).

Step 3 – Regional Characteristics

Key properties of the wave resource were determined on a regional basis (Figure 4), including an assessment of the variability in the aggregate electricity supply for each region.

For these regional analyses, device output data for an attenuator-type converter (generic Pelamis transform) was used for all sites and regions. This approach provides comparability between different regions, however it must be recognised that using a single transform at the different sites results in significantly different capacity factors being achieved at each site. Where aggregate data are presented, it is assumed that sites within the region supply an equal portion of total annual electricity yield (ie balanced on output rather than installed capacity).

Step 4 – Diversified Wave Power Systems & Optimisation

Diversification and optimisation analyses were carried out for the whole of the UK – these analyses sought to find the optimal mix of sites and contribution to electricity generation that resulted in the “best” pattern of electricity supply from the wave power system. For this study, the average hourly change in energy output, expressed as a percentage of maximum system output, was chosen as the optimisation parameter.

Since the power output time series were determined for a single device, and each device has a different annual yield related to its size and rated output, it was necessary to weight the different time series at each site such that each device produced the same long-term annual yield (the practical effect of this step is to require a greater number of smaller scale devices, and less large scale devices, such that the aggregate output is identical). By balancing output from the different regions and devices so that all options produced the same long-term amount of electricity, the optimisation results were influenced solely by the pattern of supply.

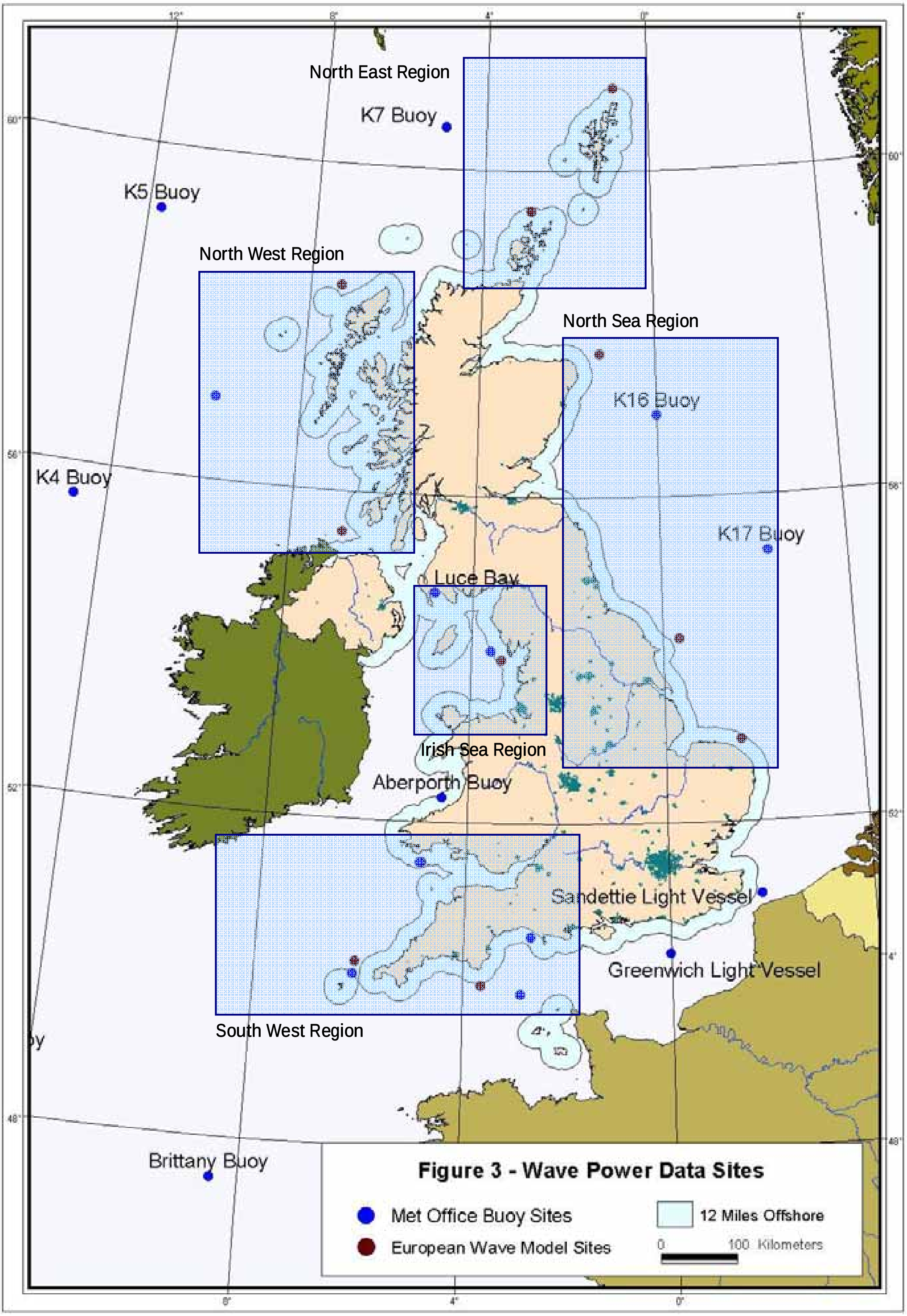
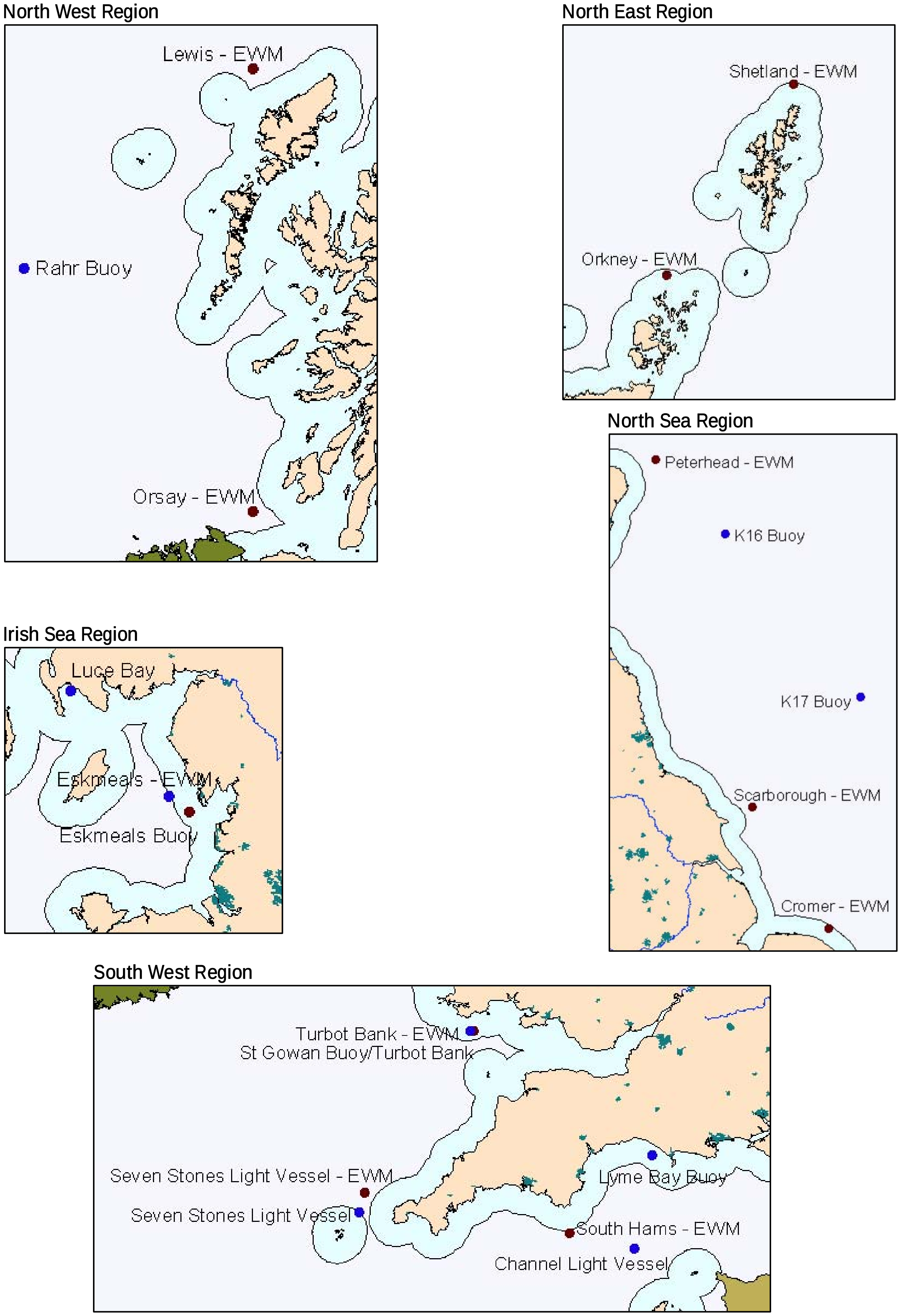


Figure 3 - Wave Power Data Sites

Figure 4 – Wave Power Development Regions



Wave Power Transform Matrices

Overview

Transform matrices provide the link between the ambient wave conditions and the anticipated output of the wave power device, with the estimated power output determined from the average wave period and height over a one hour period. Three wave power transform matrices are presented (below and next page), and have been used in the modelling of wave power output for this report.

Pelamis

The power transform matrix for the Pelamis device (below) is identical to that published by Ocean Power Delivery, and includes wave heights up to 8m (power output continues in waves over 8m – not shown) and wave periods to up to 13 seconds. The device does not generate electricity in wave heights of 0.5m or less. It is unresponsive to large, short period waves – this does not affect the overall output of the device, as waves with these characteristics are extremely rare.

Wave Dragon

The Wave Dragon power transform matrix (next page, top) is one of a range of matrices provided by Wave Dragon ApS for use in different wave energy environments. The matrix presented here is for a high energy wave environment (similar to the conditions experienced at the Shetland and Seven Stones sites). The matrix shows a large power band at rated capacity for waves over 5.0m; however, the frequency of these wave conditions is so low that the energy delivered is small compared to the overall output of the device in lower wave conditions.

Archimedes Wave Swing (AWS)

The power transform matrix for the AWS (next page, bottom) has been modified from that supplied by AWS Ocean Energy Limited, with the power output for discrete wave height and period conditions being interpolated from the ranges originally provided (necessary for the modelling process). The maximum wave height included in the matrix is 6.5m – discussions with AWS suggest that there will be power delivery during larger wave events, however this information is not yet available. Due to the low frequency of large wave events, it is unlikely that the overall performance of the device will alter significantly.

The power output of this device continues to rise along with wave height and period, rather than reaching a limit (the rated output) like the previous two devices – this raises issues with the performance and transmission requirements of the device, and these are discussed separately in the AWS performance analysis (page 58).

Device Sizing and Capacity Factor

A single Pelamis transform matrix was available, and this was applied at each site – this has resulted in a range of capacity factors being achieved, and in lower wave energy sites these are likely to underestimate the actual capacity factor. Different Wave Dragon transform matrices were used at each site to achieve a target capacity factor of 30%. An artificial rated capacity was imposed on the AWS device to achieve a capacity factor of 30% (except when this led to excessive energy spillage, where a 20% capacity factor was used).

Pelamis – Power Transform Matrix (generic performance): output in kW

Significant Wave Height Hsig – m	Wave Period – Tpow (s)																
	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	0	22	29	34	37	38	38	37	35	32	29	26	23	21	0	0	0
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	0	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	0	0	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	0	0	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	0	0	0	739	716	731	707	687	670	607	557	521	472	417	369	348	328
5.5	0	0	0	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	0	0	0	0	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	0	0	0	0	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	0	0	0	0	0	750	750	750	750	750	750	750	750	676	613	584	525
7.5	0	0	0	0	0	0	750	750	750	750	750	750	750	750	686	622	593
8.0	0	0	0	0	0	0	0	750	750	750	750	750	750	750	750	690	625

Wave Dragon – Power Transform Matrix (optimised for high average wave conditions): output in kW

	Wave Period – Tz (s)																				
Significant Wave Height - m	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	203	276	348	432	516	608	699	798	896	925	953	958	962	941	919	870	820	742	663	555	446
1.5	412	448	485	617	750	899	1049	1212	1375	1433	1491	1509	1527	1502	1477	1404	1332	1209	1086	912	737
2.0	621	621	621	802	983	1191	1398	1626	1853	1941	2029	2061	2092	2063	2034	1939	1844	1677	1509	1269	1028
2.5	1123	1123	1123	1213	1304	1609	1914	2258	2602	2752	2903	2972	3041	3017	2993	2868	2743	2504	2266	1910	1555
3.0	1624	1624	1624	1624	1624	2027	2430	2890	3350	3563	3776	3883	3989	3970	3951	3796	3641	3332	3022	2552	2082
3.5	2581	2581	2581	2581	2581	2783	2984	3588	4191	4494	4796	4870	4945	4935	4926	4845	4765	4374	3983	3372	2761
4.0	3538	3538	3538	3538	3538	3538	3538	4285	5032	5424	5816	5858	5900	5900	5900	5895	5889	5416	4943	4191	3439
4.5	4719	4719	4719	4719	4719	4719	4719	5093	5466	5662	5858	5879	5900	5900	5900	5897	5895	5658	5422	4822	4222
5.0	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5452	5004
5.5	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5676	5452
6.0	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
6.5	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
7.0	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
7.5	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
8.0	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900

Archimedes Wave Swing – Power Transform Matrix (unrestricted): output in kW

	Wave Period – Tpow (s)																										
Significant Wave Height Hsig - m	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5	18.0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	2	7	13	19	26	34	41	48	58	68	81	93	105	118	131	144	153	163	183	203	213	223	223	223	223	225	227
1.5	4	15	28	41	56	72	85	99	121	143	173	203	226	248	266	285	309	334	357	380	389	398	398	398	398	403	409
2.0	8	26	49	73	100	127	150	172	210	247	292	337	366	395	418	442	482	523	543	563	579	596	596	596	596	597	598
2.5	15	43	78	113	159	205	234	263	320	376	438	499	531	563	603	643	675	708	741	774	785	797	797	797	797	800	804
3.0	25	61	111	161	227	293	339	386	453	521	600	680	722	765	827	888	897	906	945	984	996	1009	1009	1009	1009	1003	998
3.5	35	92	155	218	305	391	454	517	605	694	772	851	913	975	1036	1096	1119	1141	1163	1185	1198	1211	1211	1211	1211	1208	1206
4.0	35	114	194	273	380	486	572	659	776	894	961	1027	1103	1179	1227	1275	1316	1357	1365	1374	1394	1414	1414	1414	1414	1415	1416
4.5	0	0	235	332	479	626	722	819	957	1096	1168	1240	1320	1401	1449	1497	1547	1598	1590	1583	1610	1637	1637	1637	1637	1616	1595
5.0	0	0	280	400	592	784	899	1014	1144	1274	1380	1487	1569	1651	1691	1731	1785	1838	1807	1777	1806	1836	1836	1836	1836	1806	1777
5.5	0	0	320	432	641	849	1033	1216	1331	1446	1568	1690	1778	1867	1919	1970	1977	1984	1994	2005	2017	2030	2030	2030	2030	1990	1951
6.0	0	0	0	0	680	944	1155	1367	1495	1623	1759	1895	1983	2072	2137	2202	2205	2207	2226	2246	2240	2234	2234	2234	2234	2194	2154
6.5	0	0	0	0	720	1123	1335	1547	1678	1809	1963	2116	2200	2284	2332	2380	2425	2470	2452	2434	2403	2373	2373	2373	2373	2354	2336

Wave Power Characteristics and Constraints

Wave Device Characteristics

Output profiles for three different devices were available for this study, reflecting three different approaches to wave energy extraction. Preliminary model runs were directed at determining if there was a marked difference in the overall wave power generation characteristics of a UK-wide system from the three different power transform functions. In addition, a “device averaged” scenario was included, where the output profile for an individual site was determined from the average hourly output of the three different devices at that site.

Investigation of the power output time series demonstrated that the output supply from the different devices was highly correlated at a site (typical correlation values of 0.95-0.99), meaning that wave power availability, rather than device performance characteristics, is responsible for most of the observed variability. From this finding, it was decided to produce a representative power time series for each site by averaging the output for the three devices for each hour in the time series. This simplified the representation of the UK wave resource from 33 independent time series (three devices at each of 11 sites) to one average device per site.

In carrying out this preliminary work, the potential contribution from each of the low power sites (Eskmeals, Peterhead, Cromer and Scarborough) was limited to approximately 3% of total wave power output – this decision was taken to reflect the reality of the wave power discrepancy between the Irish Sea and North Sea regions and other high power regions. The potential contribution from the remaining seven sites was unrestricted.

Whilst the three devices produced slightly different power output profiles, the results obtained strongly suggest that the choice of device has a limited impact on the pattern of wave power distribution. The relative contribution of each site to meeting total wave power output was consistent across the different devices, with the exception of the Orsay and Turbot Bank sites where one device (AWS) was preferred over the other two (due to difficulties in correctly sizing the other devices to the wave environment at these sites). Appendix 3 contains further details on the relative performance of the three wave devices.

Low Energy Wave Sites

At the “restricted” sites of Eskmeals, Cromer, Peterhead and Scarborough, the imposed maximum contribution of these sites to overall wave power output was almost always fully utilised by the optimisation model, suggesting that the power output patterns from these sites were highly desirable in achieving a lower variability wave power supply. This was of concern for a number of reasons, including the poor data resolution at these sites and the large generating capacity requirement in comparison to the high power sites (up to four times the generating capacity would need to be installed at Peterhead to generate the same amount of power as at one of the high wave power sites).

Further testing of the optimisation model was carried out with the capacity restriction at the low power sites removed. Under this (unrealistic) assumption, the model sought to derive around 32% of total wave power from the low energy sites. However, the impact this allocation had on overall wave power supply was mixed – variability in the total wave output was reduced (an expected result given the high number of zero output hours at the low power sites), whilst net demand variability increased slightly.

Given that the over-riding goal of this study was to optimise the integration of wave power into the existing electricity demand pattern, the insensitivity of the scenario outcome to the presence or absence of small amounts of wave power development at low wave energy sites was seen as a positive outcome. As a result, it was decided to exclude the potential contribution of the low power sites from the UK scenario modelling.

Resource Constraints

Unlike the UK tidal resource, no definitive analysis has been carried out on the capacity limits for the UK wave resource. Given the extensive nature of the resource (compared to the very site specific nature of the tidal resource), it is reasonable to assume that its contribution to current UK electricity demand would easily exceed that possible from tidal power without reaching any capacity limits.

For this study, the contribution of UK wave power to current electricity demand has been taken to be 15% unless otherwise stated. This value has been suggested by Michael Hay (British Wind Energh Association) as the current estimate of recoverable wave energy - it is used here as a guide and for continuity between analyses, rather than an estimate with a high degree of certainty.

Interpreting the Results

Interpreting the Results

This text relates predominantly to the following regional summaries – whole of UK results together with other analyses are treated separately.

For each region, a description of the findings is accompanied by four graphs, each depicting a different aspect of electricity output from the region, together with two tables of data, as described below:

Graph 1 – shows the frequency at which waves arrive from different directions. Wave direction is shown in one-degree increments, aligned to grid north. Data are grouped for all years and all seasons – where seasonal differences were identified, they are described in the text. No analysis of variation by year was carried out.

Graph 2 – shows the average monthly distribution of wave power over the year.

Graph 3 – shows the frequency with which different levels of power output would be achieved from the wave device. Data are separated into winter (December, January and February) and summer (June, July and August), and device output is shown as a percentage of rated (maximum) output, grouped into 5% increments. Note that this grouping results in the first column showing the occurrence of output at 2.5% or less of rated output, with the final column showing output at 97.5% or more of rated output – all other columns show the frequency of a 5% band of output.

Graph 4 – shows the pattern of wave power output in the region during 2001. Output is shown as a percentage of peak output (ie capacity factor), allowing easy comparison between regions without the complication of installed capacity and yield variations. Where the region had more than one site, the output is the unweighted average output of the available sites.

Table 1 – presents summary information on the average wave height and period experienced by the site during summer and winter. The top part of the table shows data from the EWM, whilst the lower part of the table (below the light blue line) shows the same data for any nearby observed sites (Met Office wave buoys). Note that the observed data are not corrected in any way – the majority of the buoy sites are located some distance from the EWM sites (with the exception of the South West and Irish Sea regions), typically being exposed to higher wave energy climates. In addition, the period of data availability for the observed data may overlap but does not match the EWM data period.

Table 2 – presents summary information on the variability characteristics of each EWM site in the region, and for the average regional output pattern. Variability is defined as the average change in power output between time steps divided by the peak output from the system, and is separated into winter (December, January and February) and summer (June, July and August), together with an annual average measure. Note that this variability is based on 3 hourly EWM data – the quoted figures are comparable between wave regions, but are not directly comparable to the tidal power variability figures given earlier (the three-hourly variability result will tend to underestimate the hourly variability figure).

Additional Analyses

In addition to the modelling work described above, a range of additional analyses were carried out, including:

- Wave power variability and electricity demand
- Variable capacity factor
- Diversity and regional variability
- Installed capacity and demand contribution
- Installed capacity and rate of change
- Cross-correlation, autocorrelation and prediction
- Time domain matrices
- Power density matrices
- Archimedes Wave Swing device

The background to each of these analyses is included in the relevant section.

United Kingdom Wave Power Characteristics

Overview

Wave power around the UK coast shows variability at a number of scales, including seasonal and inter-annular variation, and different levels of availability by location.

This section presents information on the general nature and patterns of this variability – the following pages provide an assessment of this variability on a regional and national scale, and its interaction with electricity demand.

The data used to characterise the UK wave resource are presented as both raw wave power (kW/m of wave face) and device output – the output characteristics of the wave converters studied act to significantly smooth the variability shown in the raw wave power data.

Variability by Location

The average annual wave energy experienced at each of the 11 sites is shown in the graph (right, top). It is clear that there is extremely large variability in ambient wave power at different sites. The exposure of the south-west and north-west of the UK to the North Atlantic Ocean ensures significant wave energy reaches the coast, whilst relatively sheltered areas such as the North Sea and Irish Sea exhibit very low wave energy levels. The lowest wave energy site (Eskmeals, Irish Sea Region) experiences around one tenth of the ambient wave energy of the most powerful site (Lewis, North West Region).

As a result of discussions with Wave Dragon concerning the economic feasibility of sites with very low wave energies, data limitations (low wave energy sites show artificially low variability due to rounding of the data) and the lack of an appropriate device to model wave power output from these sites, a decision was taken not to include the Irish Sea or North Sea regions in regional & optimisation analyses.

Variablilty between Years

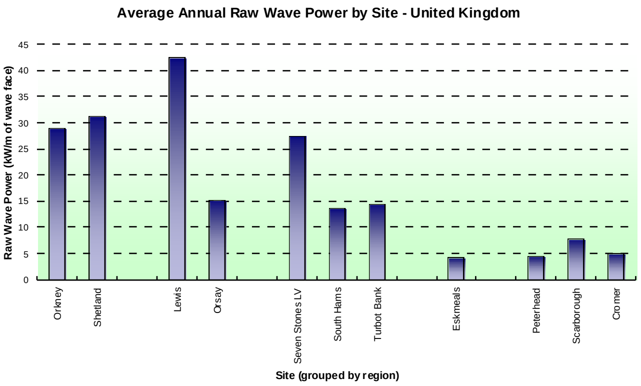
Wave power is subject to changes in annual availability, as shown in the graph to the right (middle). Data from the EWM shows that annual wave power output has varied by up to 20% from the long term average level of availability during the last 16 years. (Note that data gaps in 2003 result in an underestimate of wave power that year.)

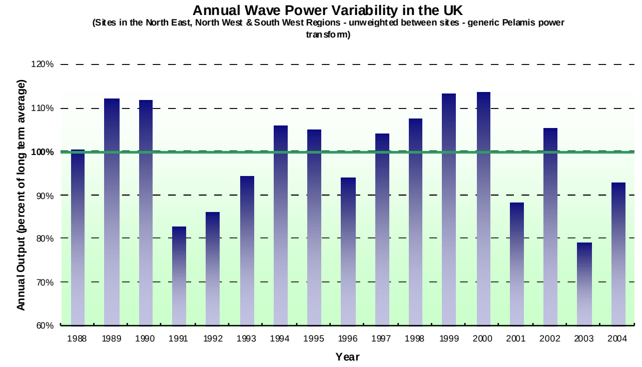
The standard deviation of annual output variability is approximately 4% (as a percentage of average annual output), based on the 16 years of data shown.

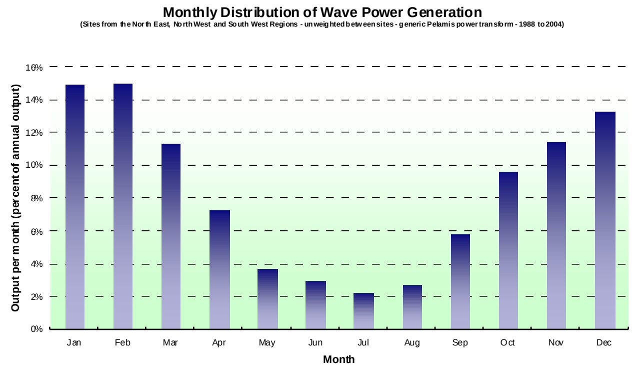
Variability by Month

Wave power shows a highly seasonal distribution (below, bottom), with output during winter months almost seven times higher than that experienced during summer. Whilst the magnitude of this difference is large, the general pattern of monthly wave power distribution is as expected, given the role of wind speed in driving wave generation and the higher wind speeds experienced in the North Atlantic and UK coastal waters in winter.

In the context of UK electricity demand patterns, this distribution should be seen as beneficial – average electricity demand levels are higher in winter than in summer, suggesting that the UK wave power resource will deliver more energy during periods of higher demand than at other times of the year.







Wave Power Properties – North East Region

Overview

The North East Region experiences a high energy wave environment, receiving 35% of the total wave energy of the five regions. Data from two EWM sites were available in this region, with both sites being located approximately 15km offshore to the north of the Orkney and Shetland Islands. A wave buoy (K7 Buoy) is located approximately 200km to the west/north-west of the Islands.

Regional Wave Climate

Waves arriving at the two EWN sites in this region show strong directional characteristics. As the Orkney and Shetland sites are located to the west of the islands, it is expected that there would be limited instances of waves arriving from the east. The wave direction graph (right, top) shows waves arriving from the south and west for around 65% of the time, with waves generated to the north accounting for the majority of the remaining time. There is little seasonal difference in wave direction distribution.

The monthly distribution of wave power output is heavily biased towards winter, with December to February accounting for 42% of all wave power. By comparison, summer accounts for just 7% of annual output. Summary statistics for the summer and winter waves encountered at the two EWM sites, together with K7 Buoy, are given in the table below – note that summer and winter wave heights are larger, and wave period longer, at the observed site.

