Programme Area: Energy Storage and Distribution

Project: Offshore Connection 1

Title: Study Scenarios Report

Abstract:

It defines appropriate scenarios of offshore generation farm type, volume, timescale and technical characteristics. Section 7 summarises the specific ‘Development Cases’ derived from the analysis which were used throughout the rest of the project to explore options for the connection of such farms.

Context:

This project examined the specific challenges and opportunities arising from the connection of offshore energy to the UK grid system and considered the impact of large-scale offshore development. It also looked into the novel electrical system designs and control strategies that could be developed to collect, manage and transmit energy back to shore and identified and assessed innovative technology solutions to these issues and quantified their benefits. The research was delivered by Sinclair Knight Merz, a leading projects firm with global capability in strategic consulting, engineering and project delivery. The project was completed in 2010.

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Offshore Connection Project

OFFSHORE STUDY SCENARIOS REPORT

- 30th October 2009

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1. Introduction

1.1. Project Outline

The Energy Technologies Institute (ETI) has engaged Sinclair Knight Merz (SKM) to identify the opportunity for the development of innovative solutions for the collection of electrical energy from individual and multiple offshore renewable energy farms, and the transportation of bulk energy from these offshore farms to the onshore power system.

The work is being carried out to allow the ETI to focus their subsequent research, development activities and funding initiatives on technologies that will increase energy efficiency, reduce greenhouse gas emissions, and help achieve energy and climate goals.

The study to be undertaken by SKM comprises of four main tasks that will enable the required project outcomes to be delivered:

1) Offshore renewable scenarios – to define the timeline of the expected volumes of offshore renewable generation capacities, an important aspect to allow the quantification of the potential benefits of future technology development opportunities. In addition, as indicated in the Statement of Work paragraph 2.2, this task will produce matrices that outline key variables that will allow the generalisation of a range of potential wind, wave, and tidal developments. These matrices will further be used to define a number of specific development cases for analysis in the subsequent project tasks.
2) State of the art of offshore network technologies – establishment of the current state of the art of offshore network technologies and their prospective future development path (through discussions with equipment manufacturers and suppliers), including an assessment of technical and financial characteristics.
3) Analysis at individual farm level – identification of the challenges and resultant technology opportunities (based on the state of the art review) that could arise in respect of the connection of individual large-scale offshore wind or marine energy farms to the UK grid system, and provision of recommendations for connection solutions worthy of further development and analysis.
4) Analysis at multiple farm level – building on the analysis at individual farm level, evaluation of the optimal architecture(s) that could be developed to collect, manage and transmit back to shore the electrical energy produced by multiple, large-scale offshore renewable energy farms.

1.2. Offshore Renewable Scenarios

The purpose of this report is to outline the generation background scenarios upon which the subsequent technical analysis will be based with particular emphasis on the renewable offshore capacities. A timeline of the expected volumes of offshore renewable has been established to aid in quantifying potential total benefits of the technological developments that will be identified in the subsequent project activities.

Based upon the generation scenarios a matrix has been produced detailing various aspects of future offshore developments including; generation type, distance to shore, development capacity and machine size, onshore network strength, and water depth. This matrix has been used to define development scenarios which will be analysed in depth during the later project tasks.

The ultimate aim of this report is to establish the direction of the remainder of the project and ensure that the final project outcome of recommendations for connection solutions worthy of further ETI funding for research and development fully meets the ETI's expectations, and addresses the specific aims and preferences of the ETI.

2. Offshore Marine Scenarios

2.1. Policy Background

Increasing the contribution from renewable energy in the UK has become an integral part of our long term energy policy. As part of the UK government's long term commitment to increasing the contribution from renewables it released the 'Renewable Energy Strategy (RES)' earlier this year. The RES forms part of a package of measures introduced by the UK government in recent years aimed at reducing CO_2 emissions and increasing the contribution from renewable generation.

Support for renewable development in the UK is currently underpinned by the Renewables Obligation, initially introduced in 2002 to encourage the use of renewable energy in order to help reduce carbon emissions and diversify sources of supply. The impact of the Renewables Obligation (RO) is to provide a fixed sum, index linked, for renewable power generated in the form of a Renewables Obligation Certificate (ROC) and to impose a penalty on those electricity suppliers who fail to meet the targets set by the legislation.

The central objective of the RO is to comply with the UK's commitment under the Kyoto Protocol to reduce greenhouse gas emissions by 12.5 per cent below 1990 levels by 2008 to 2012. While the existing Kyoto Agreement expires in 2012, the new USA president has expressed a desire for a new agreement, although this development will not be progressed significantly until Copenhagen in December.

Most recently the UK government has adopted more stringent CO_2 reduction targets in the Climate Change Act (CCA). The Climate Change Bill was introduced into Parliament on 14 November 2007 and became law, in the form of the Climate Change Act, on 26th November 2008. The CCA introduces a legally binding framework to set 5 year carbon budgets with legally binding CO_2 reduction targets. In the April 2009 budget the government presented the first three carbon budgets under the CCA, which aim to set the UK on a path to achieve the 80 per cent reduction on 1990 emissions by 2050. Emission reductions in greenhouse gasses are to be:

- 22% below 1990 by 2008-2012
- 28% below 1990 by 2013-2017
- 34% below 1990 by 2018-2022

Europe is also is setting targets – the so called 20/20/20 targets – that aim to reduce CO_2 emissions by 20 per cent, provide 20 per cent of EU energy from renewables and improve energy efficiency by 20 per cent - all by 2020. The Renewable Energy Directive sets mandatory national targets for each Member State with the aim of achieving a 20 per cent share of renewable energy in Europe's final energy consumption by 2020. Each Member States must design long-term renewable energy measures and policies and develop detailed estimations on the contribution of renewable energy in final energy consumption – so called National Renewable Energy Action Plans. For the UK the EU renewables target translates into renewables providing 15 per cent of the UK's primary energy by 2020 – enormously challenging given that we currently produce less than 2 per cent of energy from renewables. The government has suggested that, in order to meet the 2020 renewable targets then some 35 per cent of the UK's electricity must be generated from renewables by 2020. In Scotland the Scottish Government has set tougher targets of 50 per cent of Scottish electricity to be provided by renewables by 2020, with an interim target of 31 per cent by 2011.

In July 2006 the UK government initiated a reform of the RO following the publication of its Energy Review in that year. The Energy Review noted that, if the UK was to significantly increase its contribution from renewable generation, then the RO would need to be strengthened and modified to 'provide longer-term certainty and create a greater incentive for investment into those technologies that are further from the market.' The result was to initiate consultation in October 2006 on how the RO might be reformed, including introducing the concept of differing 'bands' of support for different technologies. The rationale was simple; those technologies that 'are further from the market' would receive more support than the hitherto flat support structure of one ROC per MWh.

In May 2007 the government published an Energy White Paper. This included a review of the RO and the ROC mechanism. Following the 2007 White Paper and ongoing reform of the RO, in April 2009 the Renewable Obligation Order (ROO) 2009 was published. The ROO is a statutory instrument that outlined how the RO would be calculated in 2009/10 and included applying differing bands to differing technologies and the concept of 'guaranteed headroom'.

As part of the Government's Energy White Paper strategy outlined above it then produced a consultation on a RES for the UK in June 2008 with the aim of meeting the EU target of providing 15% of the UK's energy from renewables by 2020. In July 2009 the decision document following on from this consultation, 'The UK Renewable Energy Strategy,' was finally published. The RES reiterated the commitment to the concept of banding.

In Scotland further banding has been introduced that provides additional support for marine renewables – the current banding levels include a multiple of 5 ROCs for wave generation and 3 ROCs for tidal generation. For offshore wind the UK government has announced its intention to launch an early review of the support available for offshore wind under the RO – increasing it to 2 ROCs for projects reaching financial close in 2009/10 and beginning construction by the end of 2011 and 1.75 ROCs for those reaching financial close in 2010/11 and beginning construction by the end of 2012. In Scotland the Scottish government considers that the proposed temporary uplift in support for offshore is designed for projects at an advanced stage of development. There are no offshore wind projects or proposals in Scottish waters that can be considered to be at an advanced stage of development. Therefore the Scottish government has decided that support for offshore wind in Scotland will remain at 1.5 ROCs – but has not ruled out change in the future.

2.2. The UK’s Renewable Resource Potential

The UK has considerable offshore wind, wave and tidal energy resource potential. It has been estimated that the UK’s offshore renewable resource includes an offshore wind potential of 70 GW, 21 GW of wave and 7.5 GW of tidal stream[1].

However, although the UK’s ‘ultimate probable’ offshore renewable resource is large, the ‘economically recoverable’ offshore renewable resource, based on what could reasonably be expected to be recovered, is considerably less.

We have generated two long-term scenarios to assess the UK’s economically recoverable offshore renewable resource.

- The first looks at a ‘low’ overall renewable development out to 2050.
- The second looks at a ‘high’ overall renewable strategy out to 2050.

We assess the two scenarios over the period to 2020, 2030 and finally out to 2050.

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[1] Scotland’s Renewable Resource 2001, Garrad Hassan and Partners Ltd.

3. Ultimate Probable Resource

Below we outline the key driving considerations for the ultimate probable resource potential of the three key offshore renewable technologies considered:

- Offshore wind.
- Wave.
- Tidal.

3.1. Offshore Wind

Given that the UK is largely surrounded by water, it reputably has the best offshore wind resource in Europe. A number of assessments have been made about the offshore wind potential of the UK. A study undertaken in 2002 suggested an ultimate resource of over 70 GW for the UK[2], based on:

- Sea depth of less than 30 m.
- Distance from shore of over 5 km.

A 2001 report *Scotland's Renewable Resource* suggested that some 25 GW of offshore wind was potentially available in Scottish waters with the following factors underpinning the analysis:

- Sea depth was constrained to less than 30 m.
- Site location was constrained to beyond 5 km from the coast.
- A unit analysis of 8 MW/km^2 was used.

In general terms three key parameters currently drive the potential for offshore wind; wind speed, distance from shore and depth of water – with the most attractive sites located relatively close to shore, in shallow waters with a high wind speed. In general terms offshore wind farm costs and risks increase with both water depth and distance from shore while revenues increase with wind speed[3].

Taking these factors into account, areas around the UK with considerable potential for offshore wind include the Wash, North West England, Wales, Dogger Bank, the Western Isles of Scotland and, to a lesser extent, the Solway Firth. These areas are particularly attractive given their relatively shallow bathymetry (generally below 20 metres) compared with much of the rest of the UK (Figure 1). Given that the cost of offshore wind projects increases with water depth it is reasonable to assume, all other things being equal, that those sites in relatively shallow water will

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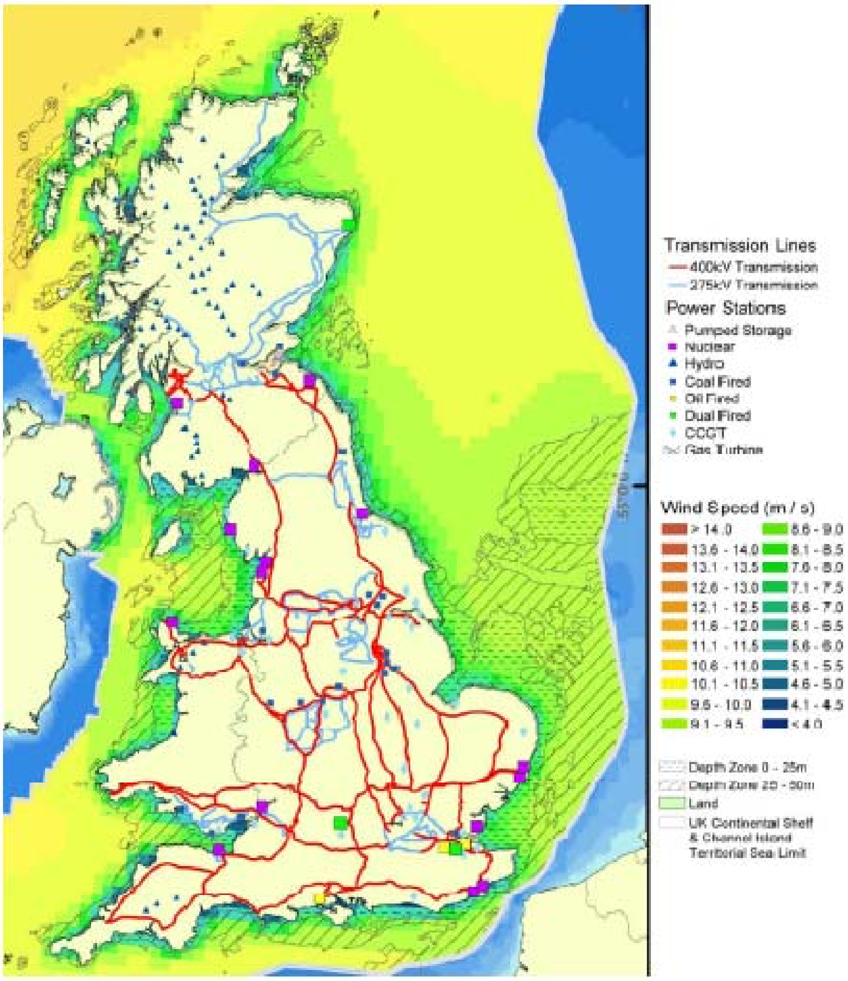
[2] http://www.offshorewindenergy.org/ca-owee/indexpages/Resource_and_Economics.php?file=resecon.php

[3] Offshore wind power: big challenge, big opportunity. Carbon Trust 2008.

be developed ahead of those in deeper water – although technologies are currently in development that may allow offshore wind farms to be located in waters deeper than 30 metres, including the Beatrice pilot project that aims to install two prototype 5 MW wind turbines in water depths of up to 45 m.

- **Figure 1: UK Wind Resource and Water Depth.**



The cost of offshore wind also increases with distance from the shore. Due to the nature of the bathymetry around Scotland much of the relatively shallow water sites are very near to shore (within the 12 nautical mile zone). In England the bathymetry is less of a constraint, with shallow water available further from shore, particularly around the Wash. Dogger Bank, while relatively shallow, is a considerable distance from shore, increasing the complexity and cost of developing this site.

The revenue of offshore wind farms increases with wind speed – as a result those areas of higher average wind speed will be more attractive for development. While wind speeds are highest around the Western Isles and Western Scotland, making these areas most attractive – recent studies have also suggested that Moray Firth and the Firth of Forth produce 42% and 25% respectively more power each year than Hornsea off the Yorkshire coast of England[4]. As a result greater potential exists for the development of wind farms off the east coast of Scotland than the 2001 study suggests. The wind speed at Dogger Bank is believed to be high – somewhat (but by no means completely) offsetting the additional risk and costs associated with developing the area. Information on wind turbine output characteristics is included in Appendix A.

More recent data suggests that the turbine density of offshore wind farms will be less than 8 MW/km outlined in the 2001 Scottish report. Increased understanding and operational experience of factors such as the impact of wake effects have led to a reduction in optimum turbine density. As a result a more applicable turbine density for assessing the potential of offshore wind projects based on current technology is around 5-6 MW/km.

The combination of these factors suggests that the reduction in offshore wind turbine density since the original assessment in 2001 and 2002 will lead to a reduction in the ultimate probable resource potential of offshore wind. However, on the other hand, the potential development of deeper water locations and closer to shore development suggest that ***70 GW represents an ultimate probable resource potential for offshore wind in the UK***.

3.2. Wave

Wave energy is widely distributed over large areas. Power density varies with distance from land, and power densities are higher on the west coast of the UK than on the east due to the contribution of the Atlantic. The most sizeable wave resource in the UK lies in Scotland where the potential wave resource compares well, in terms of MW/km, with wave regimes elsewhere in the world[5]. Waves are mainly a wind-driven phenomenon, and their energy is predominantly determined by the fetch (i.e. distance wind has blown over) and length of time of the wind forcing, as well as the wind speed. Waves may be generated by local winds (called wind waves) or by winds a long distance, up to several thousand miles, away (called swell). The seabed also influences waves in shallow water as waves will become steeper and higher as they approach the shore, and energy is lost due to the effect of seabed friction. Further information on wave farm output characteristics and wind-wave correlation have been included in Appendix A.

Within Scottish waters, the wave climate is mainly influenced by conditions in the North Atlantic Ocean, where the fetch is long enough to establish large swell waves. The north and west of

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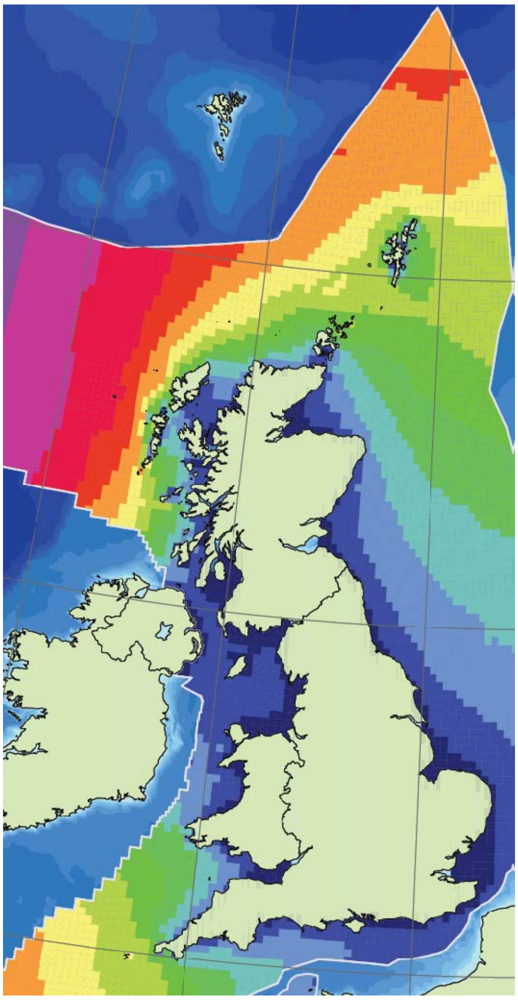
[4] Atmos Consulting. http://www.atmosconsulting.com/ Findings are based on NASA satellite measurements of UK wind speed using a scatterometer device which analyses reflections on water surface through radio signals. Atmos then correlates this with data from meteorological masts that have been offshore for the past two to three years.

[5] Harnessing Scotland's Marine Energy Potential. Marine Energy Group Report 2004.

Scotland (Hebrides, Orkney and Shetland) are most exposed to these conditions. Waves on the east coast of these islands are smaller due to their comparatively sheltered nature[6]. As a result, the optimum location for much of the wave resource is located off the Western Isles and the northern tip of Scotland. In England and Wales the optimum wave resource lies off the northern coast of Cornwall, while in Wales the best resource lies off Pembrokeshire (Figure 2).

- **Figure 2: UK Wave Power Density in kW/km.**



The 2001 *Renewable Resource* study estimated the potential ultimate wave resource in Scotland to be 14 GW based on:

- Areas of over 40 m water depth.
- A density of 20 MW/km.

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[6] Scotland's Seas – Towards Understanding their State, SEPA/FRS/SNH, April 2008.

The packing density of an array will be driven by the trade off between power output reduction due to the shadowing effect of one device on another at high packing densities, and the cost of the seabed lease and electrical cabling. This is an economic calculation dependent on parameters that are not yet known, as experience of deploying multi device farms is limited. It seems likely that the packing density will be the maximum consistent with avoiding device shadowing altogether. This depends on the nature of the device and the way in which it absorbs energy from the resource.

For wave devices, the maximum packing density is most likely determined by the ability of mooring systems to prevent devices from colliding with each other. In practice for Pelamis type devises, most developers are expected to opt for a hexagonal array with 200 to 300 m separation between each device. Smaller separation distances are likely to be possible, particularly for "point absorbers" though slack mooring systems will allow the devices considerable freedom of movement, and the envelope of one device's path cannot be allowed to overlap with another's. One device developer, Seabased AB of Sweden, is adopting a philosophy of deploying a large number of very small point absorbers, typically 10 to 20 kW rated capacity, and has stated that 1,000 of these would be deployed in a 1 km^2 array[7]. This would imply a separation of roughly 32m between each absorber. Few device developers have published details of the planned layouts of large scale facilities, however. This is most likely because few have reached the stage where they need to consider this issue. The choice of separation distance is driven by an economic trade off between the cost of seabed leasing and inter-device cabling on the one hand and the effect on energy output of inter-device interaction and shadowing on the other. The physics of the behaviour of wave energy arrays is an active research issue at the academic level[8].

Offshore wave devices have no technical limitations to the depth of water in which they can be deployed, as they are mostly floating devices held in place by slack moorings. Most device developers tend to aim for depths of ≥ 50 m.

The development of wave technology in recent years has not occurred as quickly as was envisaged when the current leading device concepts began their R&D in the late 1990s. Therefore, only limited operational experience has been gained, with development hampered by technical and financial difficulties. However, the first multi device wave farms are likely to be located at less energetic sites closer to shore, such as at the European Marine Energy Centre (EMEC) in Orkney, or the South West Regional Development Agency's (SWRDAs) planned Wave Hub facility off the North Cornwall coast. The wave energy density at these locations is between 20-30 kW/m and water depth of around 50 m. As a result, when assessing the potential of wave generation, the figures used in 2001 remain broadly relevant.

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[7] Seabased AB. Available at: http://www.seabased.com/index.php?option=com_content&view=article&id=67&Itemid=80 [Accessed October 26, 2009].

[8] SuperGen Marine Energy Research Consortium. Work Stream 4. Available at: http://www.supergen-marine.org.uk/custom/supergen2/WS4.php [Accessed October 26, 2009].

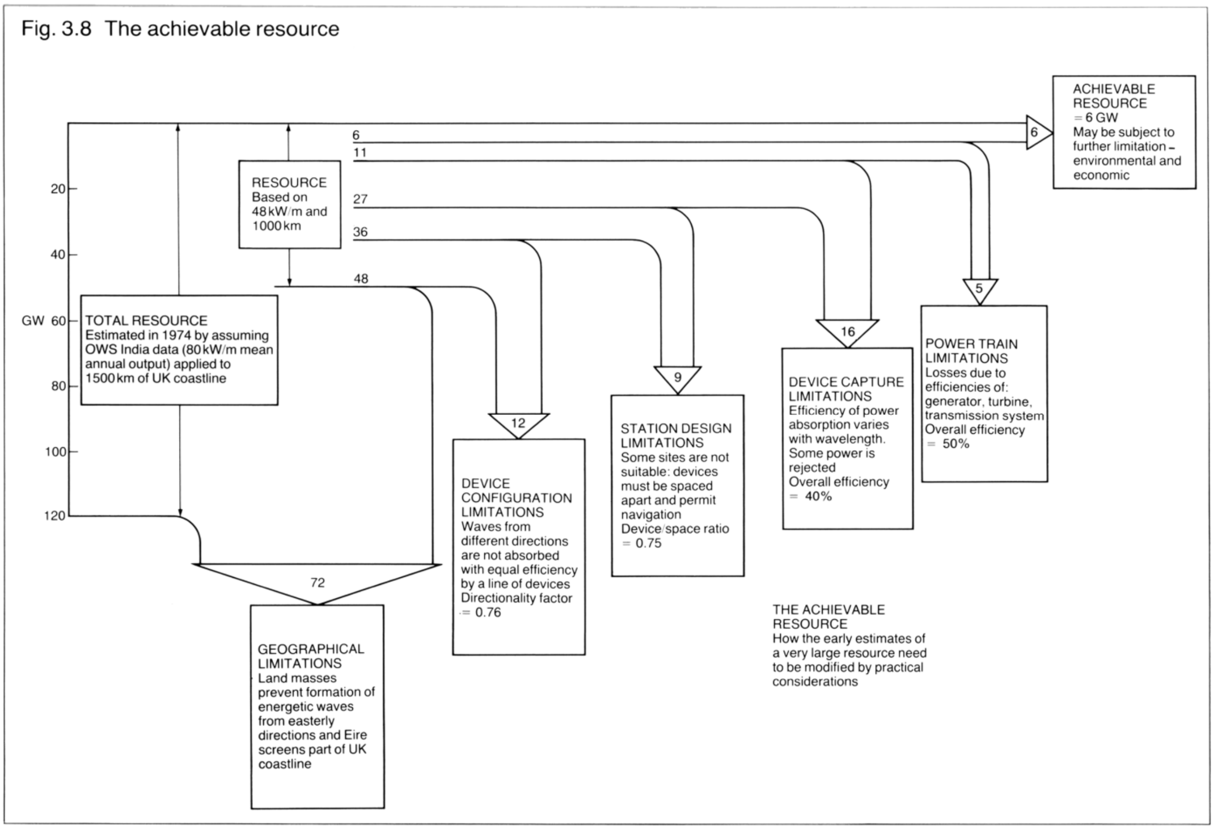
The 1985 report "Wave Energy: the Department of Energy's R&D Programme 1974-1983"[9] summarised the results of several resource studies completed during the first UK wave energy R&D programme. Figure 3 below summarises the resource assessment presented in this report. The estimate was made by assuming a value for the power density and multiplying it by a distance representing the size of a collector array (see the box in Figure 3 headed "TOTAL RESOURCE"). The results are expressed in annual average GW.