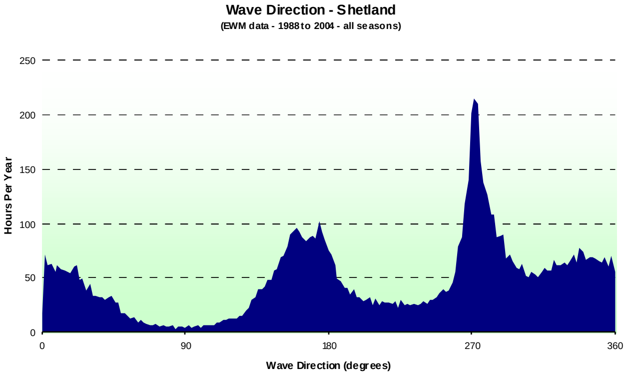
Site	Average Wave Height		Average Wave Period	
	Winter	Summer	Winter	Summer
Orkney	3.4m	1.5m	7.2sec	5.2sec
Shetland	3.5m	1.5m	7.2sec	5.2sec
K7 Buoy	4.4m	1.9m	8.6sec	6.3sec

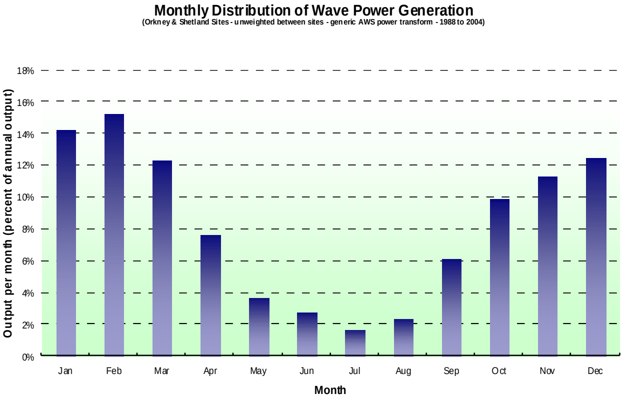
The higher energy wave climate during winter results in a very even distribution of wave power output levels, whilst in summer there is a heavy bias towards low or zero wave power output.

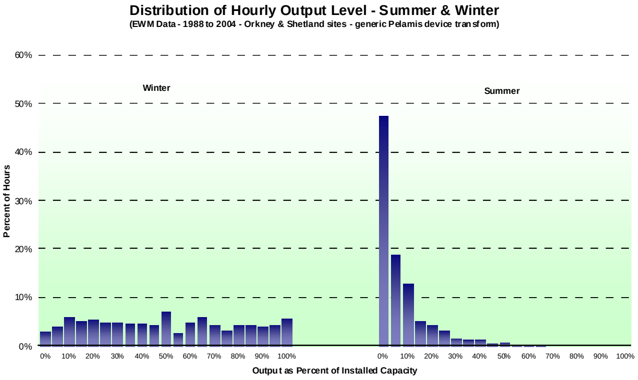
Power Output Time Series

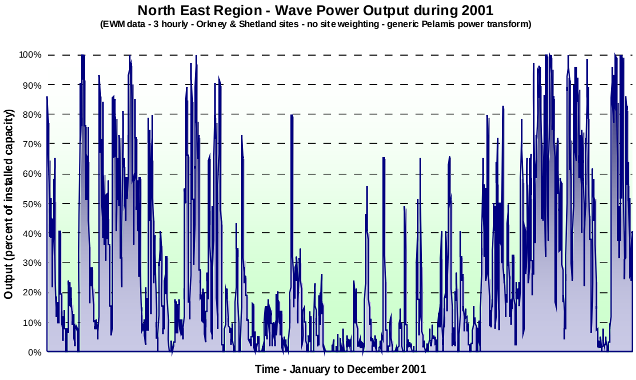
The graph to the right shows the 3 hourly wave power output from the North East Region during 2001, while three-hourly output variability averages are shown below.

Location	Average Three Hourly Variability (as % of Maximum Output)		
	Average	Summer	Winter
Single Site (Shetland)	4.4%	2.0%	6.5%
Region	3.9%	1.7%	5.8%









Wave Power Properties – North West Region

Overview

The North West Region experiences a high energy wave climate, receiving one third of the total wave energy of the five regions. Data from two EWM sites were available – the Lewis site is located around 15km NW of the Isle of Lewis, with Orsay located 20km SW of Islay. Rahr Buoy (observed data) is located approximately 170km to the west of the two sites.

Regional Wave Climate

Waves arriving at the two sites in this region show strong directional characteristics. The Orsay and Lewis sites are protected to the east, and over half of all hours show waves arriving from the west; waves generated to the north accounting for the majority of the remaining time. There is little seasonal difference in the distribution of wave direction.

The monthly distribution of wave power output is heavily biased towards winter - December to February account for 43% of all wave power, while summer accounts for just 9% of annual output. Summary statistics for the summer and winter waves encountered at the two EWM sites, together with Rahr Buoy, are given in the table below.

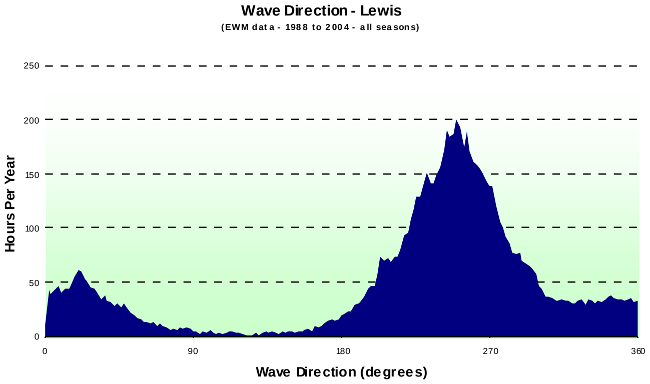
Site	Average Wave Height		Average Wave Period	
	Winter	Summer	Winter	Summer
Lewis	4.0m	1.8m	7.6sec	5.6sec
Orsay	2.4m	1.2m	6.4sec	5.0sec
Rahr Buoy	4.4m	2.2m	8.6sec	6.6sec

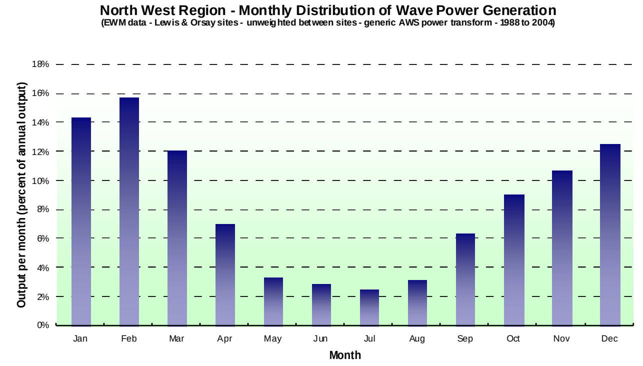
The higher energy wave climate during winter results in a relatively even distribution of wave power output levels, however there is an increased bias towards periods of lower output compared to the North East Region. During summer there is a heavy bias towards low or zero wave power output.

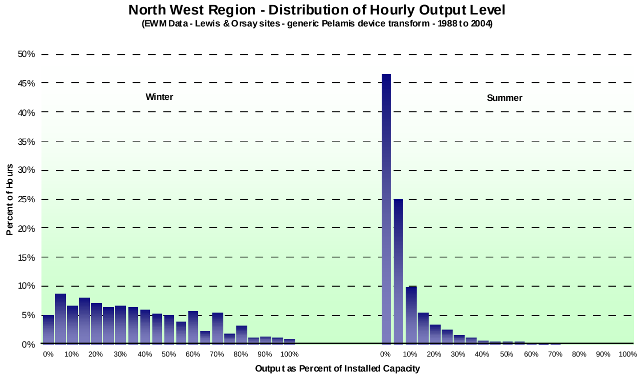
Power Output Time Series

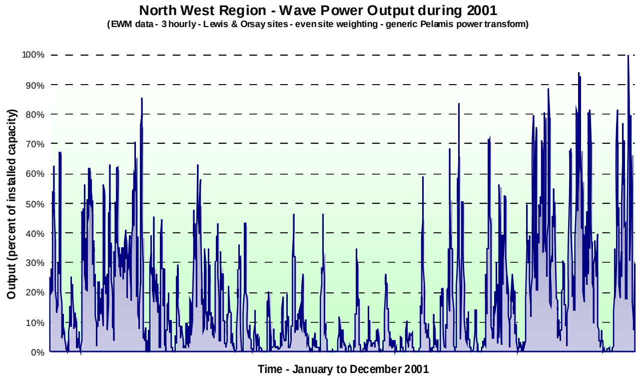
The graph to the right shows the three-hourly wave power output from the North West Region during 2001. Three-hourly output variability averages are shown in the table below.

Location	Average Three Hourly Variability (as % of Maximum Output)		
	Average	Summer	Winter
Single Site (Lewis)	4.5%	2.3%	6.5%
Region	3.6%	1.7%	5.4%









Wave Power Properties – North Sea Region

Overview

The North Sea Region experiences a very low energy wave environment, accounting for 7% of the total wave energy of the five regions. Data from three EWM sites were available in this region, located between 10-20km offshore between Cromer and Peterhead. Two wave buoys (K16 & K17 Buoys) are located between 100 and 200km offshore.

Regional Wave Climate

Waves arriving at these sites show a strong peak in instances of waves arriving form the north, with waves from this direction arriving around one-third of the time. Other directions show a relatively even distribution of occurrence. Apart from a slight increase in the incidence of waves from the south in winter, there is little seasonal difference in the distribution of wave direction.

The monthly distribution of wave power output is heavily biased towards winter, with December to February accounting for 43% of all wave power. By comparison, summer accounts for just 7% of annual output. Summary statistics for the summer and winter waves encountered at the three EWM sites, together with K16 & 17 Buoys, are given in the table below.

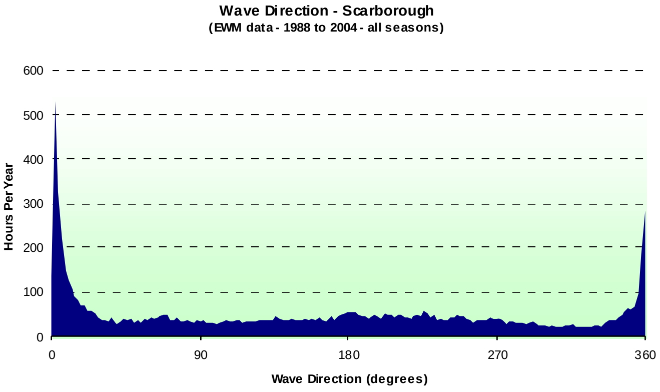
Site	Average Wave Height		Average Wave Period	
	Winter	Summer	Winter	Summer
Peterhead	1.1m	0.6m	7.2sec	5.0sec
Scarborough	1.8m	0.9m	5.4sec	4.3sec
Cromer	1.5m	0.8m	5.0sec	4.2sec
K16 Buoy	2.6m	1.3m	6.3sec	5.1sec
K17 Buoy	2.3m	1.2m	6.0sec	4.4sec

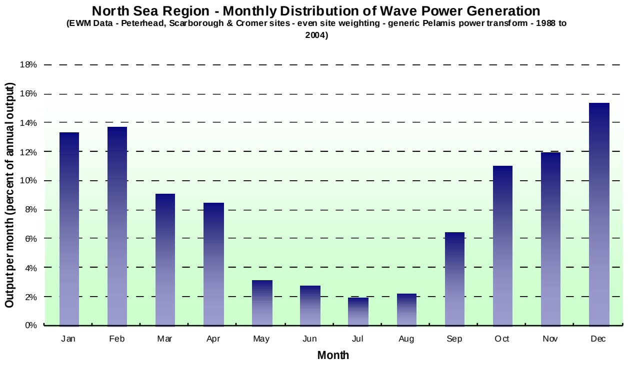
Wave power output levels are highly skewed, with both summer and winter wave conditions resulting in a heavy bias towards low or zero wave power output.

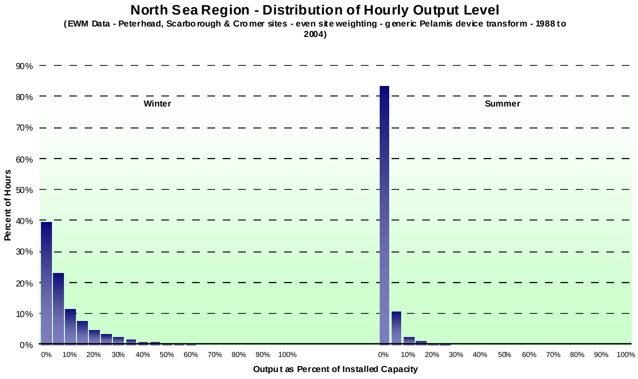
Power Output Time Series

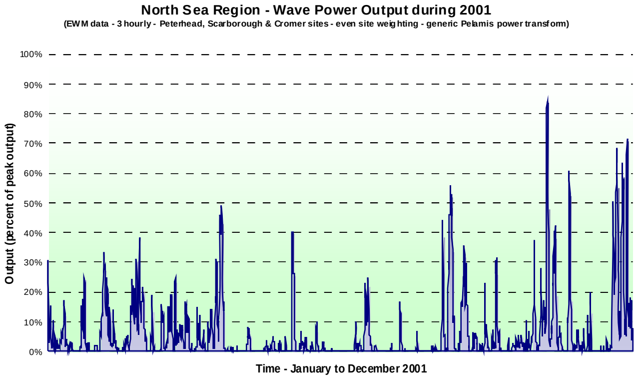
The graph to the right shows the three-hourly wave power output from the North Sea Region during 2001 – note that output does not reach 100% of peak in this year, although it does so in other years. Three-hourly output variability averages are shown in the table below. The low variability is considered a function of the high number of zero output hours rather than reflecting a more reliable wave resource.

Location	Average 3 Hourly Variability (as % of Maximum Output)		
	Average	Summer	Winter
Single Site (Cromer)	2.4%	1.1%	3.7%
Region	2.1%	1.0%	3.1%









Wave Power Properties – Irish Sea Region

Overview

The Irish Sea Region experiences a low energy wave climate, receiving just 5% of the total wave energy of the five regions. Data from one EWM site were available in this region, which was located approximately 10km west of Barrow in Furness. Eskmeals buoy (observed data) is located approximately 30km south-west of this site.

Regional Wave Climate

Waves arriving at this site show a very strong directional bias. Given the enclosed nature of the site and its proximity to the coast, the main exposure is to the south-west – around 60% of all waves arrive from the south-west to west. There is little seasonal difference in the distribution of wave direction.

The monthly distribution of wave power output is heavily biased towards winter, with December to February accounting for 53% of all wave power. By comparison, summer accounts for just 5% of annual output. Summary statistics for the summer and winter waves encountered at the Eskmeals EWM site are given in the table below.

Site	Average Wave Height		Average Wave Period	
	Winter	Summer	Winter	Summer
Eskmeals EWM	1.4m	0.7m	4.8sec	4.1sec
Eskmeals Buoy	Not available		Not available	

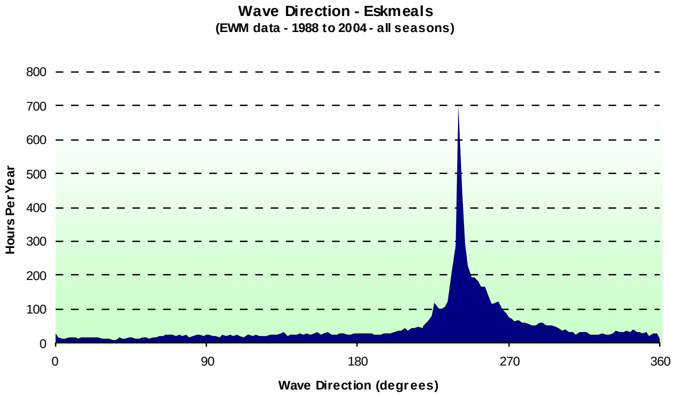
Wave power output levels are highly skewed, with both summer and winter wave conditions resulting in a heavy bias towards low or zero wave power output.

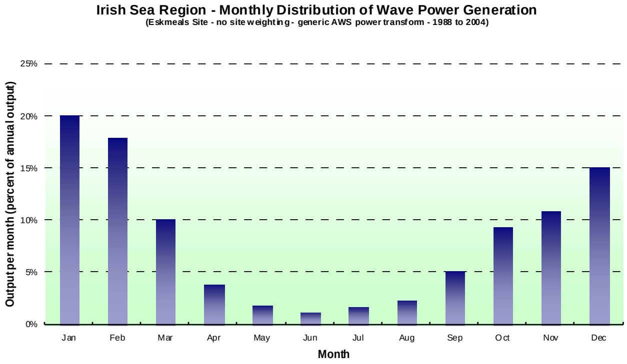
Power Output Time Series

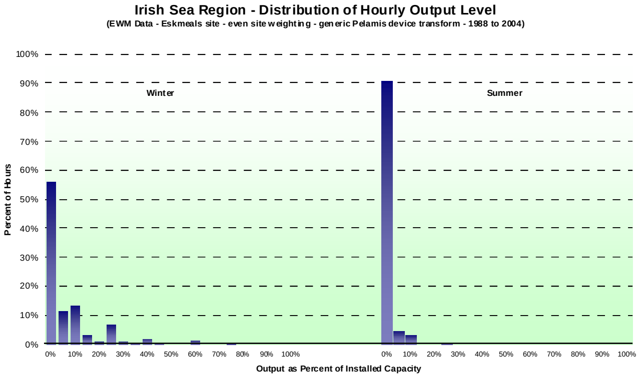
The graph to the right shows the three-hourly wave power output from the Irish Sea Region during 2001, whilst three-hourly output variability averages are shown in the table below. Note that these figures are considered an unreliable measure of variability in this region, since they are strongly influenced by the high number of zero output hours rather than reflecting a more reliable wave resource.

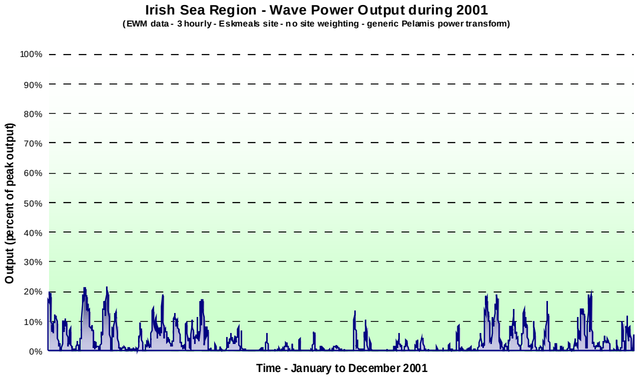
Output does not reach 100% of peak in this year, but does so in other years.

Location	Average Three Hourly Variability (as % of Maximum Output)		
	Average	Summer	Winter
Single Site (Eskmeals)	1.9%	1.0%	3.1%









Wave Power Properties – South West Region

Overview

The South West Region experiences a relatively high energy wave climate, with the region receiving around 21% of the total wave energy of the five sites studied. Data from three EWM sites were available in this region, all located around 10km to 20km offshore. Three wave buoys (Seven Stones LV, Turbot Bank and Channel LV) are located in this region – mirroring the location of the EWM sites.

Regional Wave Climate

This region's exposure to the south-west is reflected in the distribution of wave direction, with waves arriving from the south-west & west around 75% of the time. There is a slight seasonal influence – winter wave direction is more heavily biased towards the west, whilst in summer there is a small increase in waves arriving from the south.

The monthly distribution of wave power output is heavily biased towards winter, with December to February accounting for 47% of all wave power. By comparison, summer accounts for just 7% of annual output. Summary statistics for the summer and winter waves encountered at the three EWM sites, together with the three observed (buoy) sites, are given in the table below.

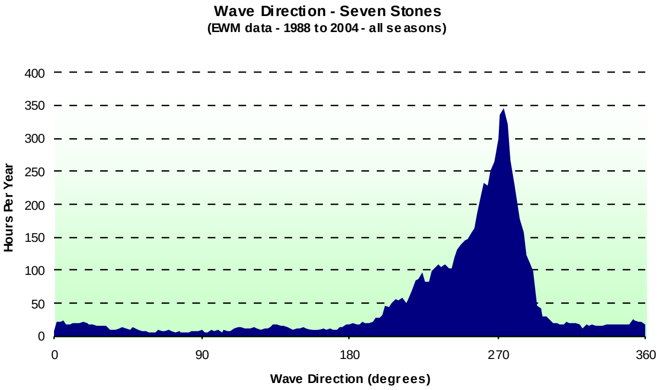
Site	Average Wave Height		Average Wave Period	
	Winter	Summer	Winter	Summer
Seven Stones	3.3m	1.5m	7.0sec	5.3sec
Turbot Bank	2.4m	1.1m	6.3sec	4.9sec
South Hams	2.4m	1.0m	6.3sec	4.8sec
Seven Stones LV	3.1m	1.4m	9.3sec	8.1sec
Turbot Bank	2.3m	1.2m	6.9sec	6.0sec
Channel LV	2.1m	0.8m	8.6sec	8.0sec

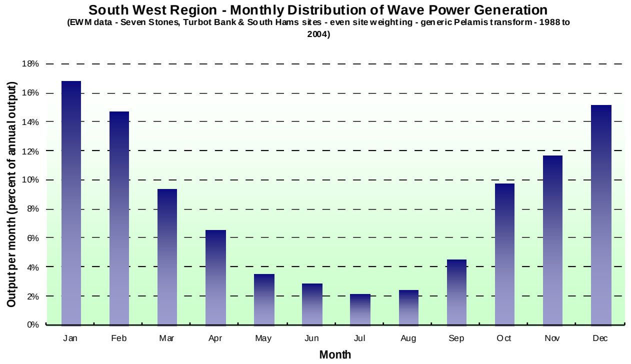
There is a strong seasonal difference in the distribution of wave power outputs, with low to zero output common in summer. During winter the distribution is far more even, however low output levels remain a feature of the power supply profile for a significant number of hours.

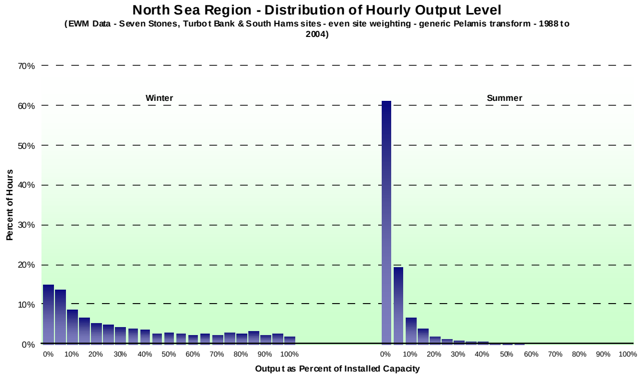
Power Output Time Series

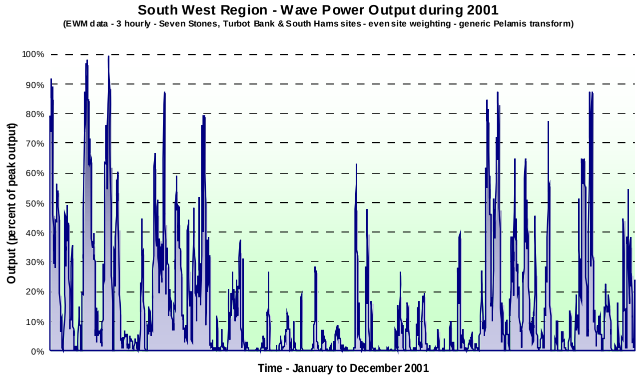
The graph to the right shows the three-hourly wave power output from the South West Region during 2001, while three-hourly output variability averages shown below.

Location	Average 3 Hourly Variability (as % of Maximum Output)		
	Average	Summer	Winter
Single Site (Seven Stones LV)	4.0%	2.4%	5.4%
Region	3.0%	1.6%	4.3%









Wave Power Variability and Electricity Demand

Interaction with Electricity Demand

While the relative variability of wave power at different locations can be assessed, it is necessary to examine the relationship between patterns of wave power availability and UK electricity demand patterns. In this context, it is important to consider the impact of the variable output of wave power on the electricity network.

For this analysis, the following assumptions have been made:

- There are no transmission constraints (necessary for this analysis, but unrealistic from a cost perspective);
- The contribution of wave power is seen as a “negative load” on the network, and
- The hourly electricity demand pattern is that of England and Wales.

Wave Power Scenario

Unlike tidal power systems, development constraints at different sites are not well known – however, it seems reasonable to assume that site-specific constraints will be less rigid than for tidal systems as wave power is not constrained by channels or headlands, but is available over a broader area.

Given this assumption, it was necessary to define some limits to the uptake of wave power. For this analysis, wave power has been sized to meet 15% of annual electricity demand – this represents a notional maximum wave power development scenario for the medium to long term. Furthermore, given the low wave power environments of the Irish Sea and North Sea regions, and the uncertainty of development occurring in these regions, the wave power scenario presented here includes only sites in the three high wave energy regions.

Electricity Supply and Demand Patterns

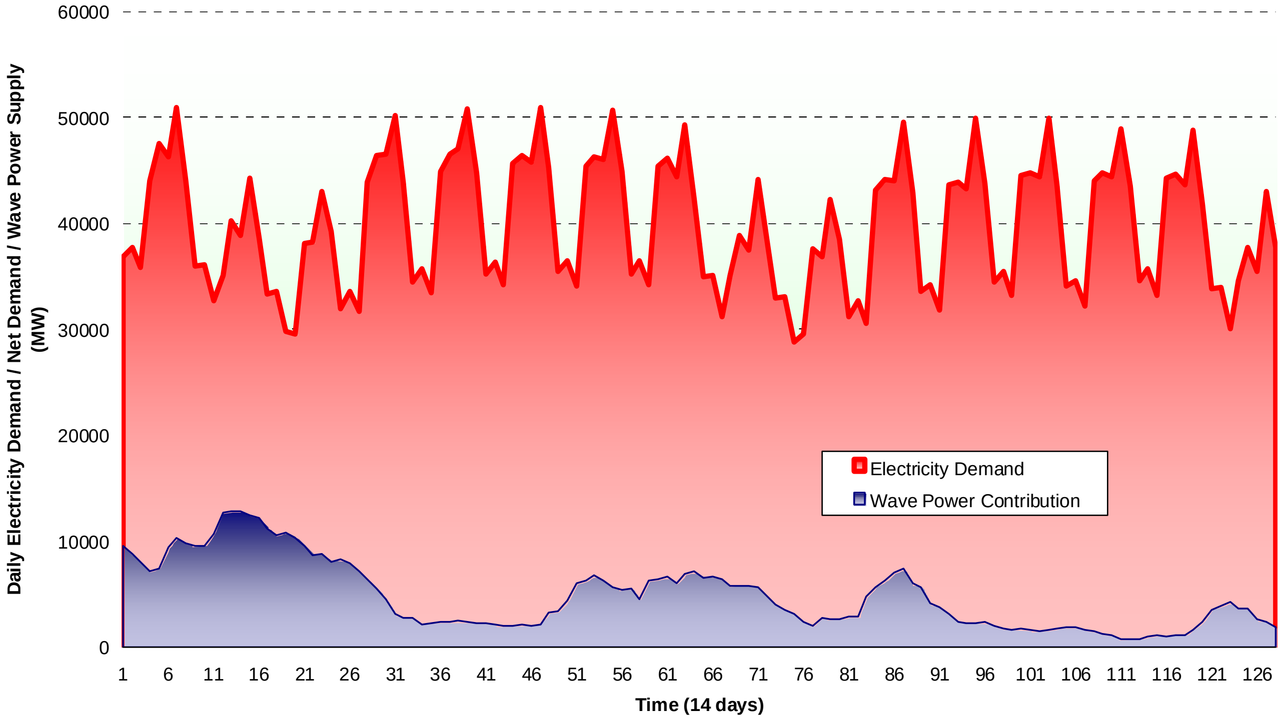
The regional descriptions of wave power demonstrated the seasonal variability inherent in the resource. With the wave power system scaled to deliver 15% of total electricity demand over the year, this seasonal distribution results in it meeting an average of 24% of demand in winter and 6% of demand in summer.