The report defined sub categories of the resource as follows:

Total Potential:	The total energy flux crossing a deep water contour around the UK, along which a single line of devices might be deployed.
Available:	Total Potential resource from only those areas deemed "suitable" for deployment of wave energy devices.
Achievable:	The power generated from the available resource allowing for device conversion efficiency.

The results of the 1985 report gave an 'achievable' resource of 6 GW, equal to around 52.5 TWh/y.

- **Figure 3: Wave Energy Resource Assessment (Department of Energy 1985 Review).**



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[9] "Wave Energy: the department of Energy's R&D Programme 1974-1983", P. G. Davies (ed), ETSU Report Number R26, March 1985.

The UK government's 1992 Review of Wave Energy[10] estimated the "technical" resource to be 7 to 10 GW (61.3 to 87.6 TWh/y) using the same approach as the 1985 review, but assuming a higher level of conversion efficiency because of a claimed improvement in the "main devices" studied.

In May 1999, the DTI published the report "A Brief Review of Wave Energy"[11], which used a similar approach to the 1992 review, but used a different set of devices again. The report estimated that the total "technical" resource was 50 TWh/y.

- **Table 1: UK Technical Resource Estimates from "A Brief Review of Wave Energy, 1999".**

Location	Annual Energy Production (TWh)
Shoreline	0.4
Nearshore	2.1
Offshore	50

In 2001 the Scottish Executive published the report "Scotland's Renewable Energy Resource 2001- Volume 1: The Analysis"[12]. This study concluded that 13.8 GW (121 TWh/y) of wave generation could be installed in Scotland for under 7 pence/kWh. The project calculated a cost surface in the sea around the Scottish coast. These are shown in Figure 4 and Figure 5 below. The surfaces were calculated assuming that the devices installed would be the Pelamis type with the following cost and performance characteristics:

- Capital Costs of the devices was £0.75 M/MW in 2010 and £0.5 M/MW in 2025.
- Annual energy yield calculated using a capacity factor of 40 % for 55 kW/m, scaled linearly with the average wave resource.
- Annual Opex = 3.5% of capex.

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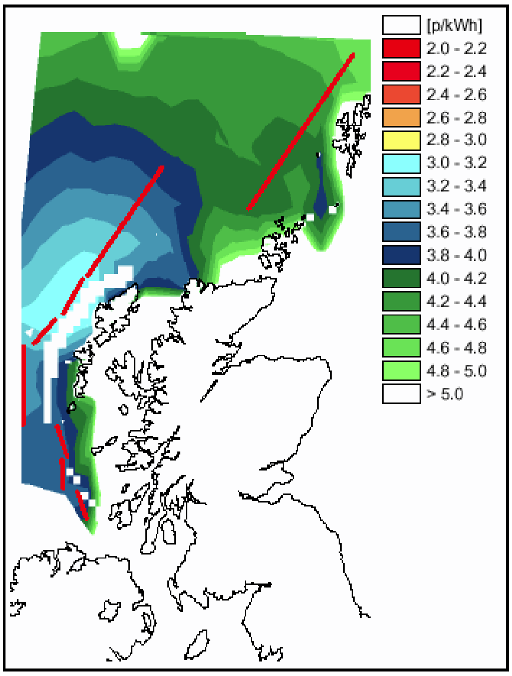
[10] A Review of Wave Energy. TW Thorpe, December 1992, ETSU R-72.

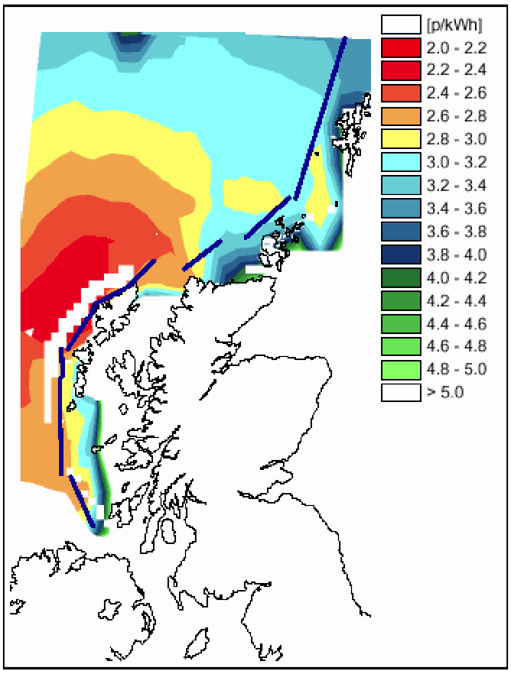
[11] "A Brief Review of Wave Energy", T W Thorpe, ETSU Report Number R120, May 1999.

[12] "Scotland's Renewable Energy Resource 2001- Volume 1: The Analysis" Garrad Hassan 2001.

Figure 4: Wave Energy Cost Surface, 2010 8% Discount Rate, with Collector Array Seaward of Shipping Routes.

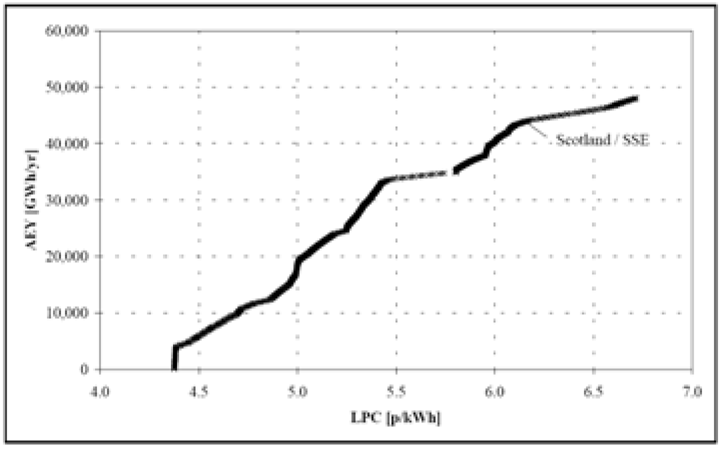


- **Figure 5: Wave Energy Cost Surface, 2025 8% Discount Rate, with Collector Array Landward of Shipping Routes.**



This report also presented its results in the form of cost-resource curves.

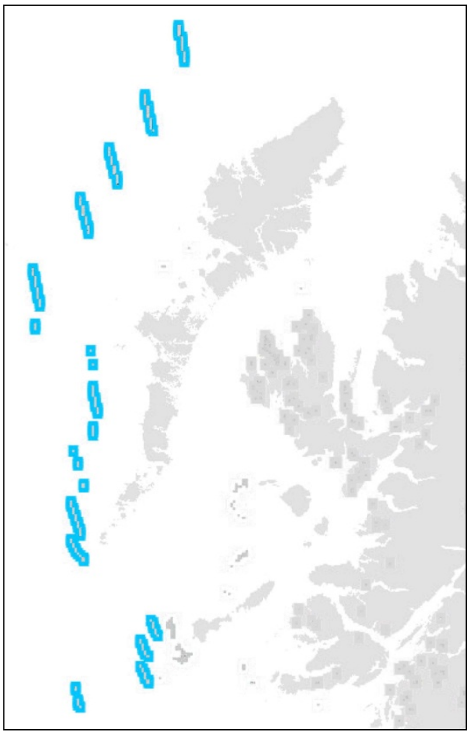
- **Figure 6: Wave Energy Cost Curve, Seaward of Shipping Routes, 2010, 15% Discount Rate for Scotland from “Scotland’s Renewable Energy Resource”.**



The generation cost surfaces shown in Figure 4 and Figure 5 and the cost resource curve shown in Figure 6 above would appear to indicate that wave energy is already (or at least by 2010 would be) cost effective under current market conditions. However, this has not turned out to be correct.

In 2006 the Scottish government published a study carried out by Edinburgh University entitled "Matching Renewable Electricity Generation with Demand"[13]. In this study six GW of device arrays were placed as shown in Figure 7 below and prioritised in terms of generation cost. The output from the arrays were then matched against demand on an hour-by-hour basis. The study concluded that 3 GW of wave capacity could achieve an annual average capacity factor of 31.7% and that this could supply 20% of Scotland's demand. The study did not report the resulting cost of generation.

- **Figure 7: Location of Hypothetical Wave Device Arrays from "Matching Renewable Electricity Generation with Demand".**



The above studies report a wide range of estimates for the "technical" or "achievable" UK wave resource. The wide range reflects difficulties associated with estimating the achievable wave resource, partly due to the differing approaches used. However, on balance 50 TWh/y from the 1999 Brief Review of Wave Energy, is the most widely quoted of the reports. We propose to adopt this figure, equivalent to around ***21 GW*** based on a 27% load factor – although achieving this level of output would require large arrays of wave energy devices, extending for hundreds of km along the West Coast of the British Isles.

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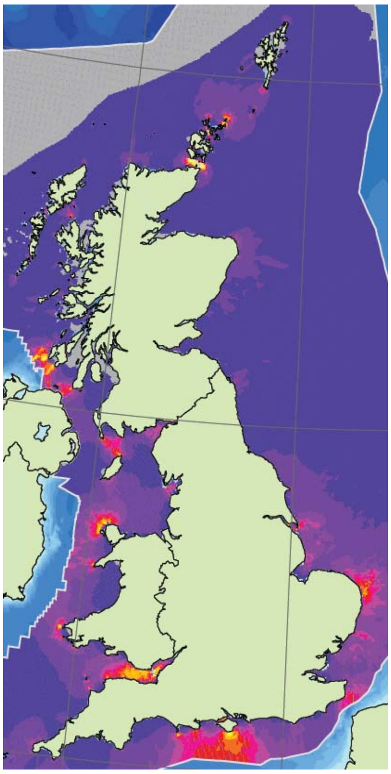
[13] "Matching Renewable Electricity Generation with Demand", a report produced for the Scottish Executive by the Institute for Energy Systems, University of Edinburgh. February 2006.

3.3. Tidal

Tidal currents are predictable and stronger than the residual current[14] in many areas and are intensified in localised areas usually where the flow is constrained by topography. Favourable conditions for tidal stream generation occur mainly in Scotland and include areas such as between Orkney and Shetland, the Pentland Firth, off the Mull of Kintyre and Hebrides where tidal streams can be as high as 3.5-4.5 m/s[15]. In England and Wales, the Bristol Channel, Anglesey, the Isle of Wight and Portland Bill offer the best tidal flow resource (Figure 8).

- **Figure 8: UK Tidal Power Density in kW/m^2.**



For tidal turbines, the devices can be as close as one device width perpendicular to the direction of flow, and about 10 to 12 device widths in the direction of flow, if one turbine is directly behind another. If the turbines in each row are staggered with respect to neighbouring rows, so that one turbine is behind a space in the row in front, then the separation between rows can be halved.

The configuration of the array would probably consist of rows of turbines arranged perpendicular to the direction of the flow, with one row behind another. The maximum width and length of the

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[14] This is the tidal current that would be observed in the middle of the ocean away from any land features.
[15] Scotland's Seas – Towards Understanding their State, SEPA/FRS/SNH, April 2008.

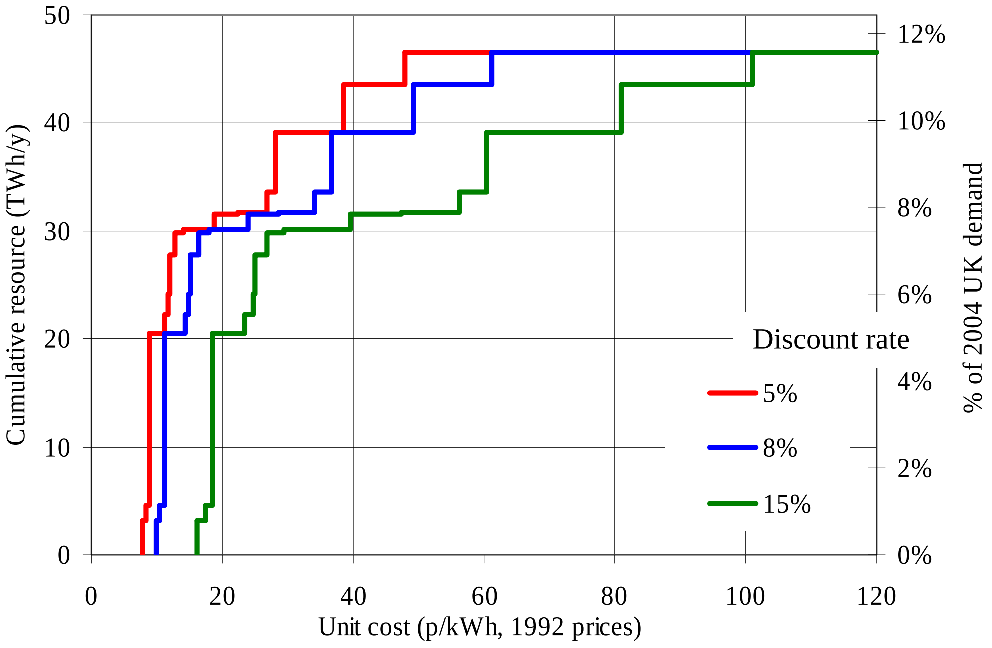
array would be determined by the dimensions of the area of fast flowing water. Further information on tidal device output characteristics has been included in Appendix A.