Whilst this correlation between high electricity demand and high wave power availability is potentially beneficial to the electricity network, it is based on the average availability of wave power – as such, it smoothes out both very high wave power output (potentially destabilising to the network) and very low output (possibly requiring additional backup).

The graph below provides an example of the contribution that wave power would make towards meeting winter electricity demand – the time period of this graph is the same as that presented for tidal power in the previous section, allowing for comparison with the tidal power output over the same period.

Wave Power Contribution to UK Electricity Demand

(January 2001 - 3 hour EWM wave power - wave power 15% of demand - multiple devices - minimum variability scenario)



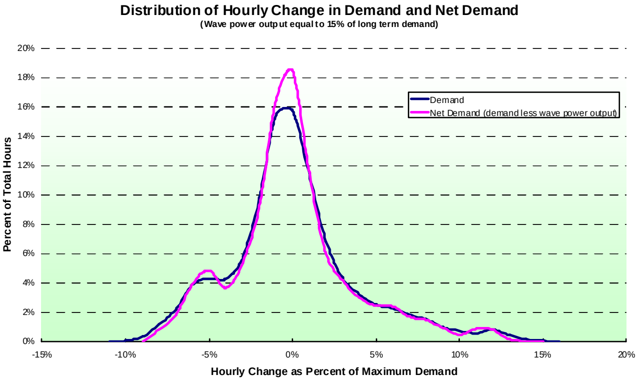
It is clear from this three-hourly resolution graph that there is considerable variability in the output of a diversified wave power system in the UK. This variability is emphasised in the figure below, which shows the average daily contribution of wave power against average daily electricity demand. The seasonal variability in wave power is apparent, however the most striking features of the graph are the peaks in wave power output – these are most apparent, and most intense, during winter.

Impact on Hourly Demand Change

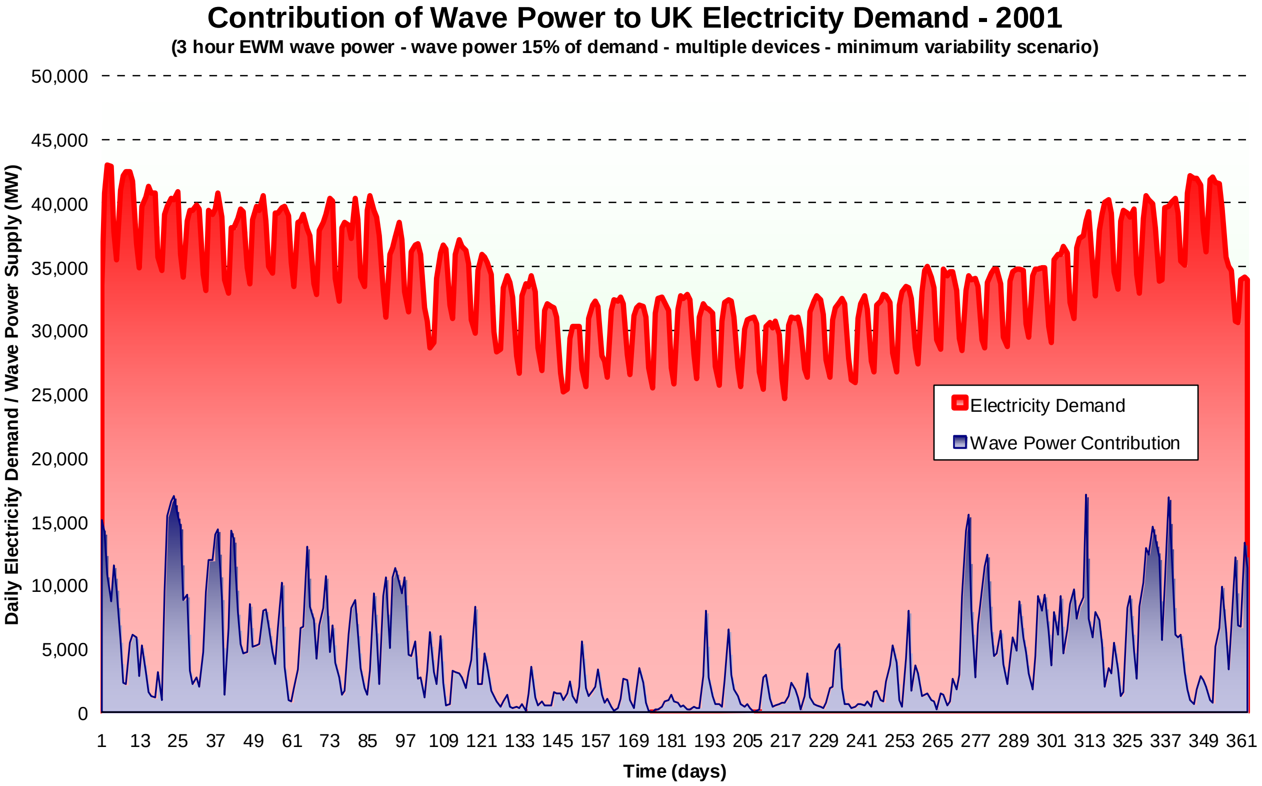
Hour-to-hour variation in electricity demand needs to be met, either though the scheduling of additional plant to meet an increase in demand, or by taking operating plant offline in response to a demand reduction. By treating the output of wave power devices as a negative load on the network, the net demand to be met by conventional capacity is simply calculated by subtracting the hourly wave power output from the hourly demand level.

Presented here are hourly variability data that have been inferred from three-hourly wave power data – by inferring hourly variability from a three-hourly some additional error may be introduced, however this is not expected to affect the overall result significantly. This approach does allow for direct comparison with the tidal power results.

The graph to the right shows the impact that wave power has on the hour-to-hour change in conventional capacity requirement. This graph suggests that the introduction of wave power to the electricity network would cause a minor increase in the load following requirement of the network – data describing this change are presented in the following table. From these results it appears that the hourly variability in wave power would have a limited impact on load following requirements of the network.



Parameter	Without Wave	With Wave
Hourly Change <±0.5%	18.4%	15.7%
Average Hourly Increase	3.70%	3.77%
Peak Hourly Increase	15%	16%
Average Hourly Decrease	-2.88%	-3.02%
Peak Hourly Decrease	-9%	-11%
St.Dev. of variability as percent of peak net demand	3.71%	3.90%



Variable Capacity Factor

Variable Capacity Factor

The capacity factor of a variable power output device refers to the amount of energy delivered by the device (over a certain period) compared to the maximum possible if the device had been operating at rated capacity for the whole time. A capacity factor of 100% would indicate continuous generation at maximum output, a situation that clearly does not apply to variable output devices such as wave and tidal power devices.

Capacity factor is seen as a “headline” figure for renewable energy generators, representing a measure of the amount of generation that occurred during a given time (typically annually). However, a key aspect of renewable power generation that is not captured by this single figure is the relationship between renewable energy generation and electricity demand. By expressing capacity factor relative to the electricity demand in each hour, the contribution of the renewable energy device to meeting demand can be understood.

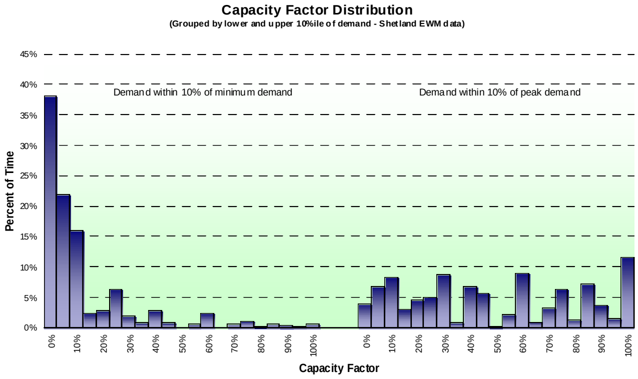
The graph below shows the average capacity factor of a wave power device (Shetland) against electricity demand (percent of peak demand) for the period 1988-2004. There is a very clear relationship shown in this graph – wave power supplies more energy at times of peak electricity demand than at other times, *on average*.

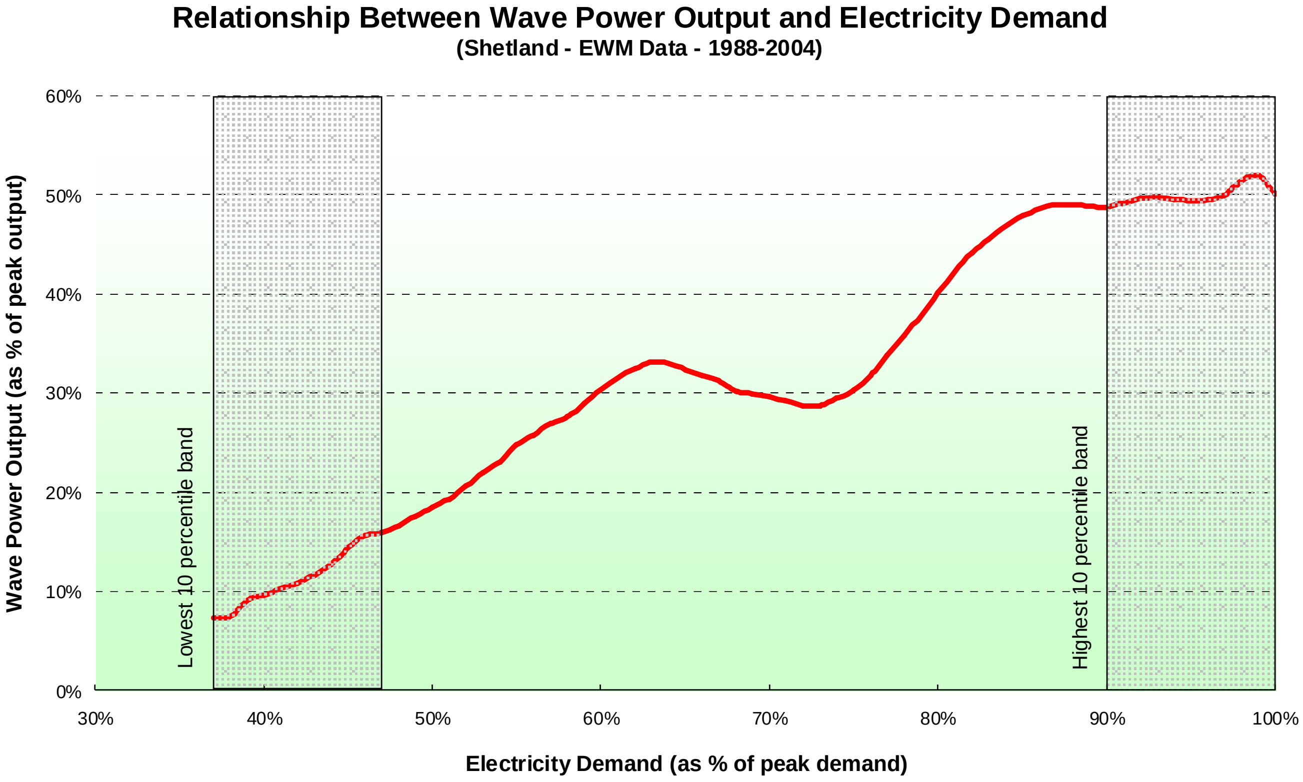
Capacity Factor Distribution

While the main graph (bottom) shows the change in average capacity factor with demand, it is important to recognise that there is a large degree of variability in hourly capacity factor at all levels of demand.

The distribution of capacity factors within 10% of minimum and peak demand (indicated in the main graph) is shown in the graph below. The graph shows the variability of hourly capacity factors in these bands, and the difference in distribution during low and high electricity demand periods.

Low or near zero output events are possible across the demand range, although they are far more common during low demand hours. During high demand periods they account for around 4% of all output hours.





Diversification & Regional Variability

Diversification and Variabiiity

The regional assessments of wave power availability and variability have quantified the impact of multiple sites (where available) within a region on the variability of the wave power supply from that region. This smoothing effect is also seen at a national level, with different wave patterns in regions acting to smooth the aggregate wave power output of the UK.

The graph below presents variability by region and for the UK. There are three main features shown in this figure:

- Differences in variability between regions;
- Differences in variability between winter and whole year figures, and
- Lower overall UK variability

Note that the low variability results for the North Sea and Irish Sea regions are not considered reliable as they are due to a very high number of low or zero output hours. These characteristics have not been incorporated into the calculation for all of UK – including them would drop the UK variability estimate to around 1.9%.

Regional Variability

The differences in regional variability for the three high-energy regions show a geographic trend, with the most northerly region (North East) having the highest variability and the most southerly region (South West) having the lowest variability. This pattern may be a reflection of both regional climate and location, with more intense storms affecting the north of the UK, whilst the south of the UK has the greatest exposure to the Atlantic Ocean and hence experiences a wave environment more influenced by distant wave generation than by local storms. The lower variability of the South West region may also have been influenced by the available data – this region includes three EWM sites (the other high energy regions have two), and the inclusion of this extra site is likely to have assisted in reducing variability in the region.

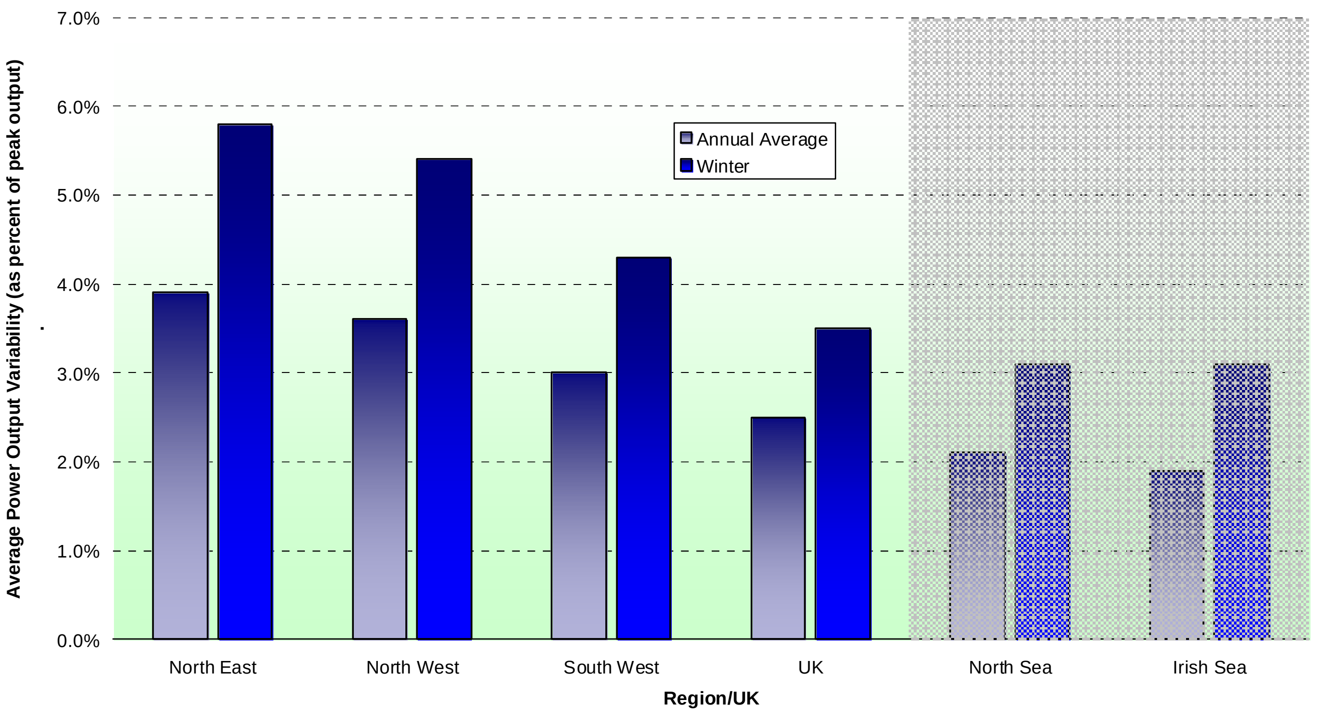
Seasonal Variability

The difference between winter and annual variability levels reflects the impact of low summer wave energies on the calculation. All regions show a large proportion of summer wave power output levels close to or at zero, lowering the summer variability estimate.

UK Variability

The overall UK variability result is lower than any individual region, showing the impact of diversification of the generating source. This effect is most apparent in winter, with the UK variability estimate around 40% lower than the worst regional figure (North East). This reduction in supply variability is particularly important given that winter is by far the dominant season for wave power generation in all regions.

Average Three-Hour Variability in Wave Power Output



Demand Contribution and Installed Capacity

Overview

The seasonal distribution of wave power availability in the UK broadly matches the seasonal pattern of electricity demand. However, the variation in wave power is more extreme than in demand – this results in there being proportionally more wave power available relative to demand in winter than in summer, illustrated by the variability of wave device capacity factor with demand.

A second feature of the wave resource is periods of high device output, particularly in winter. Consider the scenario where 15% of annual electricity demand is met by wave power – this requires an installed capacity of around 19GW of wave power devices (assuming a 30% capacity factor) which, when all generating at rated capacity, would be theoretically capable of supplying up to 77% of electricity demand during low demand hours in winter.

Scenarios

The base scenario for wave power development adopted in previous analyses was a contribution of 15% of annual electricity demand from wave power. In this analysis, a range of development levels (10%, 15%, 20%, 30%, 40% & 50% of annual electricity demand) have been assessed, allowing the impact of increasing amounts of electricity generation from wave power on the network to be estimated. The diversification/optimisation strategy is to minimise net demand variability, and is common to all development levels.

Note that only high-energy wave sites are included in the analysis. Any wave power development in the Irish Sea and North Sea sites was considered to have too small a contribution to the overall wave power output to cause any significant change in the results – this is even more likely at high development levels where the output from low energy sites would be swamped by the higher sites.

Average Monthly Contribution

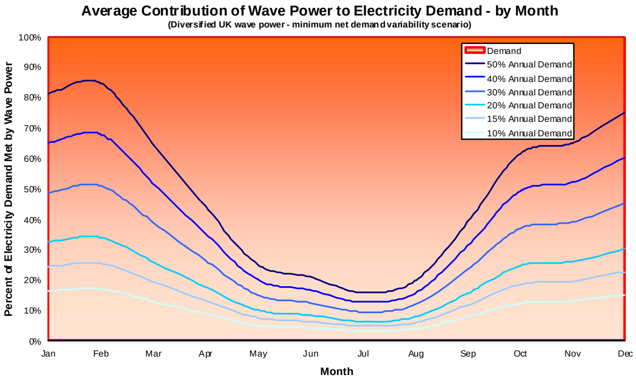
The contribution of wave power to electricity demand is presented by month (right, top) for a range of development scenarios. The average contribution of wave power in summer is modest under all development scenarios. At a low development level of 10%, the average contribution of wave power in winter reaches 16% of demand – however under higher development scenarios, the contribution of wave power in winter can reach 80% of demand from an installed capacity equal to 50% of annual electricity demand.

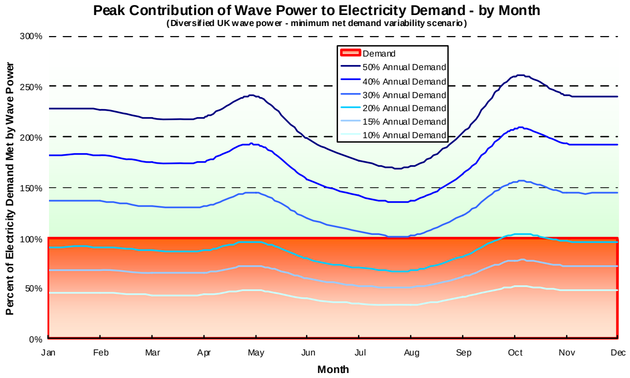
Peak Monthly Contribution

The peak monthly contribution of wave power to meeting electricity demand is shown in the graph below (lower). Peak output in winter quickly exceeds demand as development level rises, however this may be a rare occurrence. The distributions of hourly contribution shown on the following page explore this in more detail.

Summary Statistics

The table (below) presents summary statistics on the percentage hourly contribution of a diversified UK wave system under different development scenarios. The data in the table is a snapshot of the winter (December, January and February) and summer (June, July and August) data shown in the two graphs.





Wave Power Contribution	Winter		Summer	
	Average	Peak	Average	Peak
10%	16%	48%	4%	40%
15%	24%	72%	6%	60%
20%	32%	96%	7%	80%
30%	48%	144%	11%	119%
40%	64%	193%	15%	159%
50%	80%	241%	19%	198%

Hourly Wave Power Contribution

The peak contribution of wave power to meeting hourly electricity demand (graph previous page) raises questions about the ability of the UK electricity network to accommodate large developments of wave power. However, finding the peak contribution is a crude measure, as it assigns no probability to this event occurring.

To overcome this limitation, two sets of graphs are presented here – these graphs show the frequency distribution of wave power contribution to demand in each hour. Two scenarios are presented, a low development scenario where annual wave power yield is 15% of demand, and a high scenario of 50% of demand. The data are separated into winter (D, J & F) and summer (J, J & A).

Winter

The contribution of wave power to meeting winter electricity demand is highly concentrated under the 15% scenario. Although the peak contribution is 72% of hourly demand, wave power contributes less than 50% of hourly demand in 96% of all hours.

Under the 50% scenario, there is a more even spread of contribution levels – however, wave power output exceeds hourly demand in 34% of all winter hours. This suggests severe implications for the integration of such a large amount of wave power, unless large scale electricity storage or hydrogen conversion were available.

Summer

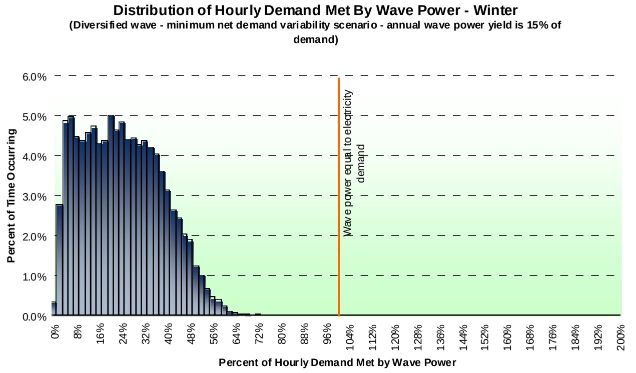
During summer the contribution of wave power to meeting hourly electricity demand is highly skewed towards low wave contribution levels for both development scenarios.

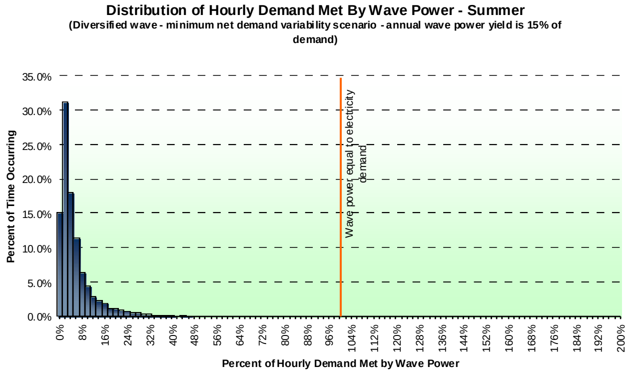
Under the low development scenario, wave power contributes less than 20% of hourly demand in 96% of cases.

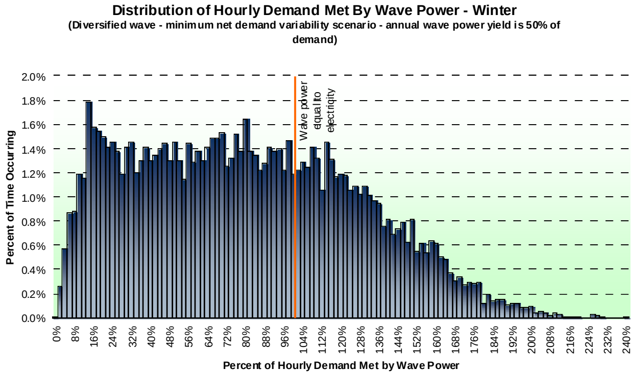
Despite the peak contribution of wave power of 198% of demand under the high development scenario, 96% of all cases show wave power contributing less than 70% of demand.

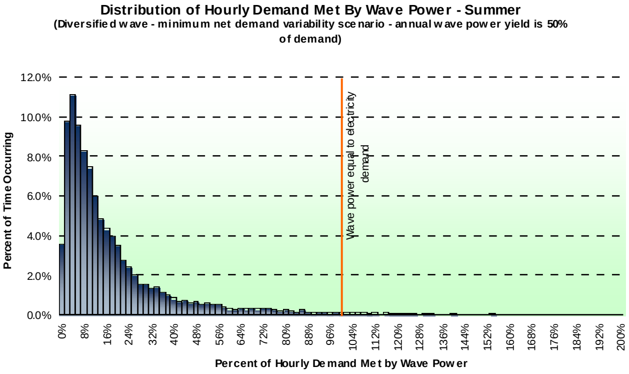
Implications

These findings suggest that, under high wave development scenarios, it may be necessary to limit the contribution of wave power in order to maintain stability on the network. This is particularly so during winter, when significant volumes of wave generated electricity would need to be spilled or stored to allow flexible dispatchable plant to operate on the network and provide backup and balancing services. Indeed, without fundamental changes to the electricity system, such as large scale storage or (potentially) diversion of wave generated electricity into hydrogen for distribution, it does not seem appropriate to consider wave power development equivalent to 50% of annual electricity demand.


Distribution of Hourly Demand Met By Wave Power - Winter
(Diversified wave - minimum net demand variability scenario - annual wave power yield is 15% of demand)


Distribution of Hourly Demand Met By Wave Power - Summer
(Diversified wave - minimum net demand variability scenario - annual wave power yield is 15% of demand)


Distribution of Hourly Demand Met By Wave Power - Winter
(Diversified wave - minimum net demand variability scenario - annual wave power yield is 50% of demand)


Distribution of Hourly Demand Met By Wave Power - Summer
(Diversified wave - minimum net demand variability scenario - annual wave power yield is 50% of demand)

Installed Capacity and Rate of Change

Installed Capacity of Wave Power

The potential installed capacity of wave power is difficult to quantify, given the large area available for the development of wave power systems (refer to the map of annual mean wave power given on p14 of the Atlas of UK Marine Renewable Energy Resources) and the lack of detailed resource development assessments. However, the figure of 15% of UK electricity demand being met by wave power provides a benchmark against which installed capacities can be determined.

Installed capacity is also a function of the capacity factor achieved at different locations – for the high energy wave sites studied in this report, capacity factors typically varied from around 20% (Turbot Bank and Channel) to over 30% (Lewis and Shetland).

Taking the 30% capacity factor figure, around 19GW of installed capacity would be required to achieve the 15% notional target. It is envisaged that this generating capacity would be spread across the three high energy regions, however the greater wave energy of the two northern regions may promote more development in these areas. Were this level of development to occur, the required installed capacity would drop slightly due to the higher capacity factors likely to be achieved in the northern regions.

In area terms, this would mean developing around 1,050km^2 (ie 32km x 32km), based on a Pelamis 750kW device, and a 240m diameter exclusion zone around each device tether point (although the actual shape of the development would tend to be linear rather than square to maximise wave energy availability to each individual device) Additional allowance may need to be made for maintenanceand navigation.

There will be factors in addition to available wave power that impact on the development locations for wave devices – proximity to transmission networks (or the ability to connect to them at reasonable cost), suitable coastlines and bathymetry, and the ability to service the devices will all have an influence on the location and amount of wave power installed capacity. However, these additional factors would not markedly change the required installed capacity for wave power to meet 15% of UK electricity demand.

Rate of Change of Power Output

The following two pages provide descriptive statistics and distribution graphs that relate to the change of power output characteristics of wave power in different parts of the UK.

This analysis is not as comprehensive as the one performed for tidal power, since the wave power data were only available at either one hour (observed) or three hour (modelled) resolution. The timestep over which rate of change data can be calculated is limited to periods equal to or greater than these resolutions.

The analysis has been performed in two stages – in the first stage, the change in power output has been determined from observed data (Seven Stones LV, South West Region) at both hourly and three-hourly timesteps. This allows a comparison to be made between the rate of change characteristics at one and three hour intervals. The second stage used three-hour modelled data to present rate of change information for the North East, North West and South West Regions – the rate of change output data shown in these graphs are considered broadly comparable to the three-hour change data shown for Seven Stones LV.

A brief description of the data accompanies each analysis – as there is no clearly defined development criteria for wave power, the rate of change data presented in MW is based on a simplified assumption of the 15% demand target being met. This supply level is met by approximately 5GW of installed wave capacity in the North East and North West regions, together with around 8GW in the South West region. Reported variability levels are based on these figures unless otherwise stated.

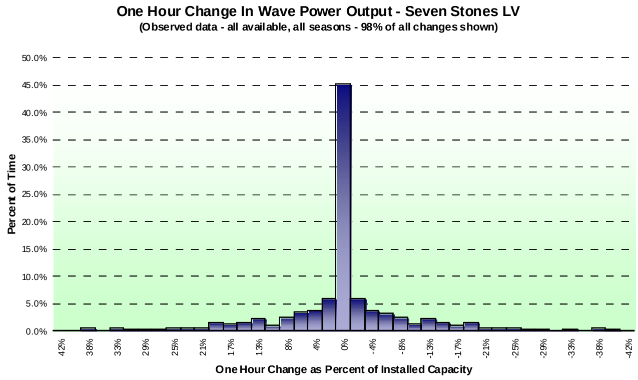
Rate of Change – Seven Stones LV

Results from the analysis of observed hourly wave data from Seven Stones LV (South West Region) are presented below. The dominant feature of these data is the proportion of consecutive hours where power output does not change (ie change is <5% of peak output). Whilst periods of low output in summer will cause this result, analysis of just the winter portion of the dataset (middle table and graph) revealed a similar output pattern. Given the high power output levels during winter, this result suggests that low rates of change of output at the one-hour timestep are a feature of the wave resource at all power output levels.

(All data based on 6GW installed capacity).

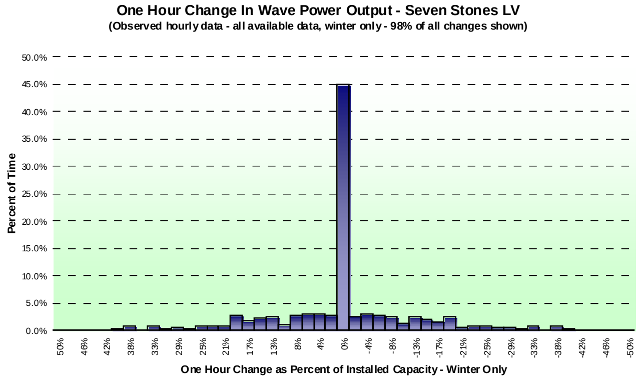
Seven Stones LV – One Hour Power Variation

Parameter	MW	Percent of Installed Capacity
Average Increase	726	12.1%
Peak Increase*	- - -	100%*
No Change	- - -	45.1%
Average Decrease	-732	-12.2%
Peak Decrease*	- - -	-98%*



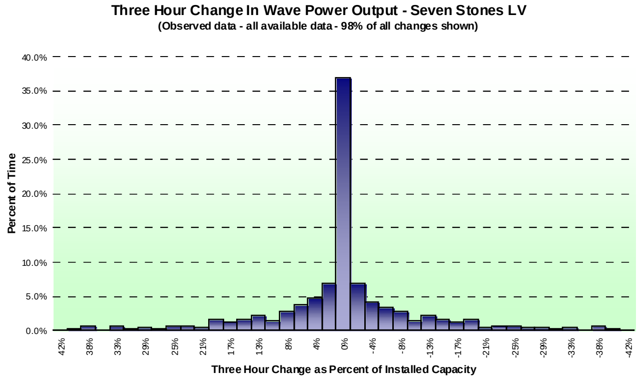
Seven Stones LV – One Hour Power Variation - Winter

Parameter	MW	Percent of Installed Capacity
Average Increase	936	15.6%
Peak Increase*	- - -	96%*
No Change	- - -	45%
Average Decrease	-954	-15.9%
Peak Decrease*	- - -	-96%*



Seven Stones LV – Three Hour Power Variation

Parameter	MW	Percent of Installed Capacity
Average Increase	768	12.8%
Peak Increase*	- - -	100%*
No Change	- - -	36.8%
Average Decrease	-798	-13.3%
Peak Decrease*	- - -	-100%*



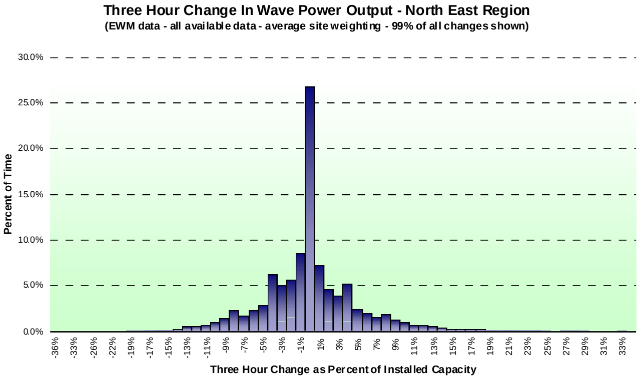
* These results are considered to be outliers resulting from errors in the observed dataset.

Rate of Change – Regions

Rate of change results for the three high wave energy regions of North East, North West and South West are presented below. Note that these results are based on three-hourly EWM model data, and can be compared to the three-hour results for the observed data at Seven Stones LV (previous page – bottom graph and table). No seasonal breakdown has been provided, as the results from Seven Stones LV suggest that the rate of change of power output does not change in distribution by season. Rate of change levels are lowest in the South West Region, however all three regions show very similar distribution patterns, with a high probability that no significant change in output will occur over a three-hour period.

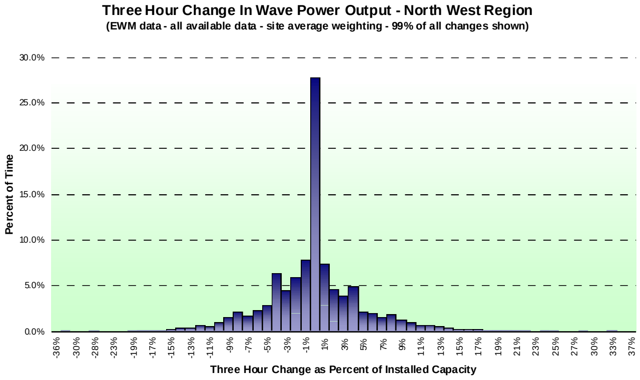
North East Region – Three Hour Power Variation

Parameter	MW	Percent of Installed Capacity
Average Increase	258	5.0%
Peak Increase*	3,455	67%
No Change	- - -	26.8%
Average Decrease	-224	-4.3%
Peak Decrease*	-3,455	-67%



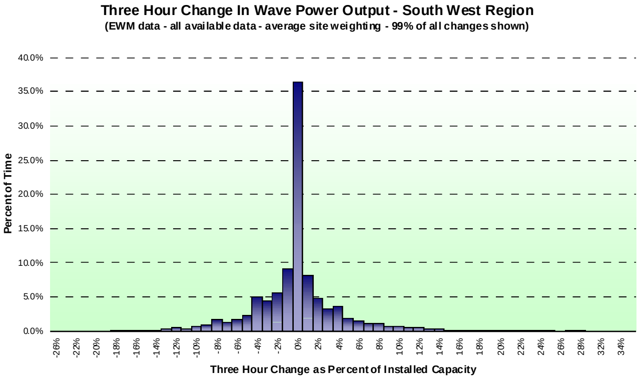
North West Region – Three Hour Power Variation

Parameter	MW	Percent of Installed Capacity
Average Increase	248	5.1%
Peak Increase*	3,333	68%
No Change	- - -	27.7%
Average Decrease	-220	-4.5%
Peak Decrease*	-3,287	-67%



South West Region – Three Hour Power Variation

Parameter	MW	Percent of Installed Capacity
Average Increase	360	4.5%
Peak Increase	3,303	41%
No Change	- - -	36.3%
Average Decrease	-312	-3.9%
Peak Decrease	-2,497	-31%



* These are extremely rare events (less than one event in five years) and may result from errors in the dataset.

Cross-Correlation, Autocorrelation & Prediction

Summary

A number of wave buoys are located in the North Atlantic, providing observed wave and wind conditons to the north, west and south of Ireland. Whilst these sites are inappropriate for wave power analysis due to their mid-ocean location (between 500km and 900km off the UK coast), the data returned from these sites may be useful as a predictor of coastal wave power conditions.

Approach

Wave power data were partitioned into winter (D, J & F) and summer (J, J & A) for all available data at the paired sites. The paired data were originally time matched – from these data, cross-correlation calculations were carried out for the time range T±36 hours and autocorrelation to T+36 hours.

Cross-correlation reveals the degree to which changes in wave power at one site coincided with changes in wave power at another site. By lagging one time series in relation to another, the correlation between wave power at one site at time T±0 and a second site at time T±HoursLag is determined. Subsequent plotting of the results reveals whether the greatest correlation between the two time series occurs at T±0 or at some time lag between the series.

Autocorrelation reveals the degree to which the wave power in a given hour relates to the wave power in previous hours at the same site. High autocorrelation values indicate that the time series is slow-moving, with the value next hour heavily dependent on the value this hour.

The table below shows selected correlation values extracted from the cross-correlation analysis. In this table, T0 refers to the correlation between power outputs from two buoys at the same time, while T-6 refers to the correlation between the same two buoys, but with the output data at the predictor site matched to data at the target site six hours later. Under the maximum correlation column, Hours Ahead refers to the number of hours ahead the data from the predictor site has been advanced to achieve the maximum correlation (which can be between one and 36 hours ahead). The correlation value can be read as the percent of variability at the Target Site that is explained by variability at the Predictor Site x-hours ahead.

Cross Correlation Results - Table

The results shown in this table suggest that oceanic buoys that are in line with the dominant wave direction (typically from the south west) do provide some forecast of future conditions for buoys closer to the coast. Three particularly good pairs of oceanic and coastal buoys have been highlighted in the table, and are considered further in the graphs on the following page. These pairs were identified as having a combination of high correlation values at the six hour prediction horizon, being a "reasonable" distance away, and having some prediction value in summer and winter.

The relatively high correlation values shown for some buoy pairs in summer may be a result of coincidence rather than causation – given the extended periods in summer when there is little or no wave power, it is more likely that both the Target and Predictor sites will experience low or zero output at the same or similar times.

Predictor sites for the Target Sites of 62301 and 62303 (Channel LV and Turbot Bank, South West Region) did not show particularly useful relationships, possibly due to the (relatively) enclosed location of the sites complicating the wave climate in these locations.

		Winter				Summer			
Target Site	**Predictor Site**	**Correlation - r^2**		**Maximum Correlation**		**Correlation - r^2**		**Maximum Correlation**	
		T 0	**T -6**	**Hours Ahead**	**Correlation**	**T 0**	**T -6**	**Hours Ahead**	**Correlation**
62301	62163	23%	13%	1	18%	22%	20%	4	22%
	62029	20%	14%	1	15%	11%	14%	9	17%
62107	62163	64%	49%	1	56%	56%	43%	1	51%
	62029	54%	48%	5	48%	38%	39%	9	43%
	62081	42%	38%	9	40%	29%	34%	10	39%
62303	62163	45%	27%	1	32%	40%	33%	5	34%
	62029	42%	27%	2	28%	28%	24%	14	26%
	62081	33%	22%	2	22%	21%	20%	10	22%
62106	62081	36%	21%	1	24%	25%	18%	1	21%
	62105	65%	38%	1	41%	69%	57%	2	60%
	62108	34%	20%	5	21%	29%	29%	10	32%
	64045	67%	36%	3	41%	69%	51%	1	54%
64046	62108	14%	8%	11	11%	10%	9%	18	19%
	64045	54%	30%	5	30%	40%	34%	9	36%

Cross Correlation Results - Graphs

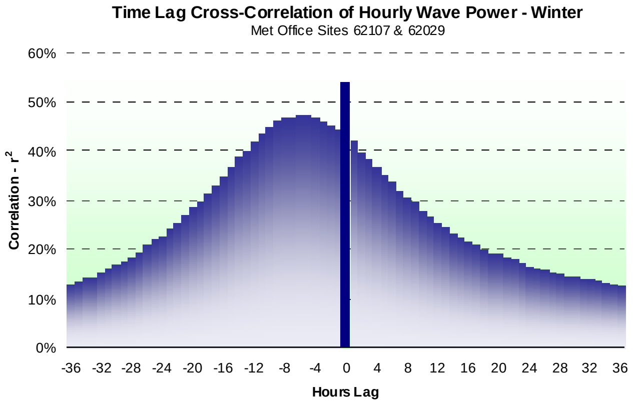
Presented below are the winter and summer cross-correlation plots for the three Target-Predictor buoy pairs identified in the previous table:

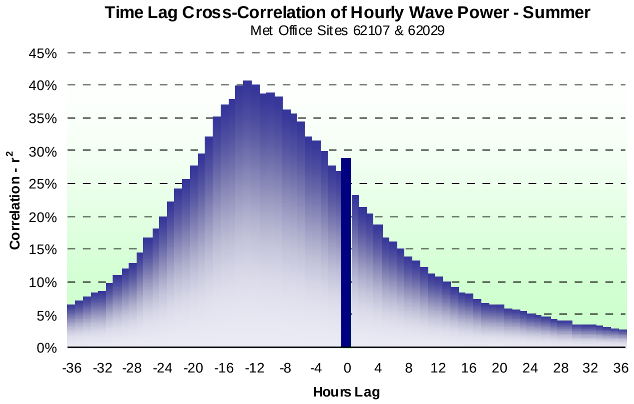
- 62107 (Seven Stones LV, South West) from 62029
- 62106 (Rahr Buoy, North West) from 62105
- 64046 (K7 Buoy) from 64045

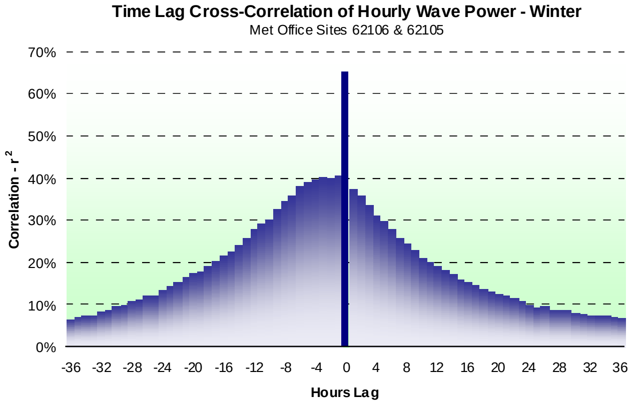
The graphs show the correlation between wave power at the two sites at different time lags. For example, the correlation shown for a lag of -6 hours means the correlation between wave power at the Target Site with that at the Predictor Site *six hours earlier*.

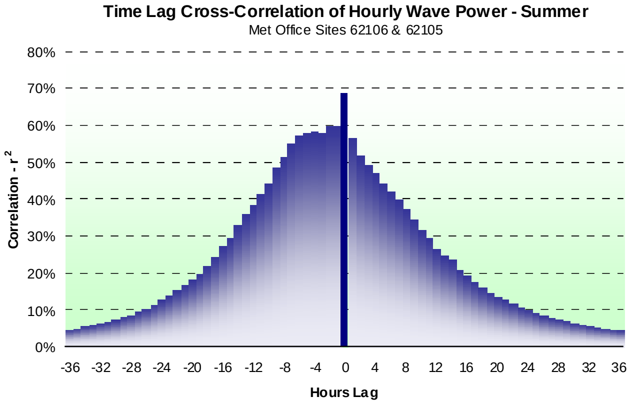
In all cases, there is a double peak in maximum correlation – one peak occurs at T0, meaning that the pattern of wave energy occurring at the same time at the two sites is similar, whilst a second (generally lower) peak occurs at some time lag between the two sites. This pattern suggests that waves are being generated both locally by a wind field that extends across both sites (zero lag correlation peak) and at some distance from both sites, arriving at the sites at different times (time lagged correlation peak).

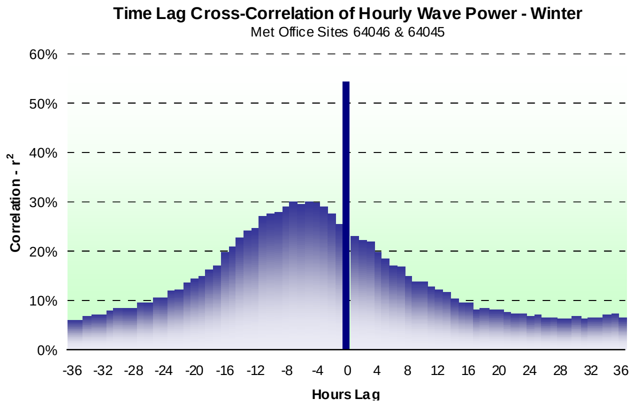
At Seven Stones LV (B62107) and K7 Buoy (B64046) the maximum (non T0) correlation with the target site occurs with the wave climate experienced by the predictor site between 6 and 13 hours earlier. This time difference reflects the time taken for waves passing the predictor buoy to arrive at the target site. This pattern is not repeated at

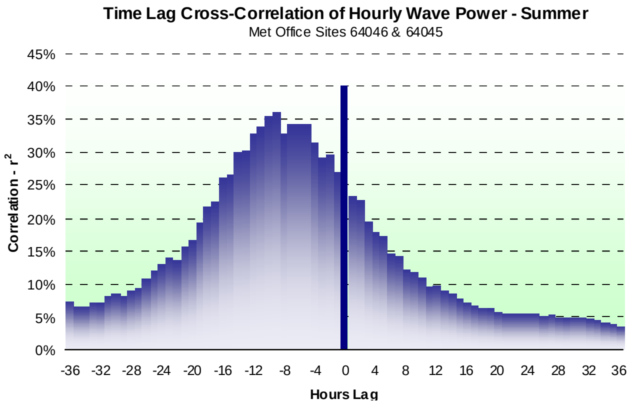












Rahr Buoy (B62106) – the predictor site of Rahr Buoy is nearby, and as a result there is far less difference in timing between the wave energy from the two sites.

There tends to be a longer time lag to peak correlation in summer, which is likely to be a result of the generally smaller, shorter period waves being generated by lighter or more local summer winds. As the groupspeed of the waves is proportional to the wave period, smaller waves will take longer to travel between the two buoys.

Autocorrelation Results - Graph

The autocorrelation properties of the three target sites were analysed, and all were found to be highly autocorrelated. Separate analyses were carried out for all data and winter only data, with the results being extremely similar. The graph (below left) shows the autocorrelation result for Seven Stones LV in winter.

This autocorrelation result suggests that wave energy in the current hour is a good predictor of wave energy in the next hour. It also shows the underlying reason why the rate of change of power output at the high energy wave sites is low, with the wave power output for the next hour likely to be close to the output experienced this hour (refer to the Rate Of Change section for a detailed analysis of hourly power output variability from wave power).

A Simple Prediction Algorithm

Following the findings of the cross-correlation and autocorrelation analyses, two linear regression models were developed to provide a forecast of power output one hour and six hours ahead. The basis for predicted output in these models is the observed power output one hour and six hours earlier at the Seven Stones LV and K1 Buoy sites; an example of this prediction is shown in the graph (below, right), and the regression equations are in Appendix 4.

The graph demonstrates that this simple model was able to broadly predict the wave power output pattern at both one-hour and six-hour time horizons, with the one-hour prediction being more accurate (as expected). Correlation between the observed pattern and the six-hour prediction was 79%, and with the one-hour prediction was 87% (Pearsons r^2).

The accuracy of this prediction model may be improved by addressing some limitations in the method used, such as:

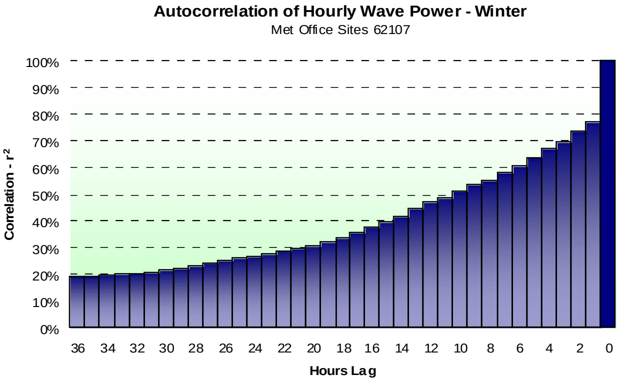
- Including wave direction in the analysis (the observed wave data used here do not include direction), and
- Developing different models for different wave energy bands, as it is likely that the relative importance of onshore and offshore sites will vary with wave energy.

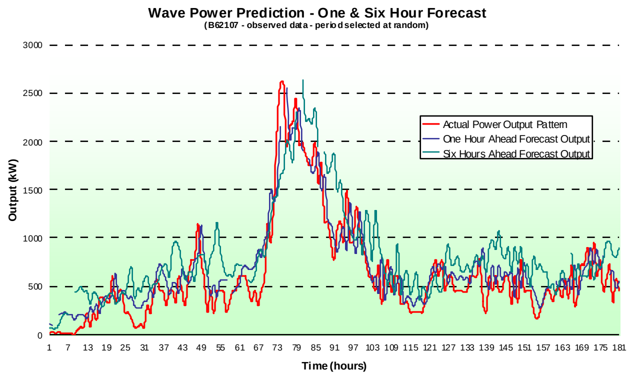
Numerical Model Forecasts

An alternative to the method presented here would be to use the forecasts generated by numerical wave models. For example, the UK Met Office runs a numerical model for wave prediction in UK waters – this model is run at three-hourly intervals, and provides wave climate predictions up to 160 hours in advance.

Using these forecast data, it would be possible to determine the accuracy of wave model forecasts at different time horizons, and quantify the reduction in uncertainty as the forecast time horizon shortened. Unfortunately, the Met Office does not routinely archive wave forecast data from its UK Waters model – this means that at present it is not possible to assess the uncertainty associated with the wave predictions made by the model. Furthermore, it does not appear that the Met Office has published any reports on forecast accuracy based on either the European or UK Waters models.

HR Wallingford Ltd has carried out an assessment of forecast accuracy for one of its high resolution wave models (the results of which will be published shortly). Further work is required to examine the accuracy of wave power forecast models for different forecast horizons, the results of which would assign a confidence level to the prediction.





Time Domain Matrices

Overview

Time domain matrices give the proportion of hours during which waves of a given height and period are present at the site.

Time domain matrices (TDMs) have been prepared for the following three observed wave sites:

- B62107 (South West Region)
- B62106 (North West Region)
- B64046 (North East Region)

These sites were chosen to be broadly representative of the wave climate experienced in each of the three high energy wave power regions.

The TDMs are presented on the following page – they have been shaded to highlight the higher and lower frequency events, whilst the percentage figures in each cell give the proportion of total hours that these conditions were experienced. Percentages are shown for all grid squares where at least one hour was recorded with that combination of wave height and period. The colours used are provided only as an aid to interpretation – where no record of the combination was found, the grid square has been greyed out and no percentage figure is given.

Individual Site Characteristics

All three TDMs showed similar characteristics, with the wave climate being dominated by wave heights in the 1m to 3m range, and wave periods in the 6 second to 9 second range. Large and/or long period waves account for a small proportion of total hours.

Site B64046

K7 Buoy is located in the North Atlantic Ocean immediately west of the North East region (Figure 3). The wave climate of this site is generally characterised by shorter period but larger waves, a result that is partly influenced by locally generated waves (which tend to be shorter period due to the limited fetch) together with waves generated in distant locations.

Waves with a period greater than 11 second account for less than 1% of observations, however waves of 5m or greater are present around 15% of the time.

Site B62106

Rahr Buoy is located in the North Atlantic ocean at the western extreme of the North West Region (Figure 4). The wave climate is similar to that encountered at B64046, with longer period waves (greater than 11sec) accounting for less than 1% of all waves - large waves (5m or greater) were experienced in almost 16% of all hours, again broadly similar to that of B64046.