Pile mounted tidal current turbines have a maximum water depth of 25 – 30 m. For deeper water, either bottom mounted turbines that only occupy a fraction of the water column, or turbines suspended underneath floating structures would probably be used. In the longer term, some developers are investigating tripods and other types of support structure that could support larger turbines that could fill a larger fraction of the water column in deeper water.

The 2001 report determined an ultimate probable tidal stream potential of up to 7.5 GW.

In 1993 the Department of Energy published a major study[16] to assess the size of the UK tidal stream resource. This was based on a two-bladed horizontal axis turbine mounted on a vertical column attached to a gravity base on the seabed. The study presented a cost-resource curve showing the cumulative resource available as a function of the cost of extracting that resource. These curves are shown in Figure 9 below.

- **Figure 9: Cost Curve for Tidemills over 100 kW Capacity (from 1993 DEn study).**



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[16] Engineering Power Development Consultants Ltd with Binnie & Partners, Sir Robert McAlpine & Sons Ltd and IT Power Ltd, 'Tidal-Stream Energy Review', ETSU T/05/00155/REP, 1993.

These curves imply that the total technical resource[17] is approximately 58 TWh/year but that none of this could be extracted at a cost of less than 9.9 p/kWh at 1993 prices at an 8% discount rate.

In 1996, the European Commission carried out a similar study covering the whole of the EU[18]. This identified more potential sites in UK waters but derived a smaller value, 31 TWh/year, for the UK technically exploitable resource.

In 2000 the DTI commissioned a further study from Binnie, Black & Veatch (BBV) to evaluate the commercial prospects for tidal-current energy in the UK[19]. BBV carried out a detailed costing of a 15.9 m diameter twin-rotor device designed to give an output of 1 MW in a velocity of 2.3 m/s. A list of sites around the UK was examined, based on those studied in the 1993 DTI report and the 1996 EC report. For each site BBV derived temporal velocity profiles by fitting a bi-sinusoidal function to the mean spring and neap velocities taken from Admiralty charts. The report did not include a full cost-resource curve, but concluded that 10 TWh/year could be exploited at a cost of 4 – 6 p/kWh. This has not been borne out in practice.

In 2004 the Carbon Trust commissioned a study from Black & Veatch Ltd (B&V) of the UK tidal-current resource. This estimated that the energy contained in the moving water at the sites studied, which were the same as in B&V's previous studies, was approximately 100 TWh/y. It then applied a novel flux-based approach, originally developed by Robert Gordon University, which uses the concept of a Significant Impact Factor (SIF), the proportion of the total energy flux that can be extracted without causing unacceptable environmental effects, e.g. on sediment dynamics. This factor is highly site specific and can only be estimated accurately by means of a major modelling study for each site. To date, such studies have not been carried out. Expert opinion[20], however, seems to be that SIFs are typically in the range 10% to 50%. The B&V study used a constant value of 20% for all sites. It identified that the exploitable resource was 16.3 TWh/year, and that the distribution of the resource according to water depth was:-

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[17] The technical resource is the maximum amount of energy that can be extracted irrespective of the cost of doing so.

[18] CEC DGXII (1996) 'The exploitation of tidal and marine currents'. JOULE II Report EUR 16683en, Contract JOU2-CT93-0355, quoted in Ref 6.

[19] Binnie, Black & Veatch, 'The Commercial Prospects for Tidal Stream Energy', ETSU/T/06/00209/REP, URN 01/1011, 2001.

[20] University of Strathclyde. Environment: Significant Impact Factor (SIF). Available at: http://www.esru.strath.ac.uk/EandE/Web_sites/05-06/marine_renewables/envimpact/sif.htm [Accessed October 28, 2009].

- **Table 2: Extractable Resource by Depth.**

Depth range (m)	Fraction of 'extractable'resource
<25	4.4%
25 - 30	2.5%
30 - 40	29.9%
> 40	63.2%
Total	100.0%

It is immediately apparent that the majority of the available resource is in water deeper than 40 m. Table 3 below shows the geographical distribution of the resource, taken from Black & Veatch's 2004 Phase I study because the later report did not contain such information.

- **Table 3: Geographical Distribution of Resource, from Black & Veatch's Resource Assessment for the Carbon Trust.**

Remote North & West of Scotland, either north of 58°N or west of 5°W	64.2%
(of which Pentland Firth)	(26.0%)
Channel Islands	20.1%
Republic of Ireland	5.4%
Total of above	89.7%
Total resource identified	**100%**

Professors Stephen Salter[21] and David Mackay[22] have argued that the basic physics of tidal energy extraction has been misunderstood, and that the actual resource could be 10 times larger than previous estimates. This is based on the idea that a considerable proportion of the energy in a tidal stream is lost due to seabed friction, and that when energy is extracted, the velocity of the stream is reduced, thereby reducing the frictional losses and freeing up the lost energy for extraction. These ideas have yet to receive extensive peer review, however, and must be regarded as tentative at the moment.

The above studies have produced a range of estimates of the technically extractable resource, ranging from 58 TWh/year (equivalent to roughly 16 GW of installed capacity assuming a capacity

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[21] Salter SH. Possible Under-Estimation of the UK Tidal Resource, a response to the DTI Energy Review Consultation. Available at: http://www.berr.gov.uk/files/file31313.pdf [Accessed October 28, 2009].

[22] Mackay D. Under-estimation of the UK Tidal Resource. Available at: http://www.inference.phy.cam.ac.uk/mackay/abstracts/TideEstimate.html [Accessed October 28, 2009].

factor of 40%) to 16 TWh/y (equivalent to roughly 4.5 GW). We have chosen a figure of 7.5 GW as being somewhere in the middle of this range.

None of the studies outlined above took into account practical constraints, in particular other potential competing uses of the sea. Based on the studies above and existing technologies, we consider ***7.5 GW*** might be an ultimate probable resource for tidal power in the UK.

4. Economically Recoverable to 2020

While the Ultimate Probable Scenario outlines the offshore renewable resource that may be theoretically possible in an unconstrained world – the second scenario focuses on what the 'economically recoverable' offshore renewable resource may be over the period to 2020 as this period represents a key milestone for UK CO_2 and renewables targets. The economically recoverable resource over the period to 2020 is largely based upon what could reasonably be expected to be recovered under current economic, location and operating conditions.

4.1. Offshore Wind

Given that the costs and risks associated with offshore wind farms increase with distance from shore and water depth, the sites most likely to be initially developed are likely to lie in relatively shallow water. Given that revenues increase with wind speed, it is also reasonable to assume that optimum areas for development will be those with relatively high wind speeds, located near to shore in relatively shallow water. However, a number of factors combine that will influence the economically recoverable wind resource by 2020, these include:

- The Strategic Environmental Assessment.
- Market Conditions.
- Technology developments.

4.1.1. The Strategic Environmental Assessment

The UK Offshore Energy Strategic Environmental Assessment (SEA) concluded that the bulk of new offshore generation capacity should be sited generally beyond the 12 nm (nautical miles) zone for large wind farms of over 100 MW[23]. As a result all round 3 sites lie beyond the 12 nm buffer. If applied rigorously in the future then the 12 nm buffer would prevent the development of much shallow water offshore wind in Scotland.

However, the SEA also suggested that the proposed coastal buffer zone was not intended as an exclusion zone and that scope may exist for offshore wind development within the area, but rather that the zone is intended to mitigate for the potential environmental effects of development which may result. Given the bathymetry of Scottish offshore waters much of the development potential for offshore wind in Scotland currently lies within the 12 nm buffer zone. As a result the Crown Estate has awarded Exclusivity Agreements for the potential development of ten offshore wind

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[23] http://www.offshore-sea.org.uk/site/scripts/consultation_download_info.php?downloadID=265

sites amounting to 6.4 GW within the 12 nm buffer zone in Scottish territorial waters[24]. The Exclusivity Agreements gives potential developers security over their chosen sites and allows them to begin (with the necessary statutory consents) site survey works and instrument deployment that require the permission of The Crown Estate.

However, the full development of these sites depends upon the outcome of the Scottish government's ongoing SEA for offshore wind, expected to report in early 2010. The grant of any agreement for lease by The Crown Estate is subject to a favourable SEA outcome. As a result the development of offshore wind in Scotland may well occur within the 12 nm buffer zone. If the outcome of the SEA is favourable then those sites awarded Exclusivity Agreements are likely to be developed ahead of those earmarked in round 3 in Scottish waters as the round 3 sites lie beyond the 12 nm buffer.

We will assume that the outcome of the SEA is favourable and will not prevent the development of those sites awarded Exclusivity Agreements.

It is also notable that the current Exclusivity Agreements are not all necessarily located in the optimum wind resource areas – in particular the considerable ultimate potential for offshore wind in the Western Isles is excluded. It is not clear whether the development potential for offshore wind in the Western Isles will be fully realised due in part to environmental factors and fishing concerns. The potential development off the Western Isles will depend on the outcome of the ongoing SEA.

We will assume that the outcome of the SEA will allow some development in the Western Isles, but that development will be limited in size to 500 MW.

4.1.2. Market Conditions

The cost of offshore wind turbines has escalated in recent years – with the capital costs of offshore wind farms increasing 100% in real terms between 2005-2008[25] with the capital cost of an offshore wind farm now over £2600/kW. The rise in capital costs of offshore wind since 2005 can be attributed to a number of effects, in particular:

1) Rising commodity prices.

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[24] As landowner of the seabed and areas of foreshore by virtue of the Crown Estate Act 1961, The Crown Estate's permission is necessary to place structures on or pass cables over the seabed and its foreshore. In addition to permission from the landowner potential developers also require statutory consents from a number of government departments responsible for the offshore wind development process. Only when all the necessary statutory consents are obtained will The Crown Estate grant a lease for development. The Crown Estate leases for the development of sites within the 12 nm (nautical mile) territorial limit, whilst the Energy Act 2004 gives the Crown Estate rights to issue leases for development beyond the territorial limit within Renewable Energy Zones (REZ) out to 200 nm.

[25] http://www.bwea.com/pdf/publications/ChartingtheRightCourse.pdf

2) Supply and demand tightening.
3) Technical issues.
4) Supply chain constraints – vessel availability.
5) Exchange rates.

Since 2005 commodity prices rose substantially to 2008 – peaking in summer 2008 with oil at \$150/barrel and coal at over \$220/tonne. The rise in commodity prices has a knock on impact on the cost of manufacturing turbines and components. For offshore wind it is estimated that around half of the increase in turbine prices since 2003 can be explained by globally rising commodity and materials costs[26].

Together with rising commodity prices the wind turbine industry began to rapidly accelerate after 2005. This expansion began to place strain on the supply/demand balance as demand outstripped supply. In addition, current offshore wind turbine technology is essentially a marinised version of the largest onshore wind designs. This has led had a key impact on the market – the engineering challenge required to operate in the marine environment is considerable and some of the early offshore turbines, such as the V90 turbines from Vestas, have experienced multiple failures, particularly in gearboxes. Such failures increased the perceived risk associated with supplying machines offshore. As a result manufacturers have limited incentive to develop offshore turbines given the very buoyant and less risky onshore market. Over the 2007/8 period the offshore industry was effectively reduced to a single supplier (Siemens Wind Power) [27]. Furthermore wind turbine manufacturers have sought to increase the profitability of their operations in a more mature onshore wind market, leading to greater margins and less aggressive pricing strategies and therefore higher costs.

Since 2007 the limited availability of installation vessels has led to a large increase in day rates. In addition the availability of electrical equipment, such as transformers and subsea cables, has been in short supply – with upward price pressure resulting.

The value of sterling has dropped dramatically against the Euro since mid 2008. The result has been that prices for UK projects approaching agreement on major construction contracts substantially increased – by as much as 25%.

Table 4 below shows the impact of changes in capital costs on the overall lifetime levelised cost of offshore wind and compares offshore wind to the current cost of onshore wind. Clearly offshore wind is substantially more costly than onshore wind – with current costs (excluding connection costs) of over £110/MWh.

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[26] Offshore wind power: big challenge, big opportunity. Carbon Trust 2008.
[27] http://www.bwea.com/pdf/publications/ChartingtheRightCourse.pdf

- **Table 4: Cost Components and Levelised Costs.**

	Onshore wind	Offshore wind		
Capex* (£/kW)	1200	2000	2600	3000
Fixed operating costs (£/kW)	25.1	52.5	52.5	52.5
Discount rate	10%	10%	10%	10%
Load factor	30%	40%	40%	40%
Life (years)	20	20	20	20
Lifetime levelised cost £/MWh	69	88.7	110.9	125.6

*Excludes the cost of offshore cabling of around £200/kW.

Given our assessment of the factors discussed above we do not consider that the cost of offshore wind turbines will change dramatically from its current high levels over the next 3-5 year period. As a result, given forward electricity wholesale prices of around £40-50/MWh and predicted ROC values for 2010 of around £40/MWh combined with the currently high capital cost of offshore wind, increased ROC support is likely to continue to be required for increased offshore development to be undertaken by 2020.

4.1.3. Technology Developments

As outlined above offshore wind turbine technology is currently an essentially marinised version of onshore technology. While a number of design developments are currently being developed to pilot stage, including floating turbines, horizontal axis turbines, given the time to design, develop and build investor confidence in radical new technology, offshore wind turbines are likely to remain fundamentally based on the existing three-blade, upwind design until 2020.

4.1.4. Summary

Based on our assessment of the factors outlined above we consider that a reasonable assessment of the economically recoverable offshore wind resource over the period to 2020 will be between 5 GW and 12 GW. The variation in the economically recovereable resource by 2020 is highly dependent upon prevailing and developing market conditions, in particular the existing subsidy system for offshore wind. The location of this resource will be based on the currently awarded Exclusivity Agreements and rounds 1, 2 and 3.

4.2. Wave and Tidal

The Scottish government's Forum for Renewable Energy Development in Scotland's (FREDS's) Marine Energy Group (MEG) report of 2009 suggests that, in a central scenario, up to 1 GW of marine energy in Scottish waters may be feasible by 2020, with an upper scenario of 2 GW and a lower scenario of 500 MW[28]. The 2009 MEG report represents a revision of its assessment in 2004 where it suggested that 1.3 GW could be provided by marine energy by 2020[29]. The MEG highlighted that marine energy in Scotland has not developed as quickly as expected in its 2004 due, in part, to technical difficulties and financial constraints relating to technology development. Marine technology in Scotland, despite its ultimate technical resource, remains an infant technology.

Following MEG's earlier 2004 report, the Scottish government commissioned a SEA to examine the potential environmental effects from the development of wave and tidal power. The SEA concluded that relative 'newness' of the wave and tidal industry compared to, for example, wind energy meant that limited information was available to fully assess the impact on the marine environment. The effect of wave and tidal devices/arrays on shipping and navigation was assessed as being of major adverse significance. This is principally due to the fact that the Pentland Firth, North Channel, Fair Isle, Hebrides Deep Water Route and the Minches are all recognised sea lanes for international navigation. The SEA has identified that the presence of wave and tidal devices in the seas around Scotland could significantly affect the use of the area for international navigation. The main effects include reductions in navigational safety (due to increased shipping densities in certain areas where vessels have re-routed to avoid devices) and collision risk, particularly in spatially constrained areas such as the Pentland Firth, the Northern and Western Isles and the West Coast of Scotland[30].

The SEA concluded that between 1,000 MW and 2,600 MW of marine renewable energy generating capacity could potentially be achieved within the SEA study area taking into account environmental effects and depending on the types of technology (including array density) deployed. The estimated marine renewable energy capacity for each area and each energy type (wave or tidal) taking into account environmental effects is illustrated in Table 5 below. These represent upper limits imposed by physical[31] and environmental constraints, within the area of the SEA, rather than estimates of the size of the resource.

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[28] Marine Energy Group Marine Energy Road Map, Forum for Renewable Energy in Scotland, 2009.

[29] Harnessing Scotland's marine Energy Potential, Marine Energy Group Report 2004.

[30] http://www.seaenergyscotland.co.uk/

[31] Physical Constraint include shipping routes, fishing, pipelines, cables, archaeological sites, MOD areas and munitions dumps.

Table 5: SEA Estimated Marine Energy Capacity.

Area	Potentially achievable capacity – physical constraints (MW)				Potentially achievable capacity – environmental effects (MW)			
	Wave		Tidal		Wave		Tidal	
	Low	High	Low	High	Low	High	Low	High
Northern Isles – Shetland	75-200	200-400	75-200	75-200	75-200	200-400	<75	75-200
Northern Isles – Orkney	75-200	200-400	75-200	75-200	75-200	200-400	<75	75-200
Pentland Firth			75-200	200-400			75-200	200-400
North Coast*								
Outer Isles	200-400	>400			75-200	>400		
Inner Isles	<75	75-200	75-200	200-400	<75	75-200	<75	75-200
Western Isles	75-200	>400	<75	<75		>400	<75	<75
Argyll and Bute	<75	75-200	75-200	75-200	<75	75-200	<75	75-200
North Channel	<75	<75	<75	75-200	<75	<75	<75	75-200
Estimated Range	**650-2200**		**650-1100**		**525-1800**		**475-800**	

Therefore, the technical possible offshore marine resource appears, at least over the period to 2020, to be limited by environmental considerations. In addition to environmental issues a range of other factors will limit the economically recoverable potential of marine offshore technology.

By 2010, we expect there will be no continuously operating wave or tidal current generation in UK waters. Our assessment is based on the current status of the various prototype devices currently under development. The most advanced of these are just commencing operation but are not expected to operate continuously for an extended period before 2010.

By 2015, the first generating facilities built under Department for Energy and Climate Change's (DECC's) Marine Renewables Deployment Fund (MRDF) and the Scottish government's Wave and Tidal Energy Support Scheme (WATES) scheme could be commencing operation. Based on the amount of funding available under these schemes, we expect that an installed capacity of 30 MW may be achievable. The likely candidate projects that could happen in this phase include:

- Marine Current Turbines Ltd's Anglesey Skerries tidal current array projected to have a nameplate capacity of 10.5 MW consisting of seven pile mounted horizontal axis turbines each of 1.2 MW capacity.

- South West Regional Development Agency's (SWRDA's) Wave Hub – this will have four berths each able to accommodate up to 5 MW of wave energy capacity. SWRDA currently expect the following five device developers to locate at Wave Hub
  i. Ocean Power Technologies (OPT)
  ii. Fred Olsen
  iii. Oceanlinx
  iv. Orecon

  However, we consider that only three developers are likely to be ready to take up these berths, leading to a total installed capacity of 15 – 20 MW at Wave Hub

- Scottish Power and Pelamis Wave Power's proposed project is funded under the Scottish government's WATES. This is expected to have a nameplate capacity of 3 MW and will be located at EMEC in Orkney. The projects total 33.5 MW.

If the above projects are successful and if sufficient levels of government support are available to make wave and tidal projects profitable, we could expect further development of marine energy. A recent report[32] by Redfield Energy Consulting and Trilemma Ltd for DECC carried out in support of the recently published RES projected that in 2020 there would be 2.9 TWh/y of generation from wave and tidal-stream combined. This would equate to about 1 GW of nameplate capacity. This is broadly in line with previous projections given in studies by Ernst & Young[33] (1.2 TWh/y of wave and 1.4 TWh/y of tidal stream), FREDS MEG's 2004 report (1.3 GW) and the FREDS MEG 2009 report (0.5 to 2 GW).

4.2.1. Summary

Given the current rate of progress of the industry and the technical challenges that it faces, the prospect of achieving the central scenario aspiration of 1 GW outlined by the MEG report in 2009 would seem to be receding to beyond 2020. We would therefore suggest that a figure slightly below the lower projection in the 2009 FREDS MEG report could be achievable if the technology deployed in the previous facilities proves to be successful and all major technical challenges are overcome. Given the pilot stage of much of the current marine technology we consider that an ambitious but realistic projection for the deployment of wave and tidal current energy in the UK may be 15-40 MW by 2015 rising to 300-800 MW by 2020. The location of the economically

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[32] 2009 Redpoint Energy Ltd & Trilemma UK Ltd. Implementation of the EU 2020 Renewables Target in the UK Electricity Sector: RO Reform. A report for the Department of Energy and Climate Change, June 2009 - URN 09D/702.

[33] Ernst & Young LLP. Impact of banding the Renewables Obligation - Costs of Electricity Production.; 2007. Available at: http://www.berr.gov.uk/files/file39038.pdf [Accessed October 1, 2009].

recoverable marine resource will be based on those sites identified in the discussion above – detail of locations is outlined in section 6.

5. Economically Recoverable to 2050

Technology change is fundamental to the move away from oil and gas and technology policy is vital, covering the full spectrum from research and development, to demonstration and early stage deployment. While factors such as the carbon price will be important to instigate technology development and innovation as it provides the incentive to invest in new technologies to reduce carbon, the market is not perfect – factors such as capital market imperfections and inertia inhibit technological development. We have not determined, in developing a view of the market out to 2050, which offshore technologies will be developed, but we assume that technological development will occur to extend the economically recoverable resource beyond 2020.

Given the uncertainty surrounding long-term technological development we have assessed the potential for offshore renewable contributions in 2030 and 2050 under both a 'High' and 'Low' scenario.

The ultimate aim of each scenario is to meet the UK's 2050 CO_2 target of an 80% cut in emissions below 1990 levels. In determining the contribution of offshore renewables we have considered the UK generation mix required necessary to achieve a near zero carbon electricity sector by 2020.

Table 6 and Table 7 outline the total volume of offshore wind, wave and tidal capacity over the period to 2050 under the 'High' and 'Low' scenarios. The location of the resource identified in each scenario is outlined in section 6.

- **Table 6: Total UK Offshore Renewable Capacity – High Scenario (MW).**

	2015	2020	2030	2050
Offshore wind	2,400	12000	18,000	30,000
Tidal stream	30	400	1500	5000
Wave	20	500	2000	6000

- **Table 7: Total UK Offshore Renewable Capacity – Low Scenario (MW).**

	2015	2020	2030	2050
Offshore wind	1,350	5,000	10,000	18,000
Tidal stream	10	80	500	2000
Wave	5	220	520	2000

6. Summary of Offshore Renewable Resource

The Table 8 - Table 10 below show the volume and physical location of the offshore renewable generation resource determined in the ‘High’ and ‘Low’ scenarios for the years 2020, 2030 and 2050.

6.1. Wind

6.1.1. Capacity by Location

Table 8: Potential Offshore Wind Capacity Locations.

	2020		2030		2050	
	Low	High	Low	High	Low	High
Wash/Thames	1500	2700	2500	3500	3500	4000
Eastern England	1000	2300	2000	3500	3000	4000
Wales	500	1500	1000	2000	1500	2000
Dogger Bank	0	0	0	2000	3000	8000
Western Scotland	500	1,500	1000	1500	1500	2000
Eastern Scotland	500	1,500	1000	2000	2000	3000
North West England	500	1,500	1000	1500	1500	3000
South West England	0	300	500	1000	1000	2000
Southern England	500	700	1000	1000	1000	2000
Total	5,000	12,000	10,000	18,000	18,000	30,000

6.1.2. Key Variable Matrix

Based on the broad geographical areas outlined there are a number of key variables that will characterise individual offshore energy farm developments. The following matrices have been developed to outline these energy farm development variables and have been developed using the previously defined resource capacities and locations.

Wind Matrix

	Technology	Offshore Connection Distance km	Onshore Connection Distance km	Farm Size MW	Distance Between Farms km	Onshore Network Strength	Water Depth m	Machine Size MW
	A	B	C	D	E	F	G	H
1	Wind	Short <30	Short <30	5000	Short <50	Strong	<25	Theoretical 10
2		Medium 30-100	Medium 30-80	2000	Medium 50-100	Weak	25-50	Large 7.5
3		Long >100	Long >80	1000	Long >100		>50	Medium 5
4				500				Small 3.6

Key Variables

The key variables have been selected based on the specific location capacity predictions and then generalised into categories to apply to a greater number of potential developments.

- Offshore Connection Distance:

  The ranges of distances selected have been chosen to be representative of the potential development locations outlined in Table 7.

- Onshore Connection Distance:

  The ranges of distances selected have been chose to be representative of a range of connection scenarios taking into account that larger developments are likely to be forced to connect further inland as much of the coastal capacity is used up by the first come smaller developments.