Given the location of this site, it is a little surprising that longer period waves are not a larger feature of the wave climate – the shorter period waves recorded at this site suggest that locally generated waves are an important (but not dominant) aspect of the wave climate.

Site B62107

Seven Stones LV is the most exposed of the wave buoys located in the South West region (Figure 4). This site showed the broadest range of hourly wave characteristics, with a wave period typically longer than that for the two northern sites, and wave height typically lower.

The longer period waves recorded at this site are likely to be a result of the sites direct exposure to the Atlantic Ocean (the dominant source of wave energy at this site). Longer period waves reflect the characteristics of the wave generating area, with long period waves being formed in areas where the wind can blow uninterrupted over long stretches of ocean (ie a long fetch).

Large waves account for around 5% of all hours, around one third the rate of the previous two sites – long period waves are apparent almost 7% of the time, a significant increase on the northern sites.

Site B64046 (North East Region)

Hsig - metres	Tz - seconds													
	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0.5	0.2%	0.2%	0.0%			0.0%								
1.0	2.3%	3.2%	0.9%	0.2%	0.0%						0.0%	0.0%		
1.5	2.4%	5.6%	3.2%	0.9%	0.3%	0.0%	0.0%							
2.0	1.1%	7.1%	5.3%	1.9%	0.4%	0.1%	0.0%	0.0%	0.0%	0.0%		0.0%		0.0%
2.5	0.1%	4.8%	6.1%	2.7%	0.8%	0.1%	0.1%	0.0%	0.0%	0.0%		0.0%	0.0%	
3.0	0.0%	1.5%	5.6%	3.1%	1.3%	0.3%	0.1%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
3.5		0.2%	3.8%	3.6%	1.5%	0.4%	0.1%	0.0%	0.0%	0.0%			0.0%	0.0%
4.0	0.0%	0.0%	2.0%	3.4%	1.6%	0.6%	0.1%	0.0%					0.0%	0.0%
4.5		0.0%	0.5%	2.9%	1.7%	0.6%	0.1%	0.0%						
5.0		0.0%	0.1%	1.8%	1.7%	0.6%	0.1%	0.0%	0.0%					
5.5			0.0%	0.9%	1.5%	0.6%	0.2%	0.0%	0.0%					
6.0				0.2%	1.1%	0.7%	0.3%	0.1%	0.0%	0.0%				
6.5				0.0%	0.8%	0.7%	0.2%	0.0%	0.0%					
7.0		0.0%	0.0%	0.0%	0.3%	0.5%	0.2%	0.1%	0.0%	0.0%				
7.5			0.0%	0.0%	0.1%	0.4%	0.2%	0.1%	0.0%	0.0%	0.0%			
8.0			0.0%	0.0%	0.0%	0.2%	0.1%	0.1%	0.0%	0.0%			0.0%	
8.5				0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%		0.0%		
9.0				0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%				
9.5				0.0%	0.0%	0.0%	0.1%	0.0%	0.0%					

Site B62106 (North West Region)

Hsig - metres	Tz - seconds													
	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0.5	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%								
1.0	1.5%	2.4%	1.3%	0.3%	0.0%	0.0%	0.0%							
1.5	2.1%	5.6%	3.4%	1.2%	0.3%	0.0%	0.0%	0.0%					0.0%	
2.0	0.6%	6.7%	5.3%	2.2%	0.6%	0.1%	0.0%	0.0%					0.0%	0.0%
2.5	0.2%	3.6%	6.0%	2.7%	0.7%	0.1%	0.0%	0.0%	0.0%					
3.0	0.1%	1.2%	6.1%	3.6%	1.2%	0.2%	0.0%	0.0%	0.0%	0.0%			0.0%	0.0%
3.5	0.0%	0.3%	3.8%	3.7%	1.5%	0.3%	0.0%	0.0%	0.0%					0.0%
4.0	0.0%	0.1%	1.8%	4.1%	1.9%	0.4%	0.1%	0.0%	0.0%		0.0%			
4.5	0.0%	0.0%	0.4%	3.0%	1.9%	0.6%	0.1%	0.0%						0.0%
5.0		0.0%	0.1%	1.7%	2.2%	0.7%	0.1%	0.0%	0.0%					
5.5		0.0%	0.0%	0.7%	1.7%	0.7%	0.1%	0.0%	0.0%	0.0%				0.0%
6.0				0.2%	1.3%	0.8%	0.2%	0.0%	0.0%	0.0%				
6.5				0.0%	0.7%	0.7%	0.2%	0.0%	0.0%					
7.0			0.0%	0.0%	0.3%	0.7%	0.3%	0.0%	0.0%	0.0%				
7.5		0.0%		0.0%	0.1%	0.5%	0.2%	0.1%	0.0%	0.0%				
8.0			0.0%		0.0%	0.3%	0.2%	0.1%	0.0%	0.0%				
8.5			0.0%		0.0%	0.1%	0.2%	0.1%	0.0%					
9.0				0.0%	0.0%	0.1%	0.1%	0.1%	0.0%					
9.5					0.0%	0.0%	0.1%	0.0%	0.0%					

Site B62107 (South West Region)

Hsig - metres	Tz - seconds													
	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0.5	0.1%	1.2%	1.6%	1.3%	0.9%	0.6%	0.4%	0.3%	0.2%	0.2%	0.1%	0.1%	0.0%	0.0%
1.0	0.3%	2.4%	5.4%	4.7%	3.6%	1.7%	0.9%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	
1.5	0.1%	1.7%	5.6%	4.8%	3.5%	2.0%	1.2%	0.4%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
2.0	0.1%	0.6%	3.5%	4.5%	3.6%	1.9%	1.1%	0.4%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%
2.5	0.0%	0.2%	1.5%	3.2%	3.2%	1.8%	0.9%	0.3%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
3.0	0.0%	0.0%	0.7%	2.2%	2.7%	1.6%	0.9%	0.3%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
3.5	0.0%	0.0%	0.3%	0.9%	1.8%	1.2%	0.7%	0.3%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
4.0	0.0%	0.0%	0.1%	0.5%	1.2%	1.0%	0.7%	0.3%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
4.5	0.0%	0.0%	0.0%	0.2%	0.8%	0.8%	0.6%	0.3%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
5.0		0.0%	0.0%	0.1%	0.5%	0.6%	0.5%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
5.5			0.0%	0.0%	0.2%	0.3%	0.4%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
6.0				0.0%	0.1%	0.2%	0.3%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
6.5				0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
7.0				0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
7.5			0.0%		0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%		0.0%	
8.0				0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	
8.5					0.0%	0.0%	0.0%	0.0%	0.0%	0.0%				
9.0							0.0%	0.0%	0.0%	0.0%				
9.5							0.0%							

Power Density Matrix – Pelamis & Wave Dragon

Overview

Power density matrices show the wave conditions under which most power from the different wave devices is generated. This distribution of power output reflects both the frequency that particular wave conditions are experienced (height and period combination), and the efficiency of the device in extracting energy from the wave under these conditions.

Shown below are the power density matrices for the Pelamis and Wave Dragon devices at site B62107 (Seven Stones LV). Despite the fundamental difference in design between these two devices and the wider reported operating range for the Wave Dragon device, there is very little difference in power output distribution.

B62107 - Pelamis

Wave Height - metres	Wave Period - seconds								
	5	6	7	8	9	10	11	12	13
0.5									
1.0		0.4%	1.2%	1.1%	0.8%	0.3%	0.1%		
1.5	0.0%	0.6%	2.8%	2.4%	1.6%	0.8%	0.4%	0.1%	0.0%
2.0	0.0%	0.4%	3.1%	4.1%	3.0%	1.3%	0.6%	0.2%	0.1%
2.5	0.0%	0.2%	2.1%	4.6%	4.1%	1.9%	0.8%	0.2%	0.1%
3.0	0.0%	0.1%	1.4%	4.3%	4.8%	2.2%	1.1%	0.3%	0.1%
3.5	0.0%	0.0%	0.7%	2.3%	4.0%	2.2%	1.1%	0.4%	0.1%
4.0	0.0%	0.0%	0.3%	1.6%	3.5%	2.3%	1.4%	0.5%	0.2%
4.5	0.0%	0.0%	0.1%	0.9%	2.6%	2.2%	1.4%	0.6%	0.2%
5.0		0.0%	0.0%	0.5%	1.9%	2.1%	1.4%	0.5%	0.2%
5.5			0.0%	0.1%	1.1%	1.3%	1.2%	0.4%	0.2%
6.0				0.1%	0.6%	0.9%	0.9%	0.4%	0.2%
6.5				0.0%	0.3%	0.5%	0.6%	0.2%	0.2%
7.0				0.0%	0.1%	0.2%	0.4%	0.2%	0.1%
7.5			0.0%		0.1%	0.1%	0.3%	0.1%	0.1%
8.0				0.0%	0.0%	0.1%	0.1%	0.0%	0.0%

B62107 – Wave Dragon

Wave Height - metres	Wave Period - seconds										
	4	5	6	7	8	9	10	11	12	13	14
0.5											
1.0	0.0%	0.0%	0.6%	1.8%	2.0%	1.6%	0.8%	0.4%	0.1%	0.0%	0.0%
1.5	0.0%	0.0%	0.6%	2.8%	3.1%	2.5%	1.4%	0.8%	0.2%	0.1%	0.0%
2.0	0.0%	0.0%	0.3%	2.3%	3.9%	3.5%	1.9%	1.0%	0.4%	0.1%	0.0%
2.5	0.0%	0.0%	0.1%	1.4%	3.9%	4.3%	2.5%	1.3%	0.4%	0.1%	0.1%
3.0		0.0%	0.0%	0.8%	3.4%	4.8%	2.9%	1.6%	0.5%	0.2%	0.1%
3.5	0.0%	0.0%	0.0%	0.4%	1.8%	3.7%	2.4%	1.5%	0.7%	0.2%	0.1%
4.0		0.0%	0.0%	0.2%	1.2%	2.9%	2.4%	1.6%	0.7%	0.3%	0.1%
4.5	0.0%	0.0%	0.0%	0.0%	0.6%	1.9%	1.9%	1.5%	0.7%	0.3%	0.1%
5.0			0.0%	0.0%	0.3%	1.1%	1.5%	1.2%	0.5%	0.3%	0.1%
5.5				0.0%	0.1%	0.6%	0.8%	0.9%	0.4%	0.2%	0.1%
6.0					0.0%	0.3%	0.5%	0.6%	0.3%	0.2%	0.1%
6.5					0.0%	0.1%	0.3%	0.3%	0.2%	0.1%	0.0%
7.0					0.0%	0.1%	0.1%	0.2%	0.1%	0.0%	0.0%
7.5				0.0%		0.0%	0.1%	0.2%	0.1%	0.0%	0.0%
8.0					0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%

(Colours used are a guide only – percent of energy generated in each height/period combination is shown)

Power Density Matrix – AWS

Two power density matrices are presented (below) for the Archimedes Wave Swing, one with an unrestricted power output (top) and one with a rated power of around 900kW (equivalent to a capacity factor of 30%). Refer to the next section on the Archimedes Wave Swing Device for a full discussion.

There is only a very minor change in the distribution of power output in relation to wave height and period between the two matrices. This finding arises from the small impact that imposing a maximum rated capacity on the device has on overall output performance – it is only during relatively rare high wave energy events that output is affected, and the impact is to “clip” rather than prevent output in these situations. For example, in the unrestricted device 38% of power output occurs in waves greater than 4m, while this is reduced to 28% in the restricted device – a smaller effect is found for wave periods over 13 seconds. Note that the overall pattern is very similar to the Pelamis and Wave Dragon devices.

B62107 – AWS (unrestricted – peak output = 3,352kW)

Wave Period - seconds

Wave Height - metres	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0.5														
1.0	0.0%	0.1%	0.4%	0.6%	0.6%	0.4%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	
1.5	0.0%	0.1%	0.9%	1.2%	1.2%	1.0%	0.7%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
2.0	0.0%	0.1%	1.0%	2.0%	2.2%	1.6%	1.1%	0.5%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%
2.5	0.0%	0.1%	0.7%	2.2%	3.0%	2.2%	1.4%	0.6%	0.3%	0.1%	0.1%	0.0%	0.0%	0.0%
3.0	0.0%	0.0%	0.5%	2.2%	3.6%	2.8%	1.9%	0.8%	0.4%	0.2%	0.1%	0.0%	0.0%	0.0%
3.5	0.0%	0.0%	0.2%	1.2%	3.2%	2.6%	1.9%	1.0%	0.4%	0.2%	0.1%	0.0%	0.1%	0.0%
4.0	0.0%	0.0%	0.1%	0.8%	2.8%	2.8%	2.2%	1.1%	0.5%	0.2%	0.1%	0.1%	0.1%	0.0%
4.5	0.0%	0.0%	0.0%	0.5%	2.2%	2.7%	2.4%	1.2%	0.6%	0.3%	0.2%	0.0%	0.0%	0.0%
5.0		0.0%	0.0%	0.3%	1.6%	2.5%	2.3%	1.1%	0.6%	0.2%	0.1%	0.1%	0.0%	0.0%
5.5			0.0%	0.1%	0.9%	1.5%	2.0%	0.9%	0.6%	0.2%	0.2%	0.1%	0.0%	0.0%
6.0				0.1%	0.6%	1.1%	1.5%	0.8%	0.4%	0.2%	0.1%	0.0%	0.1%	0.0%
6.5				0.0%	0.3%	0.7%	0.9%	0.4%	0.4%	0.1%	0.1%	0.0%	0.0%	0.0%
7.0				0.0%	0.1%	0.3%	0.7%	0.3%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
7.5			0.0%		0.1%	0.2%	0.5%	0.2%	0.1%	0.0%	0.0%		0.0%	
8.0				0.0%	0.0%	0.1%	0.2%	0.1%	0.1%	0.0%		0.0%	0.0%	
8.5					0.1%	0.1%	0.2%	0.1%	0.0%	0.0%				
9.0							0.1%	0.1%	0.0%	0.0%				
9.5							0.0%							

B62107 – AWS (restricted – peak output = 980kW)

Wave Period - seconds

Wave Height - metres	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0.5														
1.0	0.0%	0.1%	0.5%	0.7%	0.7%	0.4%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	
1.5	0.0%	0.2%	1.1%	1.4%	1.5%	1.1%	0.9%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
2.0	0.0%	0.1%	1.2%	2.3%	2.6%	1.9%	1.3%	0.6%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%
2.5	0.0%	0.1%	0.8%	2.6%	3.5%	2.6%	1.7%	0.7%	0.3%	0.2%	0.1%	0.0%	0.0%	0.0%
3.0	0.0%	0.0%	0.6%	2.5%	4.3%	3.3%	2.2%	0.9%	0.5%	0.2%	0.1%	0.1%	0.0%	0.0%
3.5	0.0%	0.0%	0.3%	1.4%	3.7%	3.1%	2.2%	1.1%	0.4%	0.2%	0.1%	0.0%	0.1%	0.0%
4.0	0.0%	0.0%	0.1%	1.0%	3.3%	3.3%	2.3%	1.1%	0.4%	0.2%	0.1%	0.0%	0.1%	0.0%
4.5	0.0%	0.0%	0.0%	0.6%	2.6%	2.7%	2.1%	1.0%	0.4%	0.2%	0.1%	0.0%	0.0%	0.0%
5.0		0.0%	0.0%	0.3%	1.6%	2.1%	1.7%	0.8%	0.4%	0.1%	0.1%	0.0%	0.0%	0.0%
5.5			0.0%	0.1%	0.8%	1.1%	1.3%	0.6%	0.3%	0.1%	0.1%	0.0%	0.0%	0.0%
6.0				0.1%	0.5%	0.7%	0.9%	0.4%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%
6.5				0.0%	0.2%	0.4%	0.5%	0.2%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%
7.0				0.0%	0.1%	0.2%	0.3%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
7.5			0.0%		0.1%	0.1%	0.2%	0.1%	0.1%	0.0%	0.0%		0.0%	
8.0				0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%		0.0%	0.0%	
8.5					0.0%	0.0%	0.1%	0.0%	0.0%	0.0%				
9.0							0.0%	0.0%	0.0%	0.0%				
9.5							0.0%							

Archimedes Wave Swing Device

Introduction

This section examines the output characteristics of the Archimedes Wave Swing device (AWS). Whilst the AWS functions in the same or similar wave climates to the Pelamis and Wave Dragon devices, its output pattern tends to be more variable. This variability results from a unique feature of the device – unlike the other devices, the AWS has no effective rated power output level; that is, power output continues to increase with wave energy, rather than reaching an upper limit (the rated power of the device) and remaining at this level irrespective of further increases in ambient wave energy. This feature of the device is apparent in the AWS transform function shown on page 33.

This operational feature of the AWS allows it to generate more power in higher energy seas – however, the drawback is that energy output in high seas tends to be very peaky, generating spikes in output that are not present in other devices. These spikes present two difficulties for integrating the devices into electricity networks – the matching of supply and demand patterns, and the transmission of large but rare high power outputs.

Supply and Demand Matching

For most intermittent renewable energy converters, the peak output of the device (ie its rated capacity) is generally around three times the long term average output. This acts to dampen the variability of the device in response to high energy events (for example, high energy waves). The effective rated capacity of the AWS is very high, resulting in peak outputs up to 10 times larger than the average device output. These occasional high energy events are more difficult to incorporate into the electricity network as balancing has to respond to larger changes in supply.

Transmission

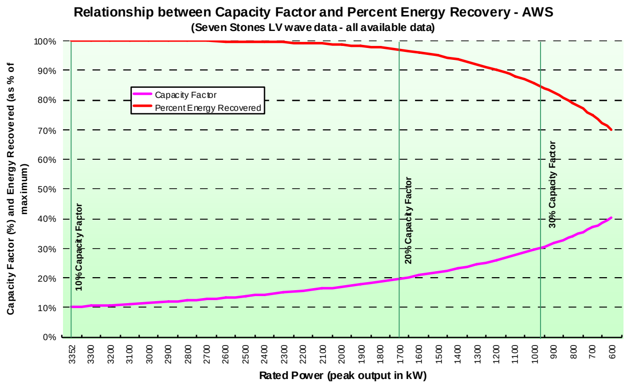
Whilst the AWS is capable of generating high power outputs, to be of use this electricity must be transmitted to a demand centre. For the total output of the device to be available, transmission capacity around 10 times the average output of the device must be installed (compared to around three times for other devices). This raises an economic question – is it worth the cost of installing higher capacity transmission to allow all electricity to enter the network, or would a smaller transmission system be effective in moving the bulk of electricity generated by the device (and having a small amount spilled).

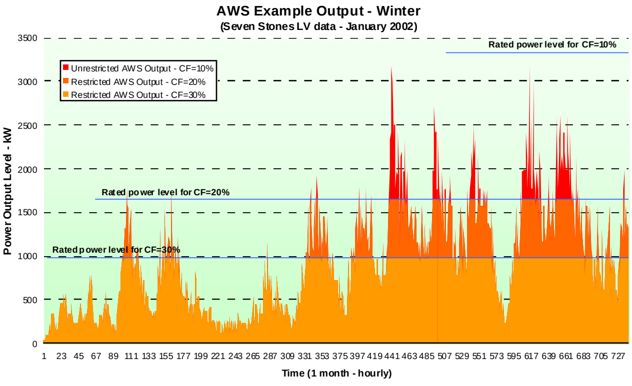
Analysis

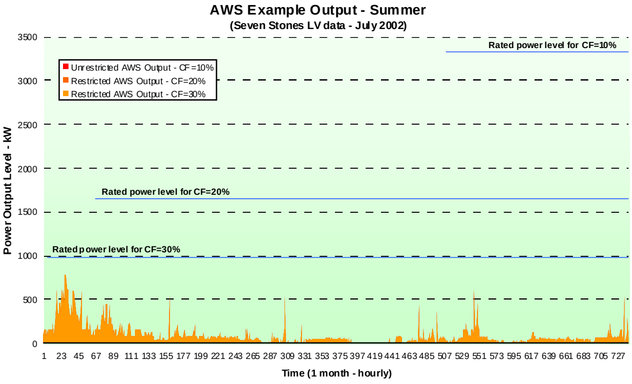
The performance of the AWS device at Seven Stones LV (observed data site) was investigated to determine the relationship between rated capacity (or transmission limitation), capacity factor and total energy recovery. The results are shown in the three graphs below.

By limiting the output of the device to a maximum of 1,700kW (originally 3,355kW), a capacity factor of 20% was achieved, with a loss in total energy delivered of 3.5%. Further limiting the AWS output to around 980kW resulted in a 30% capacity factor, with long term energy losses of around 15%.

The middle graph shows the impact that limiting the AWS output would have on winter supply patterns – significantly lower variability is achieved when the device is rated to give a 30% capacity factor. There is little impact on summer supply patterns (bottom) due to the generally low power output levels at this time of year.







Characteristics of a Diversified United Kingdom Marine Resource

Diversified UK Wave and Tidal Scenarios

Introduction

Diversifying across different resources and locations offers the opportunity to smooth both regional and resource variability. This section considers the effect of a combined wave and tidal system on marine energy supply variability.

Scenarios

Three scenarios are proposed for combined wave and tidal power development – with each scenario, the installed generating capacity is scaled to meet 10% of annual electricity demand.

- **High Tidal**: tidal current power in the Northern Islands, Pentland and Channel Isles regions is fully developed, with the balance of annual generation being provided by wave power systems (approximately 3.6% tidal current / 6.4% wave power supply split).
- **Diversified Tidal**: the same resource split as High Tidal, however there is no site restriction for tidal power.
- **Optimal Marine**: in which there is no minimum level of tidal power contribution to electricity generation.

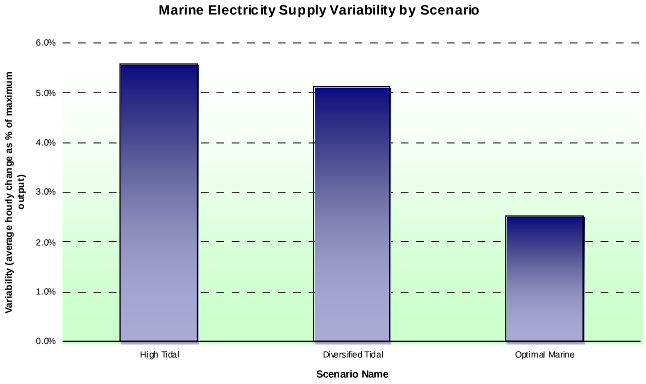
Under both the High Tidal and Diversified Tidal scenarios, tidal power development would account for around 80% of the known tidal resource in the UK. For each scenario, the objective was to identify the relative contribution of different sites and resources that would result in the lowest level of variability (average hourly variability as a percentage of peak demand) in the supplied electricity.

Note – for this analysis, three-hourly EWM wave data was combined with known hourly wave power variability patterns from observed sites located in the region. This resulted is an hourly wave power time series, which was then matched against hourly tidal current power data in the analysis.

Scenario Comparison

The graph above right shows the impact of the three scenarios on the change in average hourly output change from the diversified marine renewable system. There was a small decrease in the overall variability from the Diversified Tidal scenario compared to the High Tidal Scenario, reflecting the impact of developing sites in the North West and South West regions; however the Optimal Marine scenario showed by far the lowest average variability in supply.

There is a high degree of variability associated with tidal power output in comparison to wave power output, driven by both diurnal and Spring-Neap cycles of tidal power availability. With tidal power making a significant contribution to marine renewables under the High Tidal and Diversified Tidal scenarios, and given the sensitivity of overall tidal output variability to the level of development, the results presented here reflect the limited opportunity to diversify within the tidal sites at high levels of tidal power development.

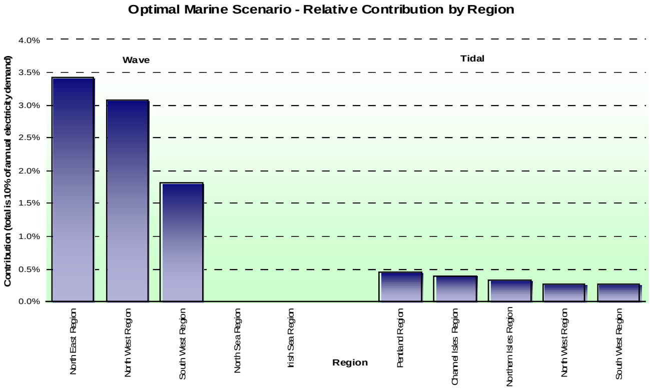


Optimal Marine Scenario

The figure below shows the relative contribution of wave and tidal regions to the lowest variability supply of marine renewable energy over the long term. As would be expected from the previous discussion, the role of tidal power is limited due to the higher relative variability of this resource in comparison to wave power.

Wave power is the dominant source of energy in this scenario, accounting for 83% of total output. However the contribution from tidal power represents a significant investment in this technology - around 38% of the UK’s tidal current generating potential would need to be developed, including around two-thirds of the potential capacity of the Channel Isles.

Despite the higher variability of tidal power, the optimal mix of marine-generated electricity requires tidal power systems to be developed. This finding demonstrates that the inclusion of tidal power generating capacity can act to improve the reliability of a diversified marine renewable system, reducing overall variability as well as increasing the predictability of overall output.



Installed Capacity

The installed capacity for each site under the three scenarios is shown in the table below. Note that the total installed capacity for each scenario changes due to the varying contribution of different sites, each with different capacity factors – tidal site capacity factors are typically higher than wave site capacity factors, resulting in less installed capacity being required for scenarios with high tidal power contributions. Sites shown in grey were not available for development in the respective scenario.