- Farm Size:

  A range of discrete farm capacities have been selected for simplification, capacity will have a major impact on the design of the offshore connection and as such must be defined precisely. The range of capacities has been selected to provide a representative cross section of developments based upon the predicted capacity by location, a range of wind farm sizes have been selected[34]. It is important to note that this is not the total capacity within a single zone or location as shown in Table 8 but the total capacity of a single farm with a dedicated connection. The capacity of a single farm is unlikely to be much more than half the total installed capacity in any one zone.

- Distance Between Farms:

  Based upon the farm capacity and the location size, this variable will have an impact on the export and connection schemes.

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[34] 5000 MW has been included for subsequent technical study, however market economics and financing make developments of this size unlikely given a capital cost circa £8 Billion (see Section 4.1.2).

- Onshore Network Strength:

  This variable refers to the network fault level. A high fault level would indicate a strong network. This variable is difficult to define numerically as the strength is subjective and dependent on the development being connected, notionally for a development of several hundred MW a fault level of 3000 MVA or less (consistent with a connection in the Scottish 132 kV system) would be considered weak and a fault level of 20000 MVA would be considered strong (consistent with a connection to the 275 or 400 kV transmission system in England). An example of a weak network would be the North of Scotland, and strong network would be the trunk of England.

- Water Depth:

  Based upon the defined depths of the likely development areas in UK territorial waters.

- Machine Size:

  The listed turbines represent the current and expected spectrum of machines, the 3.6 MW (Siemens) is tried and tested, the 5 MW (RE Power) has been used and will be available in large quantities in the 2020 time frame potentially along with its variant which will be a 6 MW, and finally the 7.5 MW (Clipper) is in development. Larger turbines like 10 MW being worked on by American Superconductors are in the early stages and are more likely to be relevant in the 2050 timeframe.

6.2. Marine

6.2.1. Tidal Capacity by Location

- **Table 9: Potential Tidal Capacity Locations.**

	2020		2030		2050	
	Low	High	Low	High	Low	High
Pentland Firth	60	140	300	700	1200	3000
Orkney	10	40	50	250	250	650
Shetland	10	40	50	200	250	650
Bristol Channel	0	40	50	200	200	500
Northern Ireland	0	40	50	150	100	200
Total	80	400	500	1500	2000	5000

6.2.2. Wave Capacity by Location

- **Table 10: Potential Wave Capacity Locations.**

	2020		2030		2050	
	Low	High	Low	High	Low	High
Northern Scotland	80	200	200	700	700	2000
Western Isles	80	200	200	700	700	2000
North Cornwall	30	50	60	400	400	1600
Wales	30	50	60	200	200	400
Total	220	500	520	2000	2000	6000

6.2.3. Key Variable Matrix

As with wind, based on the broad geographical areas outlined there are a number of key variables that will characterise individual offshore energy farm developments using marine generation. The following matrices have been developed to outline these energy farm development variables and have been developed using the previously defined resource capacities.

Marine Matrix

	Technology	Offshore Connection Distance km	Onshore Connection Distance km	Farm Size MW	Distance Between Farms km	Onshore Network Strength	Water Depth m	Machine Size MW
	A	B	C	D	E	F	G	H
1	Tidal	Short <30	Short <30	500	Very Short <10	Strong	<40	1
2	Wave	Medium 30-100	Medium 30-80	200	Short 10-50	Weak	>40	0.5
3		Long >100	Long >80	75	Medium 50-100			0.1
4				20	Long >100			

Key Variables

As with wind, the key variables have been selected based on the specific location capacity predictions and then generalised into categories to apply to a greater number of potential developments. Variations from the wind matrix are described below.

- Farm Size:

  As with wind marine farm sizes have been based upon the expected location capacities. Expected marine developments are significantly smaller than that of wind hence the smaller sizes.

- Distance Between Farms:

  A very short threshold has been included to take into account the clustering that is likely to occur with tidal farms given the highly localised nature of the resource.

- Machine Size:

  Development of tidal and wave machines is far less advanced than those for wind, the machine sizes shown are representative of current and perceived potential future devices. Although it is theoretically possible for tidal turbines to be made very large, especially in deeper water, the enormous forces exerted by moving water, which is 1,000 times as dense as air, would pose very great engineering challenges. The alternative approach of deploying a larger field of more modestly sized turbines is therefore considered more likely, even in the longer term. It is unlikely that devices will grow much larger than 1 MW[35] in the perceived timeframe, instead the arrays will simply increase in size.

6.3. Capacity Scenarios Summary

The analysis presented above has defined:

- The ultimate probable UK offshore marine generating resource.
- The economically recoverable offshore marine generating resource over the period to 2020, 2030 and 2050.
- The location of the economically recoverable resource over the period 2020, 2030 and 2050.
- Matrices of variables that will be used in Section 7 to define specific development cases for further analysis.

Over the period to 2020 those parameters that will define the contribution of offshore marine generation are considerably fewer than those that will influence the role of offshore marine generation to 2030 or even 2050. In short, the volume of offshore renewable generation that can be expected by 2020 will be based on decisions already taken, or decisions likely to be taken within the next 3-5 years. As a result, the assessment of new technology solutions that may be applied to the connection of offshore renewables will be limited by investment decisions already taken, or shortly to be taken.

The period to 2030 allows greater scope for the potential introduction and assessment of a broader range of technology solutions that might be applicable to the matrices of variables we have defined above. However, given that 2030 is only 20 years away and given the long lead times associated

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[35] Larger machines are possible however economically they are not generally attractive, the trade off is a larger machine that runs at maximum output rarely or a smaller machine that runs at maximum output for a significantly longer period. Wave device size in particular is dictated by the wave climate. Tidal devises are limited by water depth and the forces exerted on the device.

with the application of some technologies, the period to 2030 remains sufficiently short to allow a reasonably detailed assessment of the technology options available as the technologies assessed will be largely based on evolutions of existing equipment, although not necessarily currently market ready offerings.

The period beyond 2030 is subject to large uncertainties, both in terms of the types of technologies and their scale of deployment. Our projections for this timescale implicitly assume that the technical development of the technology has been successful and that reductions in generation cost have been achieved. If this did not happen, then the situation could be very different.

While the high and low scenarios developed to 2050 form the basis of the technical study to follow, given that the period to 2050 contains a significant number of potentially unknown variables, we consider that a wide scale assessment of technology opportunities beyond 2030 (particularly for wind generation) is likely to prove of limited benefit to the project given the ETI's desired objectives and financial horizon of interest. That said, we recognise the limited development of marine generation likely by 2020 and have thus included 2050 scenarios based on larger capacity development for projects of such technologies.

In conclusion, we propose to concentrate on the period to 2030 for the subsequent tasks within this project, although consideration will be given to larger marine developments potentially exploitable out to 2050. The main focus on the period up to 2030 is considered appropriate as it is close enough to the present day to assess in detail the technology connection options available, yet sufficiently distant from current investment timescales to allow the assessment of alternative technology options.

7. Specific Development Cases

From the matrices covering the entire spectrum of potential developments seven specific cases providing a representative sample of development types have been selected. The sample of developments is specific enough to accommodate the next phase of detailed analysis but varied enough to allow for cross comparison and ultimately produce recommendations that are relevant for an appropriately large number of developments.

The selected cases are largely based on the most likely developments in the given timeframes, also taken into account is the necessity for cross comparison of the future analysis. It is important that the cases selected can be meaningfully compared with respect to the identified variables. For example it will be useful to compare similarly sized wind and marine developments in order to assess the aspects that are affected by the technology without the complication of a large difference in capacity. On the other hand the range of capacities must be large enough to draw conclusions on individual effects, for example does the optimum inter-array voltage increase with generation unit capacity or is there a cycle of diminishing returns resulting in an economic cap on inter-array voltage regardless of increasing capacity or machine size.

As in this section we have defined specific cases rather than sweeping scenarios we feel that it is inappropriate to define the case timescales in terms of specific horizon years. Consequently, we have used the broad horizon year statements of short, medium, or long term. This recognises that a defined case may ultimately be relevant in 2025 or not until 2035 depending on how well the industry has grown. In terms of specific definitions, short term will refer to a case which will be relevant by 2020 given the relatively strong information that exists already. Medium will refer to a case being relevant after 2020, and long term will refer to a case that is relevant well after 2020 and out to 2050 and beyond.

Given the variation in maturity between wind and marine renewable technologies it is wind developments that will be the most significant in the short term with the cases highlighted relevant in the short or medium term and of a scale that will justify investment and development.

The marine (wave and tidal) cases presented are relevant in a medium or long term for significant development. The short term case is presented by necessity but may be too small to produce opportunities of a scale that will justify investment.

7.1. Distributed Smaller Windfarms

Technology	Offshore Connection Distance km	Onshore Connection Distance km	Farm Size MW	Distance Between Farms km	Onshore Network Strength	Water Depth m	Machine Size MW
Wind	Medium 30-100	Medium 30<80	500	Medium 50-100	Weak	25-50	Small 3.6

This case will be relevant within the short term and is representative of multiple relatively small windfarms. This scenario is representative of a wide range of developments but may be more applicable around Scotland given the lack of shallows further from shore and the weaker network.

7.2. Large Windfarms

Technology	Offshore Connection Distance km	Onshore Connection Distance km	Farm Size MW	Distance Between Farms km	Onshore Network Strength	Water Depth m	Machine Size MW
Wind	Long >100	Medium 30-80	2000	Medium 50-100	Strong	25-50	Medium 5

This case is representative of the current Round 3 view with the potential development of the Dogger Bank and Norfolk zones. This development will be relevant within the short to medium term. This case and case 7.3 below are graded capacities intended to give an overview of the effect of increasing capacity and the subsequent requirement for multiple string collection points and export circuits. These options when compared will provide a general view of the effect of the key variables of capacity, and machine size.

7.3. Very Large Windfarms

Technology	Offshore Connection Distance km	Onshore Connection Distance km	Farm Size MW	Distance Between Farms km	Onshore Network Strength	Water Depth m	Machine Size MW
Wind	Long >100	Long >80	5000	Long >100	Strong	25-50	Large 7.5

This case represents large scale concentrated development. As previously discussed a development on this scale would require multiple connections which could lead to it being considered for technical purposes as a number of smaller windfarms, however it may also be internally interconnected to provide redundancy and operational flexibility that will affect the connection design. Larger machine sizes may lead to higher inter-array voltages and less collector platforms than you would find in a smaller development. This development will not be relevant in the short term but may be in the medium and long term.

7.4. Small Marine Case

Technology	Offshore Connection Distance km	Onshore Connection Distance km	Farm Size MW	Distance Between Farms km	OnshoreNetwork Strength	Water Depth m	Machine Size MW
Tidal / Wave	Short <30	Short <30	20	Short 10-50	Weak	<40	0.5 -1

This case is relevant in the short term and represents both tidal and wave facilities.

Tidal facilities up to 20 MW nameplate capacity deployed in the shallower parts of the Pentland Firth or in the Bristol Channel, Pembrokeshire area. In some locations, because of the highly localised nature of the resource, some facilities could be located very close together, less than 10km. In other locations, however, they may be farther apart. These farms will consist of arrays of devices between 0.5MW and 1MW nameplate capacity, for the purposes of analysis we will assume 1 MW. The onshore grid could be strong if locating in the Bristol Channel/South Wales area, or weak if in the Pentland Firth, for the purposes of analysis we will assume weak.

Wave farms of up to 20 MW nameplate capacity located around Orkney, Shetland and close to shore off the Western Isles. Devices will be sized from 100kW to 1MW nameplate capacity (assume 0.5 MW for analysis). The facilities will be connected in an area of weak onshore grid.

This case is the most likely short term case for marine and is included as such for analysis, it is unlikely that opportunities will be identified specifically for this scenario that have significant potential benefit to justify investment. It may occur however that there are commonalities between this case and the more significant medium and long term cases, this could justify investment at an early stage that would benefit the short term small capacity developments but then continue to give benefits to the larger developments that will come in the future.

7.5. Medium Wave Case

Technology	Offshore Connection Distance km	Onshore Connection Distance km	Farm Size MW	Distance Between Farms km	Onshore Network Strength	Water Depth m	Machine Size MW
Wave	Medium 30-100	Short <30	200	Short 10-50	Strong	>40	1

This scenario is relevant in the medium term and represents several large wave farms located around 50 km offshore to the west of the Western Isles. Individual devices would be 1MW in nameplate capacity and facilities separated by a medium distance, up to 50 km apart. The network is assumed to be strong by the time of development given the medium or long term.

7.6. Large Tidal Case

Technology	Offshore Connection Distance km	Onshore Connection Distance km	Farm Size MW	Distance Between Farms km	Onshore Network Strength	Water Depth m	Machine Size MW
Tidal	Medium 30-100	Medium 30-80	500	Short 10<50	Strong	>40	1

This case is relevant in the long term and assumes that given the highly localised nature of the tidal resource that large scale developments take advantage of the concentrated high potential resource of, for example Pentland Firth, as opposed to a number of smaller developments. Further this option is large enough to allow comparison with the small windfarm case.

7.7. Combined Tidal and Wind Case

Technology	Offshore Connection Distance km	Onshore Connection Distance km	Farm Size MW	Distance Between Farms km	Onshore Network Strength	Water Depth m	Machine Size MW
Tidal & Wind	Medium 30-100	Medium 30-80	500 Wind 500 Tidal	Short 10<50	Weak	>40	3.6 Wind 1 Tidal

This case represents the potential for wind and tidal to be constructed in close proximity and share connections possibly in the Irish Sea between Northern Ireland and Scotland. The potential locations for this to occur are few compared to single technology locations and as such we consider it reasonable to use the previously defined small wind, and large tidal, cases for the investigation of this case. This will allow the re-use of models and save considerable time on a case with limited potential for impact on the final outcome of the project.

7.8. Specific Development Cases Summary

The seven selected development cases have been chosen to provide a representative sample of development types that cover likely scenarios in a manner that will facilitate productive cross comparison.

Three wind cases have been defined split into small, large, and very large compared to only two each (one dedicated, one shared) for wave and tidal (split into small and medium, and small and large respectively). Further, a combined wind and tidal case has been developed by combining the cases outlined in Sections 7.1 and 7.6. Wind generation has been given priority due to the current and expected dominance of wind generation over the other marine technologies up to 2050.

We recommend that these specific cases are taken forward for detailed analysis in the subsequent tasks.

The number of cases has been limited to seven as we feel that studying more than this number would make detailed analysis difficult to achieve in the defined timeframe. However, it may be necessary to analyse variations on the defined cases to a limited degree which will become apparent and be decided upon at the relevant point in the project.

Appendix A Output Characteristics

This section provides details of the characteristics of wind, wave and tidal generation power outputs and some commentary on its impact on the onshore grid system. The underlying principals and statistical comparisons will be used further in subsequent activities within the project to assist in the understanding renewable developments on the onshore grid and the effect technology type may have on the connection design. At this point in the project we have included the characteristics for information only.

A.1 Wind

Development of a Composite Wind Generation Power Output Series

SKM has previously developed a composite wind generation power output series for wind generation across Great Britain that provides a useful means of characterising wind generation power outputs. Details of the approach adopted and of the resulting wind characteristic and statistical quantification are now outlined.

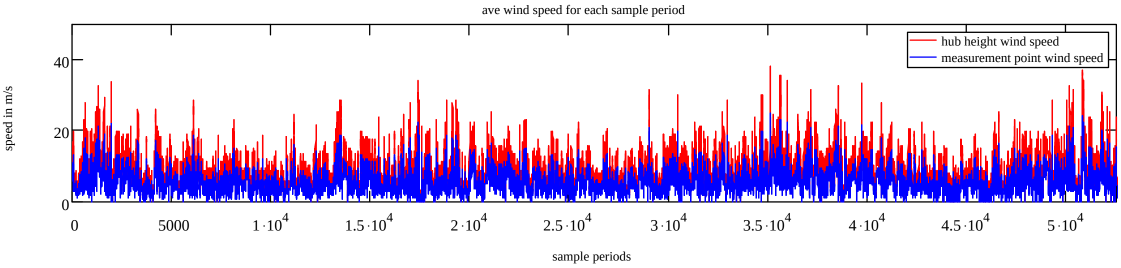
Methodology

In order to determine an overall GB wind generation power output series for a given installed capacity of wind generation, it was first necessary to break Scotland, England and Wales down into a number of zones representative of the varying climatic conditions experienced across the country. A composite wind resource for each of the zones was then established based on information evaluated from the most representative Meteorological Measurement Stations (Met. Stations) within each zone. Depending on geographical size of each zone and the number of currently operational wind farms, a different number of Met. Stations were used in developing each overall zone wind profile, each zone was essentially split into a number of sub-groups. The wind resource data for Met. Stations in each zone have been obtained from the National Climatic Data Centre (NCDC) database. This data is recorded once every hour at 10 meters above ground level (AGL).

For each of the zones a data file containing half hourly wind speed data has been established based on the measured meteorological data. The Met. Station data contained hourly data from 2003 to 2005. This hourly data set has been converted to half hourly values by interpolation, ensuring that the Weibull wind speed distribution characteristics remained unchanged. The data, which was measured at the World Meteorological Organisation (WMO) standard 10m Above Ground Level (AGL) measurement height, has been extrapolated to hub height of the generic turbines using the mean wind speeds at hub height from the UK Numerical Objective Analysis of Boundary Layer (NOABL) database. A standard hub height of 80m AGL is used.

A 3-year wind speed trace for one group in one zone is shown in Figure 10. Wind speed traces have been established for each of the wind farm groups within each zone. The wind speed recorded at 10m AGL has been extrapolated to hub height using the relation with the mean wind speed at 80m AGL from the NOABL database.

- **Figure 10: Sample of Wind Speed Trace**

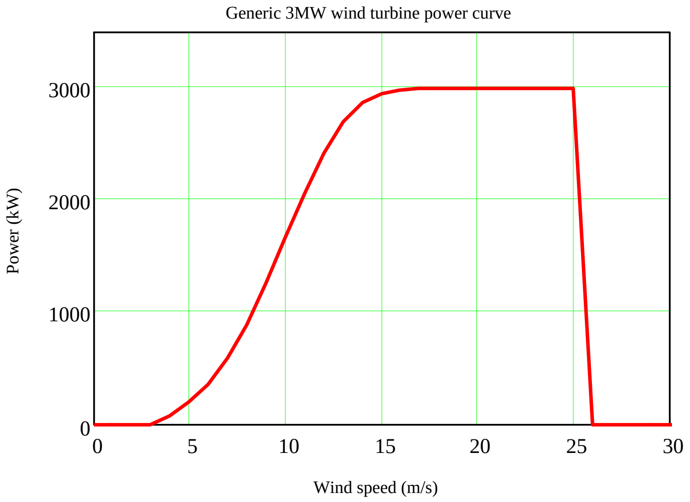


The half hourly output of each zone is a function of the following variables:

- The characteristics (power curve) of the turbines installed at each of the wind farms – see Figure 11.
- The efficiency of the wind farms, including wake effects, electrical losses, power curve degradation, availability etc.
- The manner in which the wind farms are operated, including maintenance efficiency.
- Local wind resource, as seen by these wind farms.

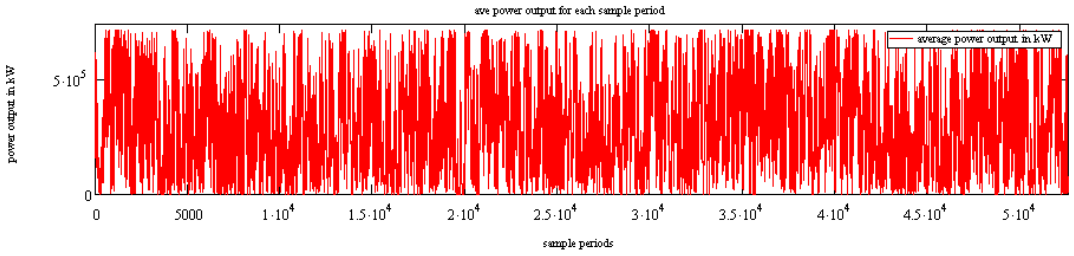
In developing the wind power output profiles for each zone a generic 3 MW wind turbine was adopted, with the typical power curve shown in Figure 11, and a generic wind power station efficiency of 85.3% was assumed. This efficiency value is due to effects which lower the overall efficiency of a wind farm or group or turbines, and includes: wake effects; electrical losses (including switchyard & substation efficiencies); power curve degradation; and losses due to unavailability of wind turbines through maintenance.

- **Figure 11: Generic 3 MW Wind Turbine Power Curve**



Using the group output profiles developed, an overall synthesised wind power output profile was developed for each zone. The half hourly power output data for Zone 1, based on the six groups, is shown in Figure 12.

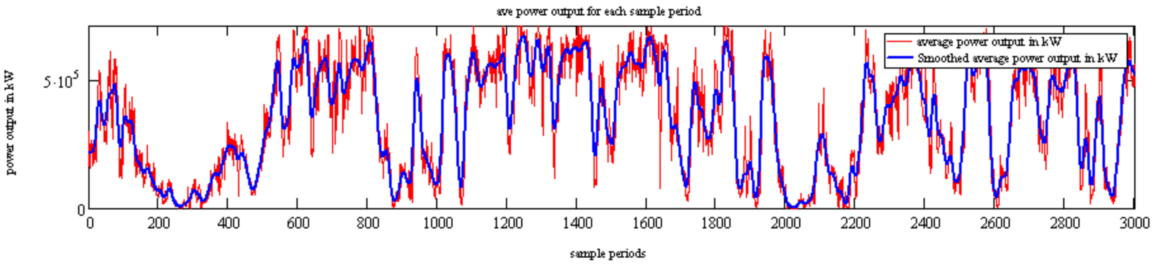
- **Figure 12: Sample of Wind Power Output Profile for One Zone**



It is important to note that each of the individual group power output profiles have been created from a single Met. Station which have then been combined to create the overall zone profile. While multiple groups have been adopted for many zones and introduced some diversity and smoothing to the overall power output profile, the resultant profile is still not as smooth as one would expect if the actual outputs from dozens of individual wind farms were summated. To this end we have smoothed the power output profile for each zone by applying a low pass filter, adjusted for each zone based on the existing and likely future geographical spread of wind farms.

Figure 13 shows the original wind power output profile for one zone and the version with the smoothed power output profile.

- **Figure 13: Example of Smoothed Wind Power Output for One Zone**

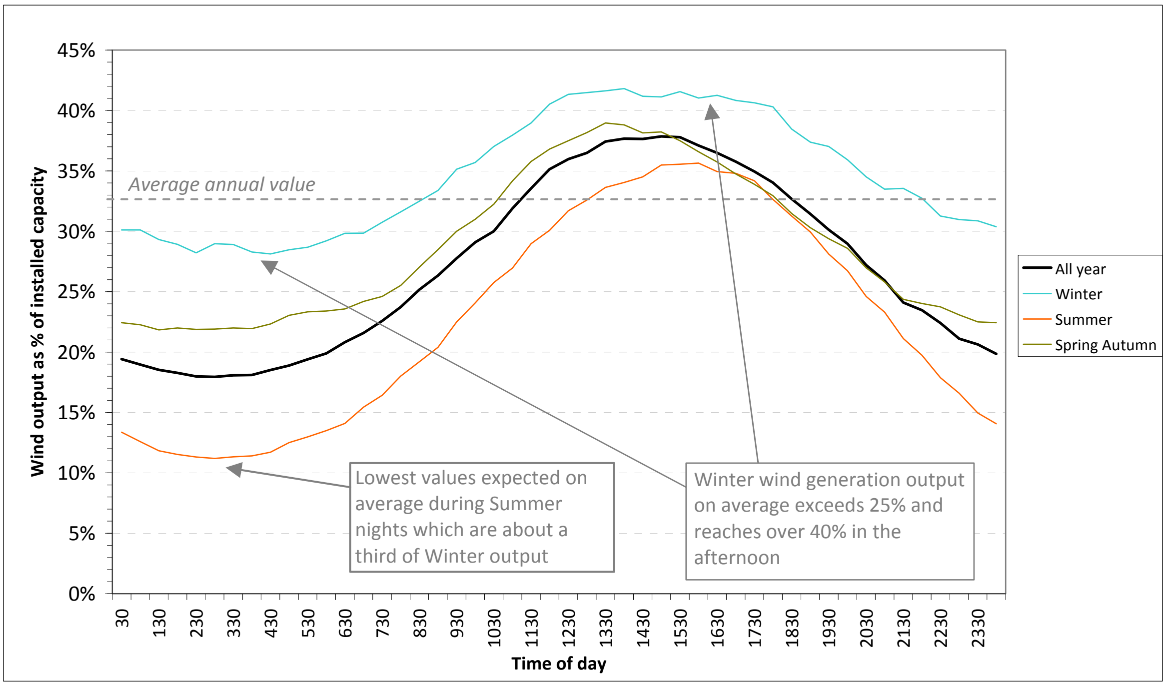


The smoothed power output profiles for each zone were then summated to develop the overall wind power output profile for the period 2003 to 2005.