	Site	Installed Capacity by Scenario - MW		
		High Tidal	Diversified Tidal	Optimal Marine
Wave Power	Shetland	1,391	1,391	1,816
	Orkney	1,429	1,428	1,864
	Lewis	1,241	1,241	1,620
	Orsay	1,134	1,134	1,481
	Peterhead			
	Scarborough			
	Cromer			
	Eskmeals			
	Turbot Bank	720	720	940
	Seven Stones	778	778	1,015
	South Hams	722	722	943
	Total Wave Power	**7,417**	**7,414**	**9,679**
Tidal Power	Casquets	106	106	76
	Guersey Big Russel	99	99	68
	Guersey North West	152	152	55
	North East Jersey	52	52	52
	Race Of Alderney	91	91	79
	Orkney Yell Sound West Channel	61	61	40
	Orkney Yell Sound East Channel	49	49	49
	Orkney Bluemull Sound NS	42	42	42
	Orkney Westray Fers Ness	18	18	18
	Orkney Papa Westray	71	71	71
	Orkney North Ronaldsay Firth	3	3	3
	Westray Falls Of Warness	51	51	51
	Orkney Eday Sound	18	18	18
	Kyle Rhea	0	7	7
	Mull Of Galloway	0	104	73
	Mull Of Kintyre	0	6	6
	Mull Of Oa	0	6	6
	Rathlin Coast	0	117	63
	Rathlin Sound	0	63	63
	Sanda Sound	0	7	7
	South Ronaldsay To Swona	277	277	79
	Pentland Inner Sound	38	38	38
	Pentland Duncansby Head	423	423	76
	Pentland Hoy	185	185	76
	Pentland Skerries South	1,271	614	78
	Bristol Channel North Lundy	0	14	14
	Bristol Channel South Lundy	0	12	12
	Bristol Channel Barry	0	32	32
	Bristol Channel Foreland Point	0	146	72
	Cornwall Cape Cornwall	0	9	9
	Cornwall Lands End	0	9	9
	Cornwall The Lizard	0	9	9
	Isle Of Wight	0	3	3
	Portland Bill	0	110	73
	Total Tidal Power	**3,006**	**3,001**	**1,425**
	Total	**10,423**	**10,415**	**11,105**

Transmission Utilisation Scenarios

Introduction

Transmission capacity, and the need to establish new transmission links to bring renewable energy sources into the UK electricity market, is often cited as an impediment to development. This is particularly relevant in remote areas with abundant renewable resources, such as the north east and north west of Scotland. However, there are relationships and strategies related to the use of transmission capacity that may be relevant to these situations.

The transmission capacity required for renewable energy development is related to the installed capacity, the capacity factor of the device, and the pattern of supply. Devices with lower capacity factors, or with more “peaky” supply patterns, will generally require substantially more installed transmission capacity in order to meet the peak transmission requirement. The utilisation of transmission capacity installed for renewable energy systems can be improved by three strategies, the first two of which are discussed in this section:

1. Transmission Limited Systems: Installing less transmission capacity than the peak output of the system, thereby curtailing output during rare high power output events;
2. Installing a diversified range of renewable power systems and sites, so that the different patterns of generation allow for more effective utilisation of the transmission capacity, and
3. Installing on-site storage to smooth out peaks and troughs in renewable energy output, thereby reducing peak transmission capacity requirements (this option is not considered further in this report).

Concepts

Renewable resources such as wave power and tidal power only rarely produce power at maximum (rated) capacity, with the majority of the time spent operating at lower power output levels. Furthermore, these rare peaks in output may account for only a small amount of the total annual electricity yield. This raises the possibility of using or installing transmission capacity that is below the peak output of the resource – some electricity will be spilled, however there will be lower overall variability in the transmitted electricity supply, while utilisation of the transmission capacity will be higher.

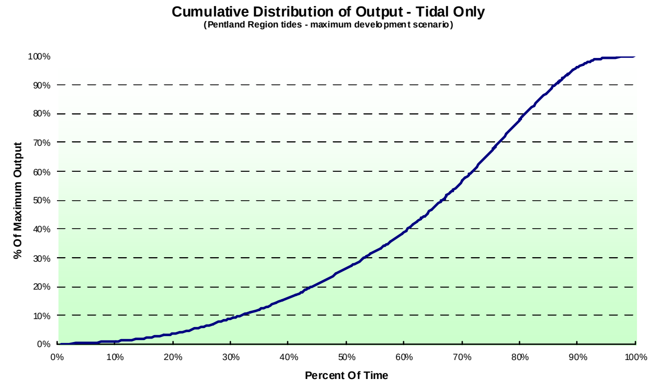
The two graphs below show the relationship between output level, transmission capacity and total energy recovery for a fully developed tidal power system in the Pentland Region. The left-hand graph shows the relationship between the tidal power output level and the amount of time this level is achieved or exceeded – this graph can be read in two ways:

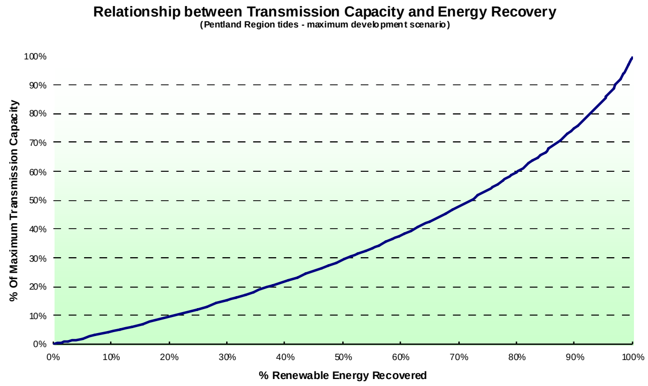
1. an output of 20% or less of installed capacity is achieved around 40% of the time, or conversely,
2. for 70% of the time output is 63% of installed capacity or less.

The right hand graph shows the impact that limiting transmission capacity has on the total amount of energy delivered from the system. In the graph shown, a transmission capacity equal to 50% of the peak output of the tidal system would deliver around 70% of annual energy, whilst 97% of annual electricity yield would be delivered using a transmission network scaled to around 88% of peak output.

The reason for this relationship is that, by limiting the peak output from the region (through a smaller transmission link) the rare peaks in output are spilled from the system. However this does not mean that the whole of the peak is lost – only that portion of the peak above the transmission limit will be lost, ensuring that the majority of the electricity being generated during any peak period is transmitted.

(Note that the axes of Percentage of Minimum Output and Percentage of Maximum Transmission Capacity represent the same concept – a limit on output as a percentage of maximum possible output).


Cumulative Distribution of Output - Tidal Only
(Pentland Region tides - maximum development scenario)


Relationship between Transmission Capacity and Energy Recovery
(Pentland Region tides - maximum development scenario)

Transmission Utilisation Scenario

The **Transmission Utilisation Scenario** examines the relationship between transmission capacity and utilisation. In this scenario, the Pentland Region tidal resource is fully developed, and a dedicated transmission link is established to meet the peak output of the tidal system. Subsequently, additional wave power generating capacity is assumed to be installed in the North West Region, with an annual output of 20% of the tidal power output. The contribution of wave power is optimally allocated between the two available sites in the region.

The two graphs on the following page show the impact that the addition of wave power into the tidal system has on overall output and transmission characteristics.

The distribution of system power output (next page, top) shows a relatively even increase in the duration of output level for most of the time, however a greater increase at low and very high output levels is apparent. This reflects the low correlation between tidal and wave power output, with occasional high energy wave events during peak tidal current periods driving the increase in peak output.

The addition of 20% wave power to the system would see the previous tidal-only peak output exceeded 17.5% of the time. However, only a small amount of energy is delivered at power output levels above the peak tidal-only power output level. This observation is confirmed in the second graph (next page, bottom), where the percent of transmission utilisation over time is shown for the tidal only and combined tide-plus-wave systems. The inclusion of wave power increases the transmission requirement of the system at all times, with the biggest impact being felt during peak output periods.

However, this graph raises another point – if transmission capacity is limited, what advantage is gained by including additional renewable energy generation on the same transmission line? By limiting the available transmission capacity to around 2,300MW (required to meet the peak tidal power output), “peaks” in the regional electricity supply would be clipped and spilt from the system. Utilisation of the transmission system (the amount transmitted by the system compared to the total volume possible) would rise from 42.3% to 49.1%.

The second graph (next page, bottom) shows the relationship between transmission limitations and the percentage recovery of energy generated by the tidal-only and combined tide-plus-wave systems. By limiting the transmission capacity in this way, around 97% of total energy generated by the combined tidal and wave power system would be delivered across the transmission network originally established for the development of tidal power alone. To deliver the remaining 3% of generation, an additional 800MW of transmission capacity would need to be available to the region.

The energy spilled from the system needs to be balanced against the cost of upgrading (or establishing in the first place) sufficient transmission capacity to meet peak output. A loss of 3% of total yield from the system equates to a loss of around 20% of wave power yield – this will increase the cost of wave power, however this needs to be balanced against savings from not having to establish additional transmission capacity, and achieving lower variability in (aggregate) electricity supply.

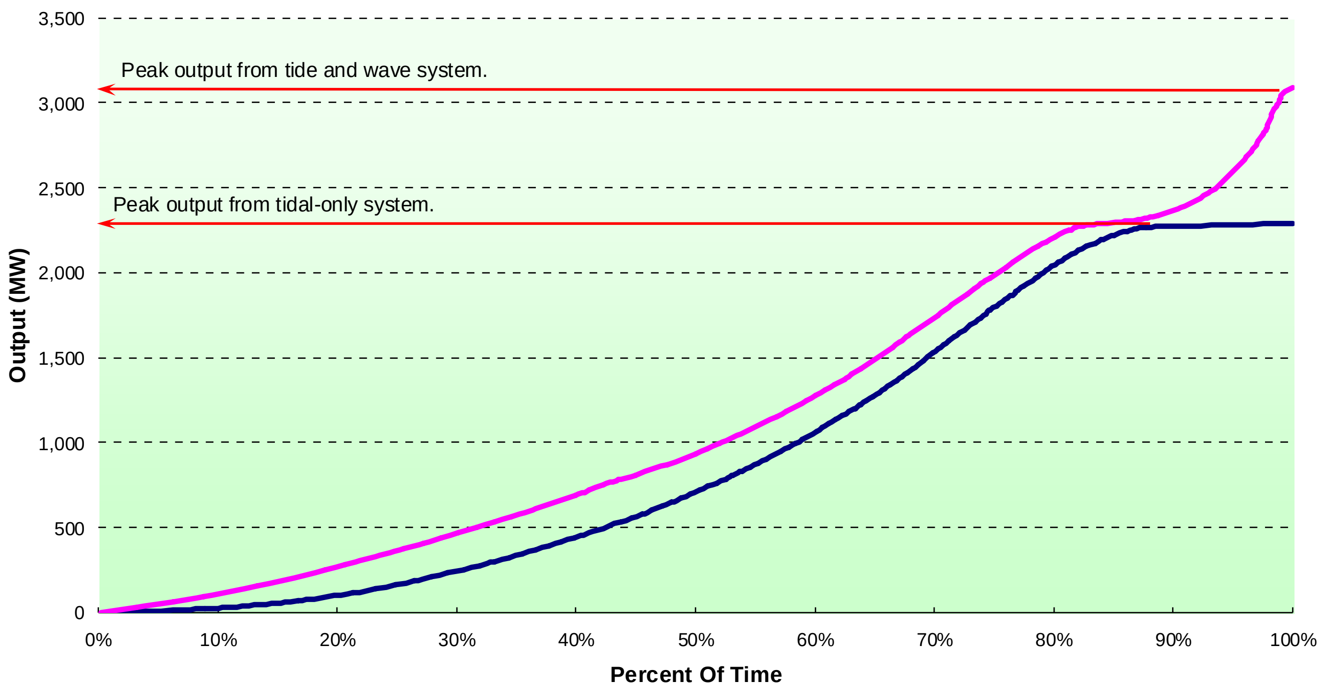
Transmission and Planning

The interaction between transmission and development of renewable energy resources discussed in this scenario has implications for the planning regime within which renewable energy projects are proposed. While this example has considered the implications of subsequent diversification of the renewables base in a region, and the opportunities for connecting this to the grid via transmission previously established for another project, an integrated planning approach could use this finding in a different way.

It may be more expensive to upgrade a transmission line that had previously been established for a tidal-only system than suffer some yield loss by using existing capacity (the assumption behind this scenario). However, it may not have been more expensive to have oversized the transmission line when it was originally constructed. By taking a view on the regional development potential for renewables, and the interaction between a diversified range of renewable power options, it would be possible to inform the planning process so that infrastructure decisions taken now would leave open the option of further diversified development in the future, rather than constraining future options through the duplication of infrastructure costs.

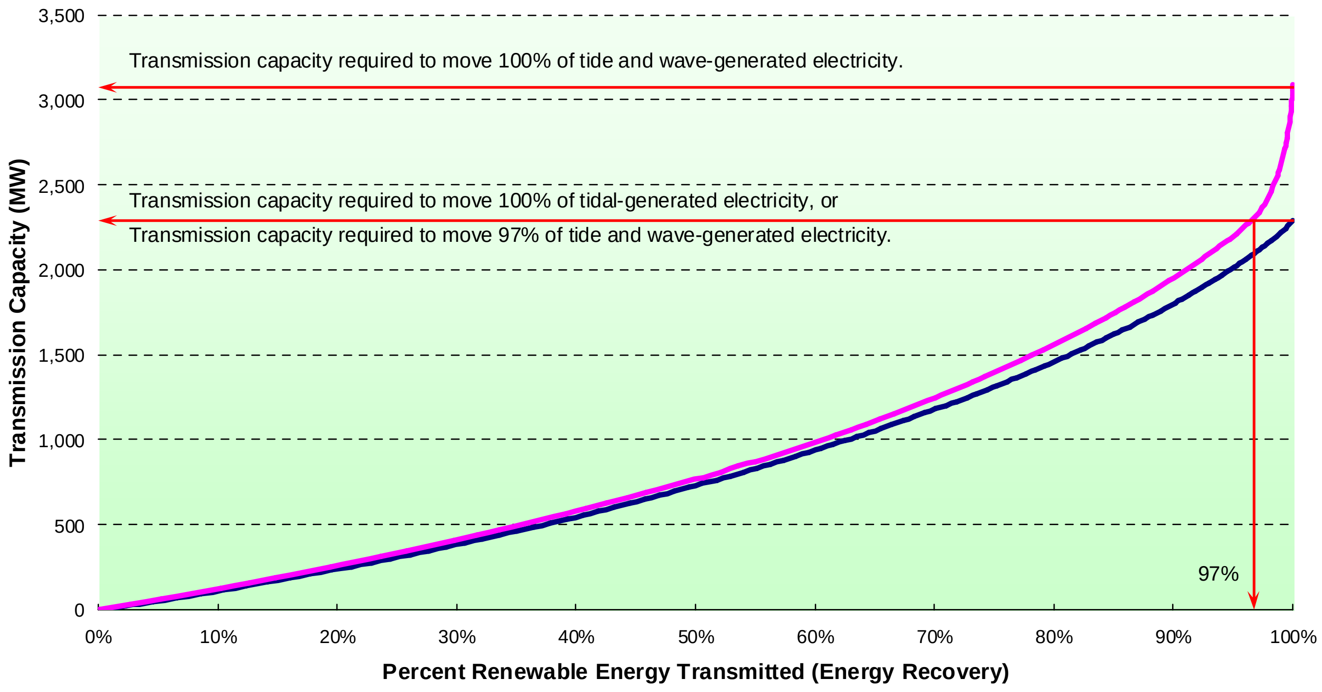
Cumulative Distribution of Output

(Pentland Region tides - maximum development scenario - North East Region wave - wave is 20% of tidal energy yield)



Relationship between Transmission Capacity and Energy Recovery

(Pentland Region, maximum development scenario - North East Region, wave power output is 20% of tidal energy yield)



Conclusion

Conclusion

Introduction

This report has presented a detailed description of the variability of UK marine renewables. Data for tidal and wave locations around the UK coast have been presented, and the patterns of energy output from these sites have been modelled at different time periods. In addition, this report has provided a range of analyses investigating the properties and impact of tidal and wave power variability, and a range of scenarios assessing the impact of site and resource diversification on renewable energy supply variability.

Tidal Current Power

The output pattern of the UK tidal resource was assessed by modelling the performance of a free-flowing axial rotor turbine at 36 sites around the UK coast. The power output pattern from tidal current power is predictable and shows very little variability by season, however at smaller timescales there is considerable variability in output.

The Spring-Neap tide cycle results in major changes to output over a 14 day cycle, with no opportunity for site diversification to reduce this variability since the cycle is synchronised globally. The intra-day variability of individual tidal current power sites is large, typically rising to two peaks in output and falling to two minimums in output every 24 hours. It was demonstrated that this variability could be smoothed by diversifying across a range of sites: however, the limited development potential of sites that were essential to smoothing total variability meant that this solution was only possible at low levels of overall development of the UK tidal resource. As total tidal resource development increases, the contribution from larger sites quickly rises, and the correlated output patterns of many of these sites dominates the overall output pattern of the tidal supply.

Wave Power

Wave power output patterns were modelled for 11 sites around the UK, grouped into three high energy and two low energy regions. Three different wave power converter devices were modelled, however the similarity in output patterns for all three devices resulted in a single average power output pattern being used at each site.

Wave power was found to be highly seasonal, with almost half of the annual output occurring in the three months of winter. Despite this strong seasonal pattern of supply, wave power showed less short-term variability than tidal power – in common with the findings for the tidal power sites, variability in the wave power resource was further reduced through regional diversification. This finding was particularly noticeable during winter, and demonstrates that there is a greater opportunity for wave power to contribute to renewable energy supply by following a diversified approach to its development.

Integrated Scenarios

The report presented findings from a range of scenarios, including the development of a combined tidal and wave programme across the UK. This scenario demonstrated that the lowest system-wide variability from an integrated marine renewables programme would require the development of both wave and tidal power at a range of sites, however the contribution from tidal current power was relatively small. By increasing the contribution of tidal power, the variability of the system rose considerably, but was still well below a large-scale tidal-only development path.

In areas with constrained network capacity, it was demonstrated that combined wave and tidal power development can increase transmission utilisation and decrease supply variability. This can be achieved at very low cost in terms of rare peaks being spilt from the system due to a lack of transmission capacity. While outside the scope of this report, local energy storage or hydrogen conversion systems may be relevant in further improving transmission utilisation and lowering variability in these circumstances.

The final scenario presented in the report demonstrated that marine renewables should not be viewed in isolation from other renewable sources. The scenario presented for the South West region demonstrated that the renewable energy supply with the least impact on net demand variability of the UK electricity network included significant supply contributions from onshore wind, offshore wind, tidal current and wave power systems. With a greater geographic range of sites, and a wider range of renewable energy sources, it is suggested that further benefits from a diversified UK renewables strategy would be gained.

Annex 1 – Data Availability Assessment for UK Wave and Tidal Resources

Introduction

Pre-Report Data Assessment

Prior to the main resource characterisation work being undertaken for wave and tidal current power, an assessment was made of the existing datasets available to support the project. This was an important preliminary step in the development of the project – the method used in the main report relies on extensive, site-specific time series datasets that would provide both a high resolution (hourly if possible) view of the variability of the underlying resources, and a long-term view to allow extremes in resource availability (or lack of availability) to be reflected in the report.

Detailed records of wave height, wave period (the time for successive wave crests to pass a given point) and tidal current velocity were needed to develop energy availability time series. Whilst data have been collected for a number of decades, wave data are limited in both geographic coverage and record length at any one site. The tidal height dataset is both extensive and representative of the UK coast, while tidal current monitoring is very scarce.

Data Sources

Three types of wave and tidal data were considered for this pre-report assessment:

Observational Data: includes any direct measurement of wave statistics or sea surface height.

Model Data: relates to the output of numerical wave simulation models that have been developed for forecasting sea conditions.

Satellite Data: includes remotely sensed satellite data routinely collected around the UK coast.

Where significant data records were identified, the completeness of the datasets were determined, and their ability to contribute to an improved understanding the variability of marine renewables was assessed.

Finally, recommendations for the design of the next phase of the project, involving the assessment of variability patterns from marine renewables and their potential for providing a reliable contribution to UK electricity supply, are presented.

Wave Model Data

Overview

There is a range of wave data modelling products available for the UK coast, including global, European and UK scale, which are run routinely to provide predictions of wave conditions. In practice, these form a nested model structure, with the low resolution global model providing boundary condition inputs for the medium resolution European model, which in turn provides boundary condition inputs to the higher resolution UK wave model.

Of particular interest to this project is the “hindcast” ability of the European and UK wave models, where known observational data is used to inform and improve the accuracy of model-generated wave data for past conditions. In addition, purpose-built high-resolution wave models that utilise hindcast data to determine site-specific wave conditions are also available.

European Wave Model

The European Wave Model (EWM) is a medium resolution model, which includes the north-western European shelf seas, the Baltic Sea, Mediterranean and Black Sea. Sites are located on a grid measuring 0.25° latitude by 0.4° longitude (approximately 35km resolution), with the grid centred on 0° latitude, 0.06°W longitude. Wave data are available from July 1988 to present for around 200 model sites within 12 miles of the UK (mainland and islands), and around 700 sites within 100km.

United Kingdom Wave Model

The UK wave model is a higher spatial resolution model, encompassing the region from 12°W of the European mainland (around the location of K2 Buoy), and from 48-63°N (from Brittany Buoy to the Faeroe Islands). Sites are located on a grid measuring 0.11° latitude by 0.17° longitude (approximately 12km resolution). Wave data are available from April 2000 to present for around 1,000 model sites within 12 miles of the UK coast. A total of almost 4,000 model sites are available within 100km of the UK coast.

Data Availability

European and UK wave model data are available on a three-hourly time step with the following outputs:

- Recording time (year, month, day, hour)
- Location (latitude and longitude)
- Wave height (Hsig) and wave period (Tz)
- Wind (speed and direction)

In addition, the model produces wave energy data as a 1D spectral output (essentially wave energy categorised into Tz groupings). However, as the power output performance for wave energy converters is generally given for a specific wave height and period, spectral data was not recommended for this project.

Figure 1 shows the grid locations of the EWM within 100km of the UK coast – note that the higher resolution of the UK wave model results in five to six times the number of grid points with available wave data within the same geographic area.

Assessment of Model Data

Both the EWM and UK wave models produce data with two distinct advantages over observed data:

1. The datasets are complete, both over time and across all sites, and
2. Sites can be selected in locations of interest, rather than being restricted to locations of prior monitoring.

There are, however, limitations to the use of model data:

1. The short duration of the UK wave model makes it unlikely that the full range of wave conditions would be included in the model data;
2. The three-hour time step is likely to result in a lower measure of variability than at hourly resolution, and
3. Higher resolution variability would need to be inferred through paired model-generated and observational data.

Despite these limitations, model wave data provide continuous records over a consistent time period, and allows sites to be selected that are both representative of likely wave power development areas and located close to monitoring sites, to allow for comparison of observational and model data.

Purpose-Built Wave Models

For very high resolution data, HR Wallingford Ltd develops wave models for individual clients, providing wave data for local areas. The models use UK wave model hindcast data at a three-hourly time step, together with detailed coastline and bathymetry information, to produce data at a one-hour or better resolution, and a spatial resolution of 100m or better (dependent on the quality of the bathymetry data).

Although limited to the period of operation of the UK wave model (April 2000 onwards), this is the highest resolution model-generated data available. HR Wallingford has previously carried out work for wave power developers, suggesting that some relevant data has already been generated.

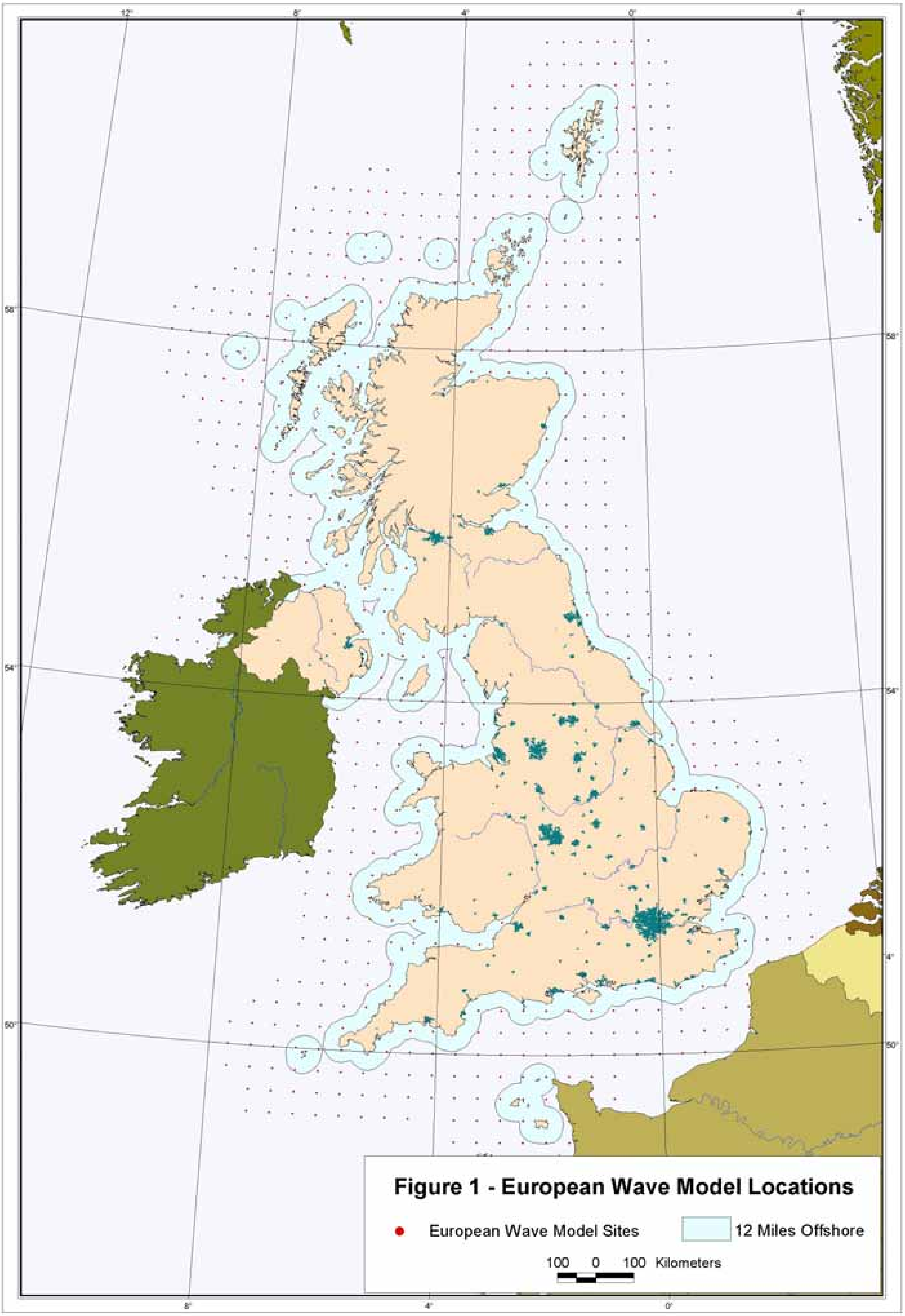


Figure 1 - European Wave Model Locations

Wave Buoy Data

Overview

Observed wave data are recorded around the UK coast by an array of fixed buoys owned and operated by the UK Met Office. Data are available from 1989, when one buoy (Channel Light Vessel - 62103) was operational. Since this time, buoys have been deployed at 19 sites – in 2004 there were 11 operational buoys in the programme.

Figure 2 shows indicative locations of the 19 recording sites that make up the wave buoy programme. Of these sites, 16 were evaluated for the quality of data produced, with the remaining three sites excluded for the following reasons:

- Brittany Buoy (62163): known short record
- Eskmeals Buoy (62302): low wave energy area
- Luce Bay (62110): low wave energy area.

The 16 sites can be broadly grouped into three categories – Atlantic, North Sea and Southern Coastal. Atlantic comprises seven sites, all located between 150km and 900km from the UK coast. North Sea comprises two sites, located between 100km and 200km off the east coast. Southern Coastal comprises the remaining seven sites, with all but two located within around 20km of the coast.

Data Recorded

Data returned by Met Office buoys is at a 1 hour resolution, and includes:

- Recording Time (year, month, day, hour)
- Wave height (Hsig)
- Wave period (Tz)
- Location (latitude & longitude)
- Wind (speed & direction)

Buoys occasionally drift off-station, however an examination of a sample of the data suggests that this is a low frequency occurrence. As latitude and longitude are provided for each hourly record, data can be excluded where a buoy has drifted significantly from its prime location.

Assessment

Three primary sites, Seven Stones Light Vessel (62107), St Gowan Buoy (62303) and Rahr Buoy (62106) were considered highly valuable for further wave climate research. All three are located in likely wave energy production areas identified by previous research. Although Rahr Buoy is located some 120km west of the Western Isles, the known high wave energy of this region warrants this sites inclusion. During the eight years 1995-2003, these three sites returned data for 85% of all hours.

There are seven secondary sites of interest, as indicated on Figure 2. All sites except 64046 have a good data return rate, with an average of 81% of all data being returned over the same eight year time period as above. Site 64046 is the newest site, being established in 1999, and has a data return rate of 66% for the 5 years to 2003 – however, its location warrants its inclusion for further analysis. Details for primary and secondary sites are given in Table 1.

For the remaining sites, it was considered that they would add little to the understanding of near-shore variability in the wave climate of the UK due to their remote location, and these sites were not recommended for further consideration.

Table 1 – Summary Information for Selected Met Office Buoys

WMO Number	Site Name	Start Date	End Date	Completeness (@ 1 hour)	Comments
Primary					
62106	Rahr Buoy	June 1994	April 2003	93%	
62107	Seven Stones Light Vessel	January 1995	Current	82%	
62303	St Gowan Buoy/Turbot Bank	October 1992	Current	85%	
Secondary					
62305	Greenwich Light Vessel	July 1994	Current	86%	
62103	Channel light Vessel	January 1979	July 2003	76% (1989-2003)	No data prior to 1989
62101	Lyme Bay Buoy	January 1990	October 2002	59%	75% return 1995-2002
62105	K4 Buoy	January 1992	Current	73%	340km offshore
62109	K16 Buoy	July 1995	August 2003	83%	
64045	K5 Buoy	December 1994	August 2003	82%	300km offshore
64046	- unnamed -	June 1999	Current	76%	Short record period

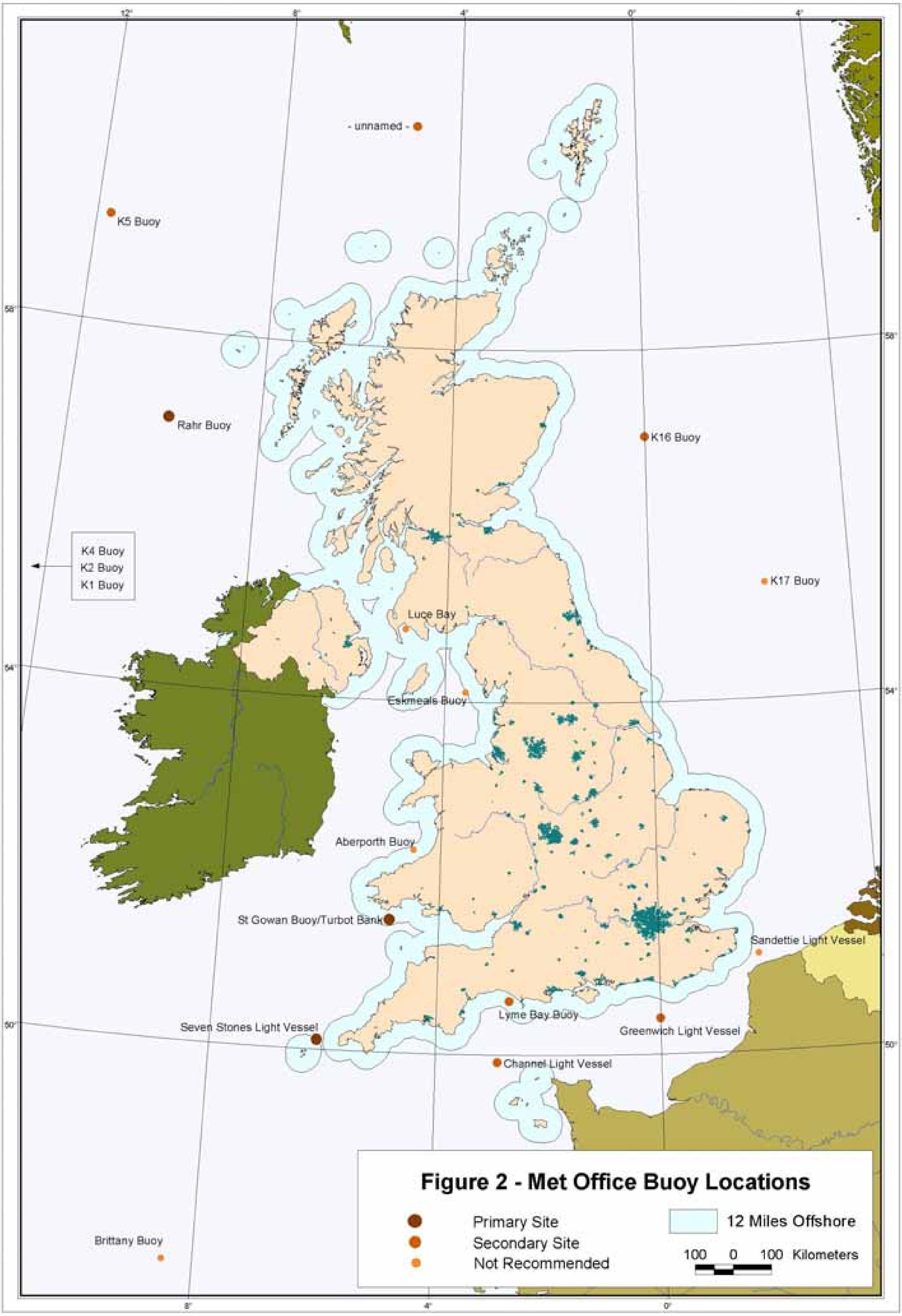


Figure 2 - Met Office Buoy Locations

Platform Data

Overview

The UK Met Office collects wave data from a range of "Platforms" (stationary oil drilling infrastructure) operating in and around UK waters. Data have been collected since 1985, with a total of 59 sites identified in the Met Office records over the following 19 years. Of these sites, 16 were selected for further analysis, with the selection based primarily on the inferred period of data collection and location.

Figure 3 shows the location of Platform data sites around the UK. Due to their strong association with oil and gas production, these sites are heavily represented in the North Sea, with the majority (42 monitoring sites) being located in the northern sector of the North Sea between Scotland and Norway. Of these sites, only four are located within 100km of the UK coast, with the remainder between 100km and 300km offshore. A further cluster of 12 sites is located off the Norfolk & Lincolnshire coasts, generally within 100km of the shore. Just one site (Morecombe Bay) is located off the western coast of the UK, in a low wave energy area.

None of the sites are in prime wave energy production areas, however there are some sites located to the northeast of Orkney that may experience stronger wave energies. Table 2 provides summary information for the 16 assessed sites.

Data Recorded

Data returned from Platform sites conforms to a standard Met Office structure, and includes:

- Recording time (year, month, day, hour)
- Wave height (Hsig)
- Wave period (Tz)
- Location (latitude and longitude)
- Wind (speed and direction)

The resolution of the data record varies from site to site, with three-hourly resolution and overnight blackout periods being common features of many sites. The location of the sites is generally fixed, with the position confirmed by latitude/longitude data.

Assessment

The Platform data represent a generally poor data series for wave energy assessment, with a restricted geographic coverage of UK coastal waters, a limited number of high quality data sites and with many of the sites located considerable distances offshore. Only the most promising sites were assessed, and of these five sites were identified as having useful information. However, their poor coverage of higher energy wave areas of the UK coast means that these sites would be a secondary source of observational data for this project.

Table 2 – Summary Information for Selected Met Office Platforms

WMO Number	Site Name	Start Date	End Date	Completeness (@ resolution)	Comments
Assessed – Good Data					
62112	Brae Alpha AWS	January 1985	November 2003	64% @ 1hr	
63103	North Cormorant AWS	January 1985	Current	60%@1-3hr	Hourly record since 1992
62129	Leman AWS (Amoco)	January 1985	April 2002	61% @ 1hr	88% complete 1986-1997
63113	Crawford FPP	June 1998	Current	80% @ 1hr	Minor records back to 1989
62126	Morecambe Bay AWS	Nov. 1987	Current	34% @ 1hr	No wave records since 1997
Assessed – Not Useful					
62125	Morecambe Bay AP1	April 1986	Current	66% @ 3hr	No wave records since 1997
63108	North Alwyn	February 1987	Current	69% @ 3hr	
62117	Buchan Alpha	April 1985	Current	48% @ 3hr	64% complete 1986-1996
62128	Viking Bravo	December 1985	March 2003	36% @ 3hr	Wave records 1988-1990 only
63112	Cormorant Alpha	October 1990	Current	28% @ 3hr	No wave records 1998-2003
62114	Tartan Alpha	January 1985	Current	78% @ 6hr	No wave records since 1997
62130	Hewett Alpha	January 1985	Current	30% @ 6hr	No wave records since 1997
62115	Beatrice Alpha	January 1985	Current	15% @ 6hr	No wave records since 1997
62138	Captain WPP Alpha	June 1998	Current	- - -	No wave recording
62120	Fulmar Alpha	January 1985	Current	- - -	Effectively no wave recording
62161	Tiffany Platform	July 1994	Current	- - -	Effectively no wave recording

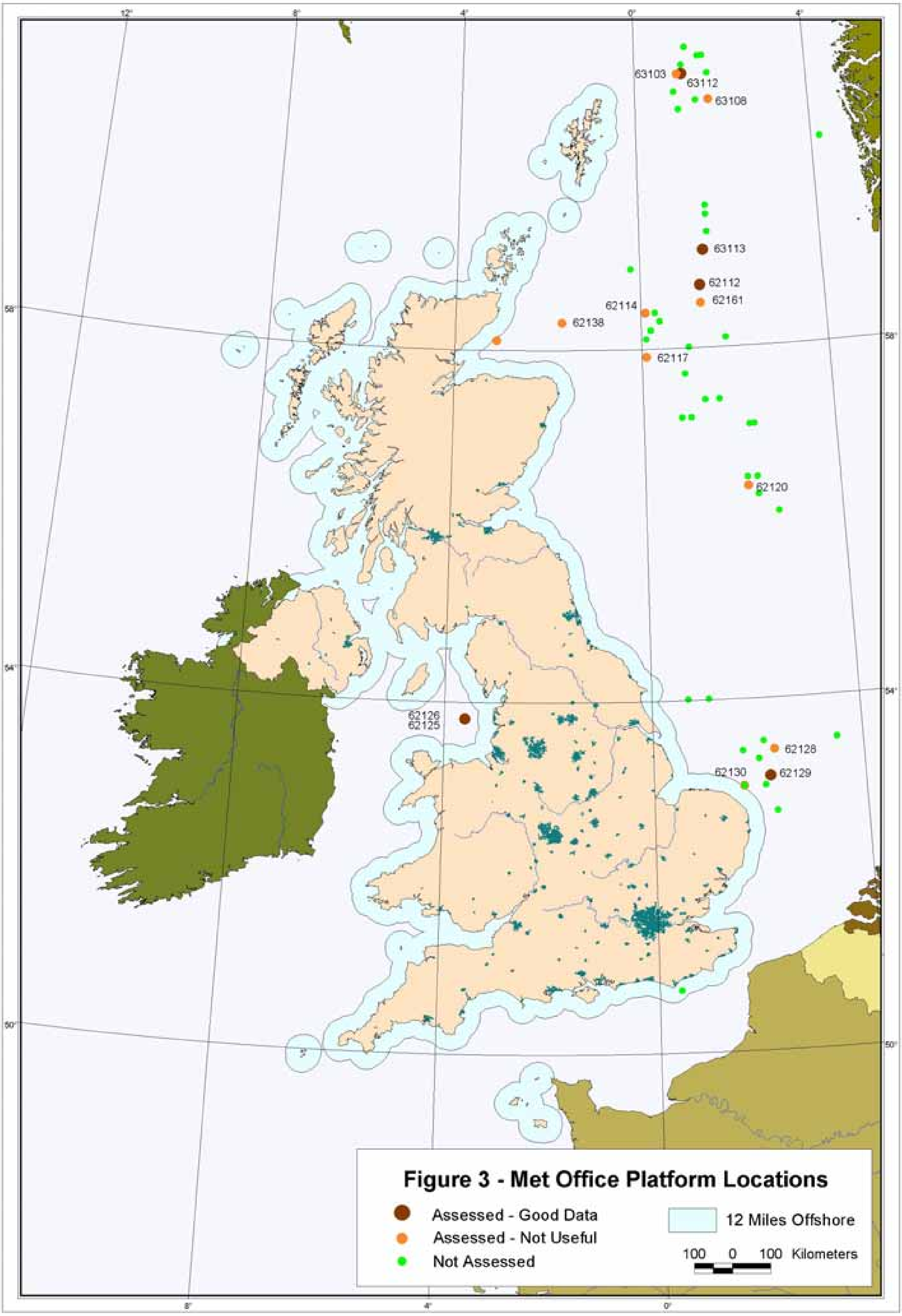


Figure 3 - Met Office Platform Locations

Rig Data

Overview

The UK Met Office collects wave data from a range of "Rigs" (mobile oil drilling infrastructure) operating in and around UK waters. Indicative locations of the Rigs during the period 1991-2004 are shown in Figure 4 – the Rig locations are generally highly concentrated around oil and gas fields, with these areas typically being over 100km offshore.

Rig data have been collected since the 1980s, however the data supplied by the Met Office currently covers the period 1998 to present (retrieval of data prior to this date is difficult). However, it is still possible to assess the usefulness of Rig data from this limited dataset.

The mobile nature of Rigs, and their movement in and out of UK waters, results in generally short run time series for wave data at a location. This mobility also complicates the selection of valid data – whilst individual wave records come with latitude and longitude data for each hour of the record, they have to be time and position matched with other datasets. This process is likely to lead to records being excluded from the dataset due to monitoring at inappropriate sites.

From the Rig data available, a subset of 12 sites have been selected for detailed assessment – these were selected on the basis of their inferred positions, and on the length of the available wave record. Table 3 provides summary information for the 12 sites.

Data Recorded

Data returned from Rig sites conforms to a standard Met Office structure (similar to Platform datasets) and includes the following:

- Recording time (year, month, day, hour)
- Wave height (Hsig)
- Wave period (Tz)
- Location (latitude and longitude)
- Wind (speed and direction)

The resolution of the data record is nominally three to six hour, however missed recordings and overnight blackout periods are common at many sites. Site location is variable due to the mobility of the Rigs, although they do tend to stay on-station for a significant period of time before moving to a new location. However, the locations given in Figure 4 should only be treated as indicative of each Rig's operating area.

Assessment

Of the 12 promising sites selected for assessment, only two had any significant wave data records – 118 observations were made at the remaining 10 sites over the five and a half year period of the dataset, with 78 of these observations being recorded at one site. The single most useful Rig was Galaxy 1, however on average it returned only one record per 13 hours for the period 1999-2003, with these data being collected from a range of four prime locations and 30 additional locations over the five year period,

Given the extremely poor rate of return of wave data, clustering of the recording sites, and movement of individual Rigs, it was decided that Rig data would not be included in further wave climate analyses.

Table 3 – Summary Information for Selected Met Office Rigs

WMO Number	Site Name	Start Date	End Date	Completeness (@ Resolution)	Comments
Assessed – Not Recommended					
62137	Galaxy 1	December 1998	Current	47% @ 6h, 24%@ 3h	3 hourly since 2002
63118	Sonat Arcade Frontier	July 1999	Current	12% @ 6h	Very incomplete record
Assessed – No Data					
63116	John Shaw	June 1998	Current	0%	78 wave records
62166	Santa Fe Monarch	June 1998	Current	0%	15 wave records
62159	Sedco 714	June 1998	Current	0%	6 wave records
62168	Santa Fe Britannia	June 1998	Current	0%	6 wave records
62154	Sedco 712	November 1998	September 2003	0%	2 wave records
63117	Drill Star	June 1998	Current	0%	1 wave record
62141	Ocean Guardian	November 1998	Current	0%	1 wave record
62150	Glomar Arctic III	June 1998	Current	0%	1 wave record
63115	Ocean Alliance	January 1999	May 2002	0%	No wave data recorded
62135	Santa Fe Rig 135	August 1998	February 2003	0%	No wave data recorded

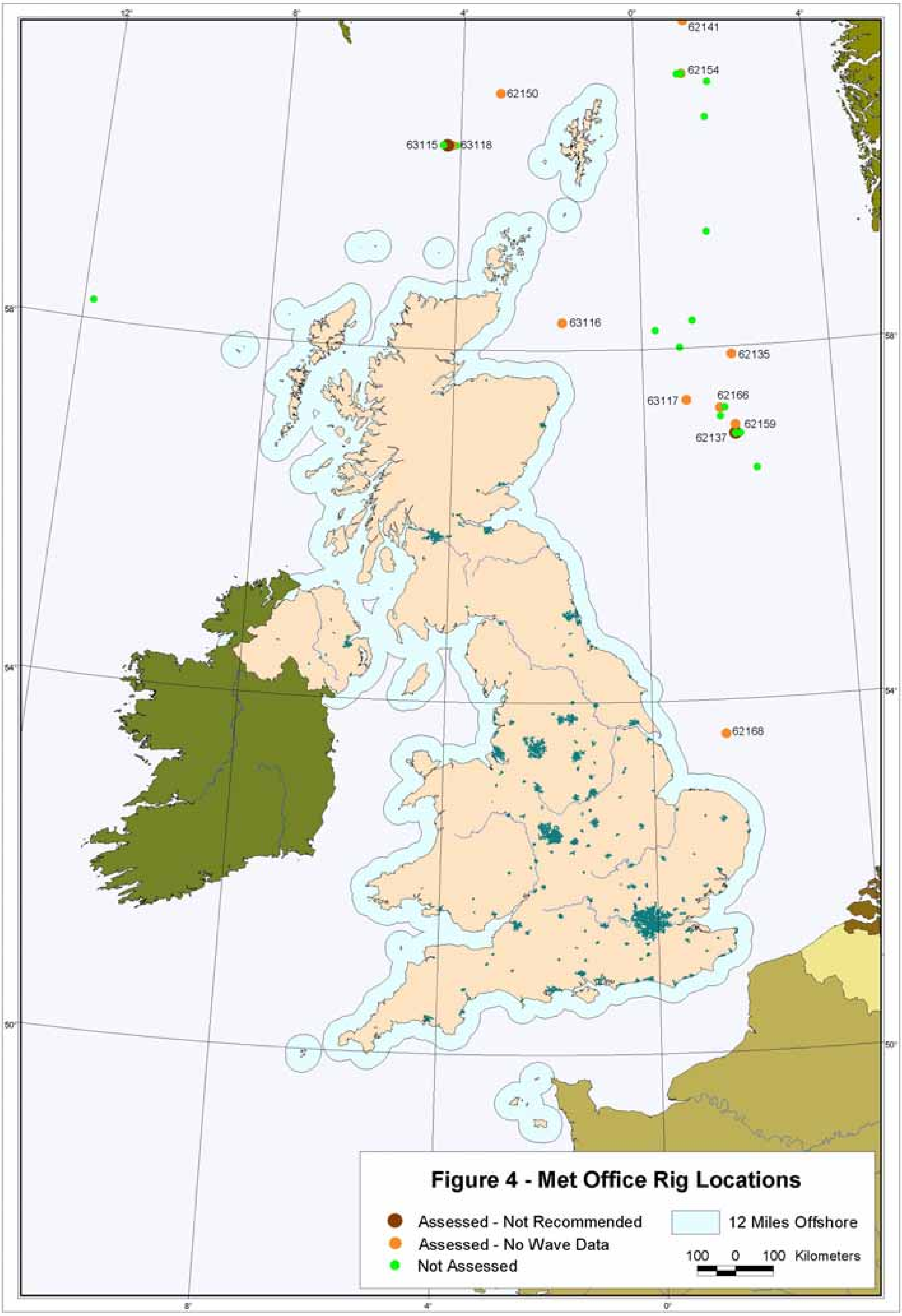


Figure 4 - Met Office Rig Locations

WaveNet Data

Overview

WaveNet is a programme funded by the Department of Environment, Food & Rural Affairs (DEFRA) to develop a real-time coastal wave data system. The programme involves both the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) and the Met Office, with the focus of data acquisition being for coastal defence, model calibration and (in the future) climate change studies.

WaveNet provides a data centre for fixed buoys, incorporating both established Met Office buoys, dedicated WaveNet buoys and buoys from other institutions. Due to data licensing agreements, WaveNet can only distribute data collected from its own array of buoys. However, the third party sites accessed by WaveNet are either included in other datasets assessed in this report (eg Met Office Buoys) or offer short-term datasets in locations that are of low importance regarding wave energy production in the UK.

WaveNet buoys generally offer a high temporal resolution (30 minute recording frequency since 2003), however they are limited in their geographic coverage of the UK coast. The buoys are located around the English and Welsh coasts, with a focus on south-eastern England – there is no buoy coverage in locations such as northwest Scotland or Orkney. Furthermore, the WaveNet system has only been recently established; as a result, most datasets are relatively short term.

Data Available

All WaveNet data are recorded using Directional WaveRider MkII wave buoys, which record the following data:

- Recording time (year, month, day, hour)
- Average wave period (Tz)
- Dominant wave direction
- Dominant wave period
- Significant wave height (Hsig)
- Temperature
- Wave spread

Table 4 provides an assessment of data availability at each site established by WaveNet, whilst Figure 5 shows the location of proprietary WaveNet monitoring sites. (Note that many of those sites that form part of the WaveNet program but are operated by other institutions are assessed in other sections of this report.)

Assessment

The high temporal resolution of the WaveNet sites, combined with very high rates of data return, is a positive feature of these sites. However, the limited period of collection, combined with the restricted geographical coverage, make this dataset unsuitable for a stand-alone assessment of the UK wave resource.

This dataset may be useful for complementing other datasets, and offers an excellent opportunity to investigate the variability of wave height and period at a better than hourly resolution; however, this dataset was not appropriate for the longer term analysis carried out in this report.

Table 4 – Summary Data for Selected WaveNet Data Sites

WMO Number	Site Name	Start Date	End Date	Completeness (@ 30 Minutes)	Comments
62289	Dowsing	October 2003	Current	94%	Poor location
62288	Hastings	November 2002	Current	59% – 89% Since July 2003	Poor location
62287	Liverpool Bay	November 2002	Current	64% - 92% since June 2003	Poor location
62290	Poole Bay	December 2003	Current	89%	Very short record
62286	West Gabbard	August 2002	Current	72% - 91% since February 2003	Poor Location
62291	West Lundy	January 2004	Current	46%	Good location but very short record

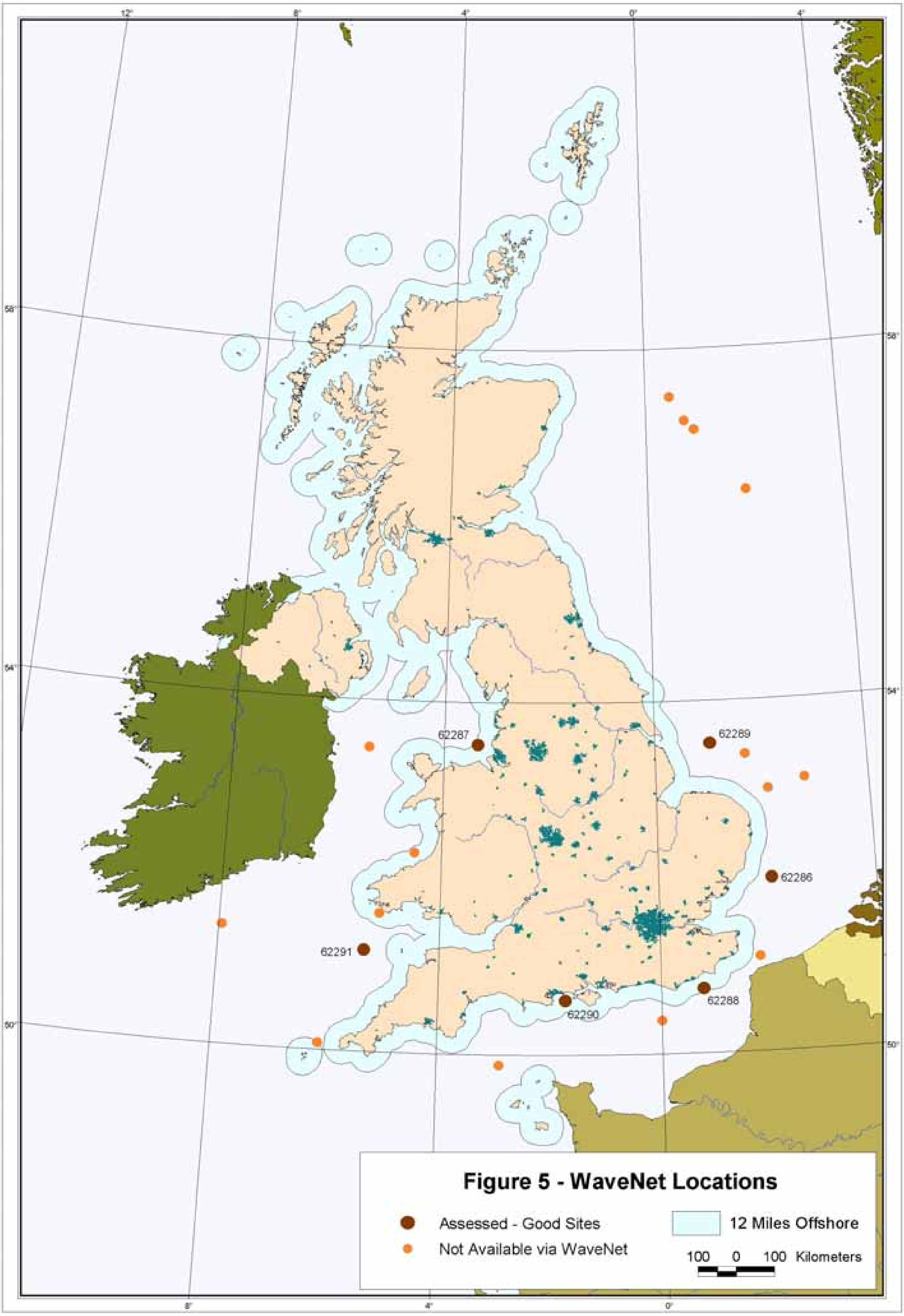


Figure 5 - WaveNet Locations

BODC Wave Data

Overview

The British Oceanographic Data Centre (BODC) maintains an archive of wave data collected throughout UK waters. This archive is composed of data from a variety of sources, the bulk of which was collected in the 1970s and 1980s, with some records dating back to the 1950s and 1960s. Around one quarter of observational records originate from the 1990s, and there are no records for UK waters since 2000.

With minor exceptions, data collection periods tend to be limited, with sites being operational for as little as one day. Around two thirds of the 500-plus observational records are for periods of one month or less, however a significant number of these combine to form sequential records at the same site. One exception to this is the continuous record available for three sites off the west coast of South Uist Island that were operational from 1976 to 1984.

Data Available

The BODC wave data archive is composed of data obtained from accelerometer and pressure sensor readings via a range of structures, including buoys, coastal and offshore structures, seafloor mounted sensors and ship-borne measurements.

The data returned varies by site, with wave statistics (most useful), 1D spectra and directional spectra each being returned from different sites. However, all records contain a standard output that includes, at a minimum, wave period and height data.

Assessment

Around 200 data records representing 60 unique sites were assessed, with selection based on location and record period. Those that were found to have significant periods of returned data (ie more than 10,000 hours) or that were in highly desirable locations are described in Table 5, and their locations are shown in Figure 6.

The array of nearshore (4km), offshore (14km) and deepwater (30km) recording sites on the west coast of South Uist Island offers a unique case study of changing wave characteristics with distance from shore. Data from all three sites are available for a two-year period (August 1980 to July 1982), whilst a more extensive record (August 1978 to July 1982) is available for the nearshore and offshore sites. Whilst data resolution at these sites is limited to three-hourly recordings, this array could be considered for a one-off case study of nearshore wave changes.

While data at some sites (eg Seven Stones Light Vessel) would extend the observational record available from other datasets, these are of limited value due to a lack of complementary model or observational data available during these times (typically the 1970s). Given the short record times, low data resolution, poor data return rates, inconsistent recording periods compared with other observed or modelled datasets, and locations unsuitable for wave power development, it was decided that these sites would not be included for further analysis.

Table 5 – Summary Information for Selected BODC Wave Data Sites

Site Name	Start Date	End Date	Completeness (@ Rate)	Comments
South Uist				
South Uist - Deepwater	August 1980	November 1984	73% (@ 3 hourly)	1.5 hourly post July '83
South Uist - Nearshore	August 1978	July 1982	68% (@ 3 hourly)	
South Uist - Offshore	March 1976	February 1983	65% (@ 3 hourly)	
Assessed – Not Recommended				
Stevenson Light Vessel	February 1973	February 1976	97% (@ 1 hour)	
Forties	May 1974	June 1980	92% (@ 1 hour)	
Fitzroy Buoy	December 1973	May 1976	47% (@ 1 hour)	
Boyle Buoy	May 1974	May 1977	42% (@ 1 hour)	
Assessed – Not Useful				
Famita	October 1969	May 1977	90% (@ 3 hourly)	Winter records only
Dowsing	November 1975	December 1984	87% (@ 3 hourly)	Also 1970 records.
WBEX-FM	May 1973	November 1977	81% (@ 3 hourly)	
Budsalt	April 1973	December 1977	78% (@ 3 hourly)	
Channel Light Vessel	September 1979	December 1982	78% (@ 3 hourly)	
Gow	August 1975	December 1982	74% (@ 3 hourly)	
Mumbles	July 1974	December 1977	69% (@ 3 hourly)	
Port Talbot	May 1975	November 1977	68% (@ 3 hourly)	
Seven Stones Light Vessel	May 1962	October 1977	49% (@ 3 hourly)	

Figure 6 - BODC Wave Locations

Tidal Resource Data

Tide Height Measurement

The National Tidal and Sea Level Facility (NTSLF) operates a series of 44 sea surface height measurement sites around the coast of the UK. Those in operation prior to 1993 recorded observed sea surface height at hourly resolution, whilst all sites since 1993 have records at 15-minute intervals. Since 1990 both sea surface height and residual (the difference between the predicted height and the observed height) have also been recorded. Table 6 provides details of commencement dates for the sites (no cessation date is given as all 44 sites are currently operating), together with an assessment of the completeness of all data recorded since 1990. Figure 7 shows the location of the sites around the UK.

Data Availability

Observed tide height data is distributed via the British Oceanographic Data Centre (BODC). All tide data from 1990 onwards are available via the internet, except for data collected in the last three months which must be ordered (as does pre 1990 data).

Tidal Stream Measurement

No routine tidal stream measurement programme has been identified for UK coastal waters. However, the United Kingdom Hydrographic Office (UKHO) publishes a series of Tidal Stream Atlases for coastal waters, which are based on short-term tidal current observations made by the UKHO over several years.

These Atlases provide a method for calculating tidal current velocity and direction for UK coastal waters, the only data requirement being the tide record for Dover (or Lerwick when the Dover record is incomplete). The Atlases can then be used to reconstruct historic tidal currents for coastal areas (note that the data represent an area, not a specific site). The ECI has developed an algorithm that allows this process to be automated.

Model Tidal Stream Velocity

Proudman Oceanographic Laboratory offers a software package called PolPred that will provide tidal stream velocity data for any site in UK coastal waters. The software can work at very fine resolution (minute to minute variation in velocity), is site specific and calculates longer-term fluctuations in tidal current velocities.

Assessment

The tide height record for the UK is extensive and relatively complete, however for tidal stream assessment the Dover (and occasionally Lerwick) tide records are the sole requirement. Model tidal stream velocity data are preferred over that derived from the Tidal Stream Atlas method as they are site specific, provide higher temporal resolution, and includes variations in current speeds that cannot be included using the Atlas method.

Table 6 – Commencement date and completeness for NTSLF tide gauge sites

Site	Start Year	Completeness	Site	Start Year	Completeness	Site	Start Year	Completeness
Aberdeen	1930	95%	Jersey	1992	91%	Port Ellen, Islay	1979	96%
Avonmouth	1961	80%	Kinlochbervie	1991	81%	Port Erin, I.Man	1992	84%
Bangor	1994	67%	Leith	1981	91%	Portpatrick	1968	10%
Barmouth	1987	90%	**Lerwick**	**1959**	**80%**	Portrush	1995	91%
Bournemouth	1996	93%	Liverpool	1927	89%	Portsmouth	1991	91%
Cromer	1973	94%	Llandudno	1994	17%	Sheerness	1952	95%
Devonport	1961	93%	Lowestoft	1964	4%	Stornaway	1976	93%
Dover	**1924**	**93%**	Milford Haven	1953	14%	St. Mary's	1994	93%
Felixstowe	1982	98%	Millport	1978	12%	Tobermory	1990	84%
Fishguard	1963	97%	Moray Firth	1994	27%	Ullapool	1966	88%
Heysham	1964	88%	Mumbles	1989	22%	Weymouth	1989	96%
Hinkley	1990	100%	Newhaven	1982	15%	Whitby	1980	96%
Holyhead	1964	72%	Newlyn	1915	2%	Wick	1965	96%
Immingham	1953	97%	Newport	1993	9%	Workington	1992	97%
Ilfracombe	1968	66%	North Shields	1946	5%			

Notes
"Start Year" refers to the first year data were recorded at the site: data may not have been recorded in all subsequent years.
"Completeness" refers only to the completeness of the dataset post 1990 (or later if the site first commenced operation at a later date).
The Dover record is 88% complete for the period 1970-1989, whilst the combined Dover/Lerwick record is 99% complete for 1990-2003.

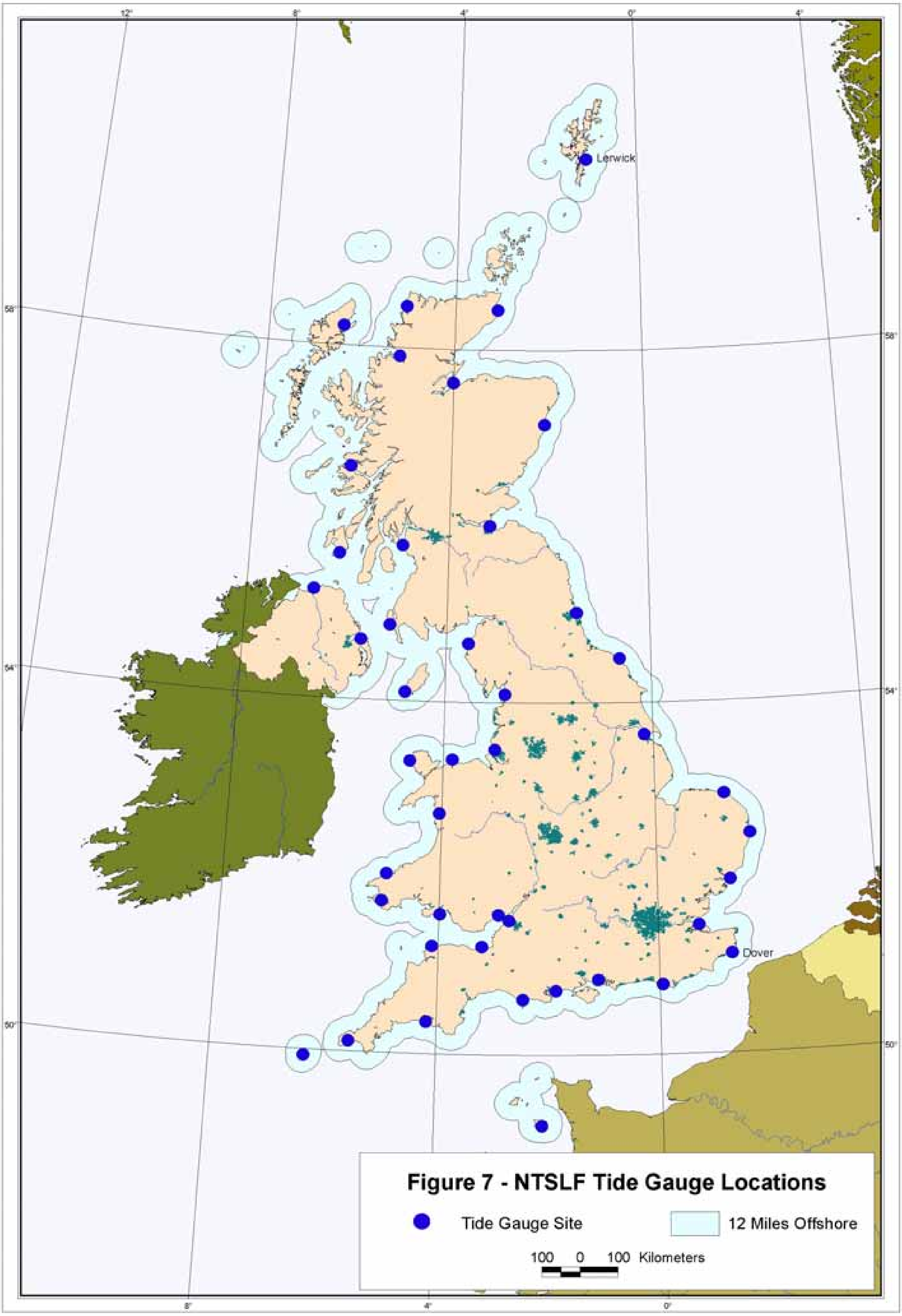


Figure 7 - NTSLF Tide Gauge Locations

Additional Data Sources

Overview - Satellite Data

Remote sensing of wave conditions offers a method for assessing a wide range of sites around the UK coast. However, discussions with Satellite Observing Systems Ltd regarding the applicability of remotely sensed wave data have identified significant limitations with this dataset.

Remotely sensed wave conditions are based primarily on altimetry, where the return signal from a satellite-based radar is interpreted to provide relevant information. For wave data, the GeoSat satellite launched in 1985 provided a discontinuous record of altimetry measurements. This satellite was superseded in 1991, and since 1995 there has been access to two satellite-based radar altimeters.

Satellite altimetry data has a relatively low rate of repeat observations. Prior to 1995, observations occurred about once every 24 hours – since 1995 this has improved to one observation every 12 hours with the addition of a second satellite. Due to this low rate of repeat observations, wave state data based on satellite altimetry is typically restricted to providing monthly wave statistics, with one-off daily data being suitable for model verification.

The resolution of the data is low, with the best commercially available data being on a one degree grid square basis –approximately 10 times coarser than the European wave model output.

Assessment

Due to the low rate of observation, and the poor spatial resolution, the use of satellite altimetry data for inferring wave conditions is not recommended. Satellite altimetry data is also not appropriate for the measurement of tidal stream velocities.

Overview – OceanNet

OceanNet is maintained by the UK Marine Environmental Data Network (UKMED), and provides a single access point to a database of over 600 marine data sets held by 90 UK laboratories. The dataset includes both routine and project specific data collected over many decades from both UK waters and international projects.

Assessment

A review of datasets relevant to UK waters has been carried out. Of those datasets was identified as holding potentially relevant information, the majority have already been assessed in other sections of this report.

A small number of wave datasets were identified that may potentially add to the observational data record – these were associated with observations made onboard oil rigs and platforms that may not have been included as part of the Met Office and BODC datasets examined in this report. Whilst these datasets may be useful to a larger study, they do not represent a significant addition to the data used in this report.

Appendices and Bibliography

Appendix 1 – Tidal Current Sites

Region	Site	Latitude	Longitude	Data Source[1]	Rated Velocity (ms^{-1})	Contribution[2] (% of total)
Channel Isles	Casquets	49° 45' 39.0" N	2° 18' 57.0" W	CS20	3.0	7.6%
	GuerseyBigRussel	49° 26' 27.0" N	2° 26' 6.0" W	CS20	2.75	1.8%
	GuerseyNorthWest	49° 31' 37.0" N	2° 41' 31.0" W	CS20	2.0	2.3%
	NorthEastJersey	49° 16' 33.0" N	2° 0' 54.0" W	CS20	3.5	0.8%
	RaceOfAlderney	49° 40' 15.0" N	2° 8' 42.0" W	CS20	4.0	7.8%
Northern Isles	OrkneyYellSoundWestChannel	60° 30' 0" N	1° 12' 0" W	Admiralty	2.225*	1.2%
	OrkneyYellSoundEastChannel	60° 30' 30" N	1° 10' 0" W	Admiralty	2.275*	0.6%
	OrkneyBluemullSoundNS	60° 42' 0" N	0° 59' 0" W	Admiralty	3.25*	0.7%
	OrkneyWestrayFersNess	59° 12' 36.0" N	2° 56' 23.0" W	CS20	2.5	0.2%
	OrkneyPapaWestray	59° 23' 30.0" N	2° 52' 0.0" W	CS20	2.75	1.0%
	OrkneyNorthRonaldsayFirth	59° 18' 32.0" N	2° 29' 24.0" W	CS20	2.75	0.0%
	WestrayFallsOfWarness	59° 8' 24.0" N	2° 50' 20.0" W	CS20	3.25	0.8%
	OrkneyEdaySound	59° 13' 30" N	2° 42' 0" W	Admiralty	2.0	0.2%
North West	KyleRhea	57° 15' 0" N	5° 37' 0" W	Admiralty	4.5	0.1%
	MullOfGalloway	54° 37' 22.0" N	4° 51' 46.0" W	CS20	3.25	4.0%
	MullOfKintyre	55° 16' 48.0" N	5° 51' 21.0" W	CS20	2.75	0.1%
	MullOfOa	55° 34' 37.0" N	6° 21' 54.0" W	CS20	3.75	0.1%
	RathlinCoast	55° 13' 30.0" N	6° 4' 30.0" W	CS20	2.25	4.0%
	RathlinSound	55° 15' 32.0" N	6° 19' 22.0" W	CS20	2.5	1.1%
	SandaSound	55° 17' 27.0" N	5° 35' 16.0" W	CS20	2.5	0.1%
Pentland	SouthRonaldsayToSwona	58° 43' 19.0" N	2° 59' 5.0" W	CS20	4.25	7.0%
	PentlandStromaSwona	58° 42' 54" N	3° 5' 31" W	CS20	4.5	12.8%
	PentlandInnerSound	58° 39' 46.0" N	3° 9' 36.0" W	CS20	3.5	0.7%
	PentlandDuncansbyHead	58° 39' 14" N	3° 0' 25" W	CS20	4.25	9.4%
	PentlandHoy	58° 45' 58" N	3° 18' 32" W	CS20	4.0	6.4%
	PentlandSkerriesSouth	58° 41' 20.0" N	2° 59' 56.0" W	CS20	4.25	18.1%
	SouthRonaldsayToPentlandSkerries	58° 42' 32.0" N	2° 55' 8.0" W	CS20	3.75	5.3%
South West	BristolChannelNorthLundy	51° 13' 19.0" N	4° 41' 24.0" W	CS20	2	0.2%
	BristolChannelSouthLundy	51° 8' 42.0" N	4° 38' 34.0" W	CS20	2.5	0.1%
	BristolChannelBarry	51° 23' 9.0" N	3° 11' 13.0" W	CS20	2.5	0.4%
	BristolChannelForelandPoint	51° 15' 25.0" N	3° 47' 20.0" W	CS20	3	2.5%
	CornwallCapeCornwall	50° 8' 31.0" N	5° 44' 9.0" W	CS20	2.0	0.1%
	CornwallLandsEnd	50° 2' 27.0" N	5° 44' 9.0" W	CS20	2.0	0.1%
	CornwallTheLizard	49° 57' 39.0" N	5° 12' 14.0" W	CS20	2.0	0.1%
	IsleOfWight	50° 33' 21.0" N	1° 14' 16.0" W	CS20	4.0	0.0%
	PortlandBill	50° 29' 27.0" N	2° 26' 16.0" W	CS20	3.25	2.0%

Note 1
CS20: data source from Proudman Oceanographic Laboratory CS20 high resolution UK water tidal model.
Admiralty: data calculated from UK Hydrographic Office Tidal Stream Atlas.

Note 2
Contribution: shows the proportion of total UK tidal current electricity generation that would be generated at the site, and assuming maximum site development at all sites with a total UK potential of 15,444GWh/y generation. Data obtained from Black & Veatch (2005).

* Correction factor applied to bring Admiralty estimate of site velocity up to that identified by Black & Veatch (2004).

Appendix 2 – Wave Power Sites

Region	Site	Latitude	Longitude	Data Source[1]	Identifier (observed data)
North East	Orkney	59° 30' 0" N	2° 51' 36" W	EWM	
	Shetland	61° 0' 0" N	0° 51' 36" W	EWM	
	K7 Buoy	60° 30' 0" N	5° 0' 0" W	Buoy	B64046
North West	Lewis	58° 30' 0" N	7° 15' 36" W	EWM	
	Orsay	55° 30' 0" N	6° 51' 36" W	EWM	
	Rahr Buoy	57° 0' 0" N	9° 54' 0" W	Buoy	B62106
North Sea	Peterhead	57° 42' 36" N	1° 34' 12" W	EWM	
	Scarborough	54° 18' 0" N	0° 2' 24" W	EWM	
	Cromer	52° 58' 48" N	1° 39' 36" E	EWM	
	K16 Buoy	57° 0' 0" N	0° 0' 0" W	Buoy	B62109
	K17 Buoy	55° 18' 0" N	2° 18' 0" E	Buoy	B62026
Irish Sea	Eskmeals	54° 0' 0" N	3° 21' 36" W	EWM	
	Eskmeals Buoy			Buoy	
South West	Seven Stones	50° 7' 12" N	6° 9' 36" W	EWM	
	South Hams	50° 0' 36" N	3° 52' 12" W	EWM	
	Turbot Bank	51° 26' 24" N	4° 58' 12" W	EWM	
	Seven Stones LV	50° 6' 0" N	6° 6' 0" W	Buoy	B62107
	Channel LV	49° 54' 0" N	2° 54' 0" W	Buoy	B62103
	St Gowan Buoy / Turbot Bank	51° 30' 0" N	4° 54' 0" W	Buoy	B62303
Other Observed Data Buoys	Brittany Buoy	47° 30' 0" N	8° 30' 0" W	Buoy	B62163
	K1 Buoy	48° 42' 0" N	12° 24' 0" W	Buoy	B62029
	K2 Buoy	51° 0' 0" N	13° 18' 0" W	Buoy	B62081
	K3 Buoy	53° 30' 0" N	19° 30' 0" W	Buoy	B62108
	K4 Buoy	55° 36' 0" N	12° 42' 0" W	Buoy	B62105
	K5 Buoy	59° 12' 0" N	11° 42' 0" W	Buoy	B64045

Note 1
EWM: model data from the European Wave Model, supplied by the UK Met Office
Buoy: observed data from buoys and light vessels, supplied by the UK Met Office

Appendix 3 – Wave Device Performance

Overview

Three different device technologies were used in the wave power modelling component of this study – an articulated attenuator device (Pelamis), a floating wave terminating device (Wave Dragon) and a submerged point absorbing device (Archimedes Wave Swing). Despite the obvious design differences between these devices, there was relatively little difference in performance. This appendix provides a comparison of the three devices, and assesses the implications of the findings.

Analysis Design and Limitations

To carry out this analysis, it was necessary to find a site where each device could be appropriately sized to the wave climate of the site – in practice, this required the devices to be sized so that they returned the same capacity factor.

For the AWS device this was straight-forward, as the rated output was adjusted to achieve the required capacity factor (refer to page 58 for a full description). The range of power transform matrices provided by AWS Ocean Energy Limited also simplified the selection process. For the Pelamis device, only one power transform matrix was made available – this limited the sites available for comparison to just the Shetland site (North West region) where the Pelamis returned a capacity factor of 30%.

With the devices appropriately sized, the analysis was carried out on the full EWM three-hourly wave data record. Two measures were used to compare the two devices, the total annual output and seasonal variability of each device.

Note – the graphs presented in this appendix appear similar to those given for the UK wave resource on page 36. However, the results presented for on page 36 represent the average result for the UK, whereas the results presented here relate only to the wave power encountered at Shetland – whilst the monthly distribution is very similar, there are differences in the pattern of annual output due to the site specific nature of the data used in this analysis.

Performance Evaluation

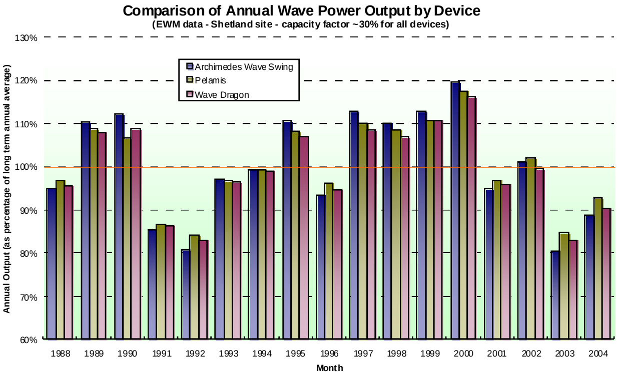
The total annual output in the graph (left, top) shows the output of each device for each year in the study period – output is expressed as a percentage of long term average annual output, and the graph shows the deviation in each year from the long term mean.

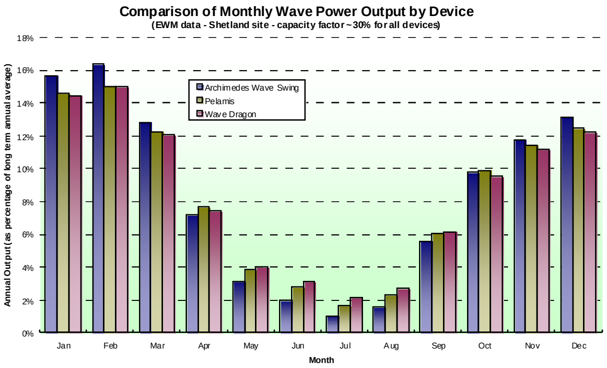
On average, there was less than 3% difference in output between the three devices in any one year. The AWS device tended to out-perform the other devices during higher wave energy years, and under perform during low wave energy years. This pattern may reflect the extension of the AWS transfer matrix to longer wave periods than that captured by the other devices, and for this reason it would be useful to have greater certainty about the device properties of the Pelamis and Wave Dragon devices at longer wave periods. The Pelamis device tended to outperform the other devices in low wave energy years.

The seasonal distribution of wave power was again relatively insensitive to device type, with the general pattern of high output during winter and low output in summer common to all devices. The AWS device again outperformed the other devices during higher energy periods, whilst the Pelamis device performed best during the intermediate months of April and October. The Wave Dragon device delivered the most energy during low energy periods, achieving up to twice the output of the AWS during July. While the Wave Dragon showed the lowest seasonal variability, the improvement was considered marginal in comparison to the overall monthly pattern of energy delivered by all devices.

Overall Decision

The similarity in output of the three devices demonstrated that raw wave energy availability was the dominant driver of seasonal and annual supply patterns. Given this finding, subsequent analyses were carried out using a device-averaged output profile.


Comparison of Annual Wave Power Output by Device
(EWM data - Shetland site - capacity factor ~30% for all devices)


Comparison of Monthly Wave Power Output by Device
(EWM data - Shetland site - capacity factor ~30% for all devices)

Appendix 4 – Regression Equations

The regression equations used to model the predicted wave power output of B62107 were generated from 1hr and 6hr lagged time series from both B62107 (autocorrelation time series) and B62029 (time-lagged cross-correlation time series.

The equation for the 6hr forecast horizon prediction is:

6HrEstimate = [CrossCorrelation-AWSWebB62107PowerOutput-Lags]![B62107-T6]*0.525
+[CrossCorrelation-AWSWebB62107PowerOutput-Lags]![B62029-T6]*0.424

Where:
[CrossCorrelation-AWSWebB62107PowerOutput-Lags]![B62107-T6] is the B62107 wave power time series at a lag of 6 hours, and
[CrossCorrelation-AWSWebB62107PowerOutput-Lags]![B62029-T6] is the B62029 wave power time series at a lag of 6 hours.

The equation for the 1hr forecast horizon prediction is:

1HrEstimate = [CrossCorrelation-AWSWebB62107PowerOutput-Lags]![B62107-T1]*0.735
+[CrossCorrelation-AWSWebB62107PowerOutput-Lags]![B62029-T6]*0.213

Where:
[CrossCorrelation-AWSWebB62107PowerOutput-Lags]![B62107-T1] is the B62107 wave power time series at a lag of 1 hour, and
[CrossCorrelation-AWSWebB62107PowerOutput-Lags]![B62029-T6] is the B62029 wave power time series at a lag of 6 hours.

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