Time of Day Distributions

The following chart (Figure 14) shows the diurnal distribution for the median wind generation output on an annual and seasonal basis for 3.1 GW of installed wind capacity in Scotland.

- **Figure 14: Wind Generation Output Diurnal Distributions (Scotland)**



Lowest values expected on average during Summer nights which are about a third of Winter output

Winter wind generation output on average exceeds 25% and reaches over 40% in the afternoon

The following is concluded from the above:

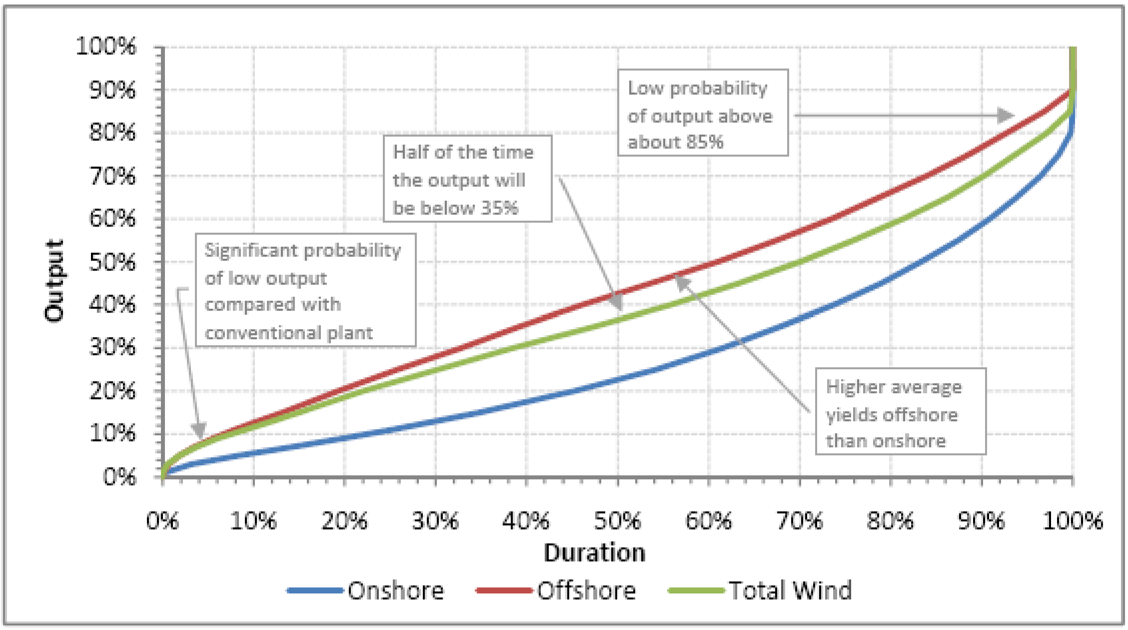
- Wind generation output shows a marked diurnal distribution pattern with output levels in all seasons during the day more than doubling the levels during the night.

- Peak wind generation output levels are generally higher between about 1 pm and 5 pm across all seasons. Average wind generation peak summer output reaches just over 35% whereas in winter it reaches over 40%.
- Lowest average values are found during summer nights, between about 1 am and 5 am an average output of less than 15% can be expected. By comparison the wind output in winter would be about double.
- The daily rise and fall in wind generation output very broadly follows the daily rise and fall in demand although the average daily variability of demand is larger than that of wind generation output.

Annual Wind Output

Figure 15 illustrates annual wind power output duration curves for onshore and offshore wind as obtained from the synthesized GB power output series. It is evident that average yields from offshore wind outputs are considerably higher than onshore.

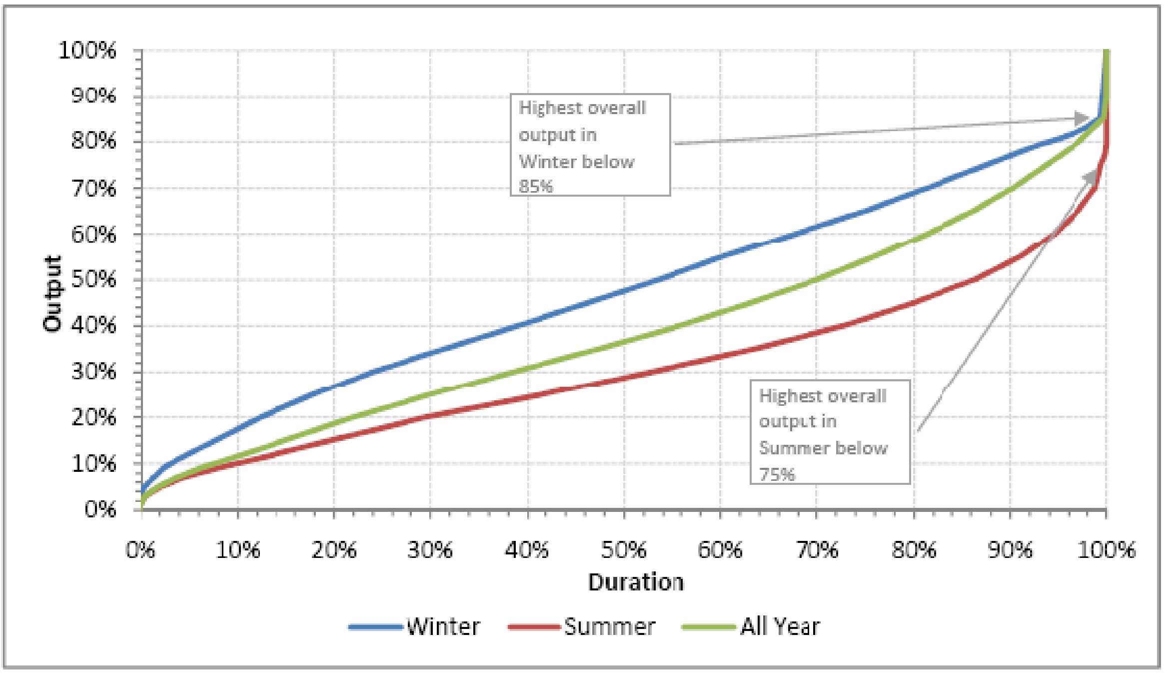
- **Figure 15: Annual Wind Power Output Duration Curve**



Seasonal Wind Characteristics

Wind farm output in GB shows marked seasonal and daily characteristics. Figure 16 shows the statistical seasonal distributions extracted from the wind power output record discussed above.

- **Figure 16: Seasonal Wind Output Distribution**



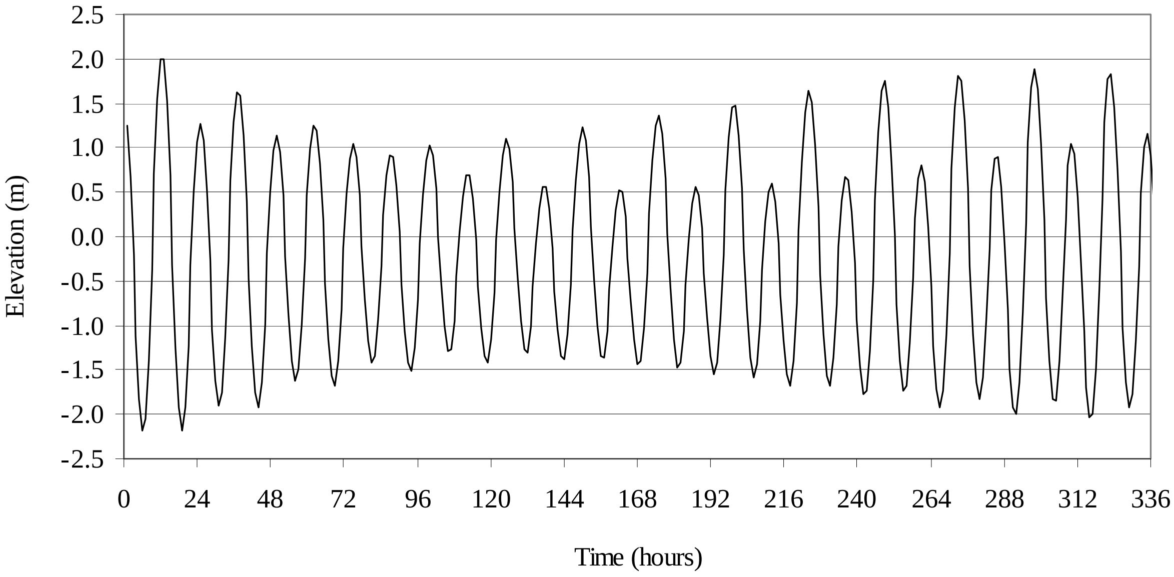
The seasonal distribution shown in Figure 16 also shows that the seasonal effects of diversity in the probability of high wind output. It indicates negligible probability of outputs higher than 85% in winter and 75% in summer.

A.2 Tidal

Time Variation of Tidal Elevation, Velocity and the Power Output of Tidal-Current Devices

The predictions of tidal *elevations* are made by summing sinusoidal waves with different frequencies, amplitudes and phases. These amplitudes and phases are called tidal constituents or harmonic constants. Figure 17 below shows an example of a prediction over a period of 14 days made using 18 tidal constituents/harmonic constants.

- **Figure 17: Typical Tidal Variation over 14 Days, Calculated Using 18 Harmonics**

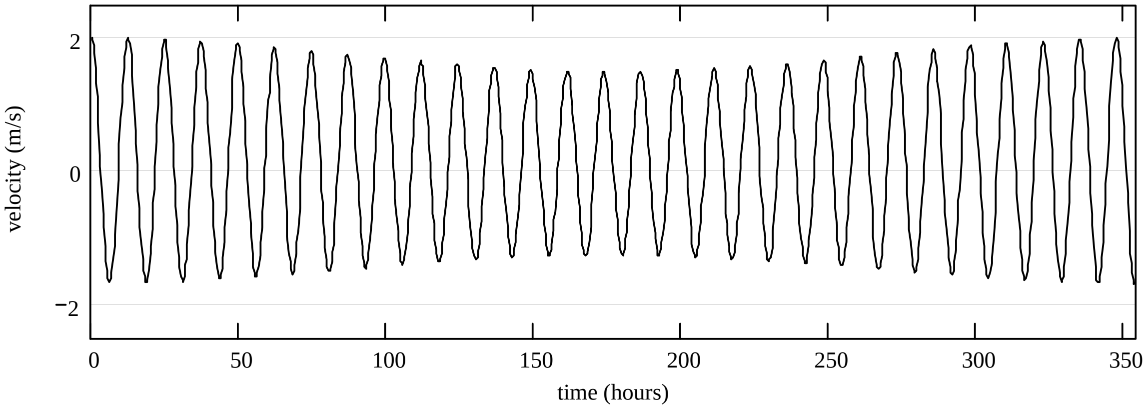


Tidal *current velocities* can also be predicted using the same harmonic analysis method as for tidal elevation. This requires an extended time-series of current-velocity measurements, both magnitude and direction, for the specific location in question. However, no extensive set of such measurements is available, and studies of the tidal-current energy resource in the UK have used a simpler approach, expressing the velocity is a product of cosine functions fitted to the mean peak spring and neap velocities from Admiralty charts. This is equivalent to the use of only two harmonics. If a bi-sinusoidal function is plotted for an extended period of time, the spring-neap pattern exactly repeats itself, whereas in actual tides different spring-neap cycles often differ from one another.

As with wind turbines, the power input to a tidal turbine is proportional to the cube of the water velocity, and the power output is roughly proportional to the power input above a cut-in velocity and below the rated velocity. Above the rated velocity it is held constant by the devices control system to avoid damage to the generator and gearbox.

The velocity of a tidal current varies between zero and a peak value roughly every 6.2 hours, and the peak velocity in an individual tide varies between a maximum when the tide is a spring one and a minimum when it is a neap. Figure 18 below shows the variation in current velocity over a full spring-neap-spring cycle of 354 hours at a site whose velocity profile follows a bi-sinusoidal function with a peak spring velocity of 2 m/s and a peak neap velocity of 1.5 m/s.

- **Figure 18: Velocity over 354 Hours**



The optimum choice of rated capacity is a complex economic trade-off between the capital cost savings achieved and the value of the electricity lost over the lifetime of the plant.

The blue curve in Figure 19 shows an idealised power output profile over the first 24 hours of the velocity profile depicted in Figure 18 above. This is the power output that would be obtained if the rated velocity of the device were greater than or equal to the maximum velocity encountered, although this would not be done in practice. The red curve shows the power output for a device with the same capture area but a rated velocity of 1.5 m/s (i.e. 75% of the maximum velocity).

- **Figure 19: Idealised Tidal-Current Power Output Profile for 25 Hours**

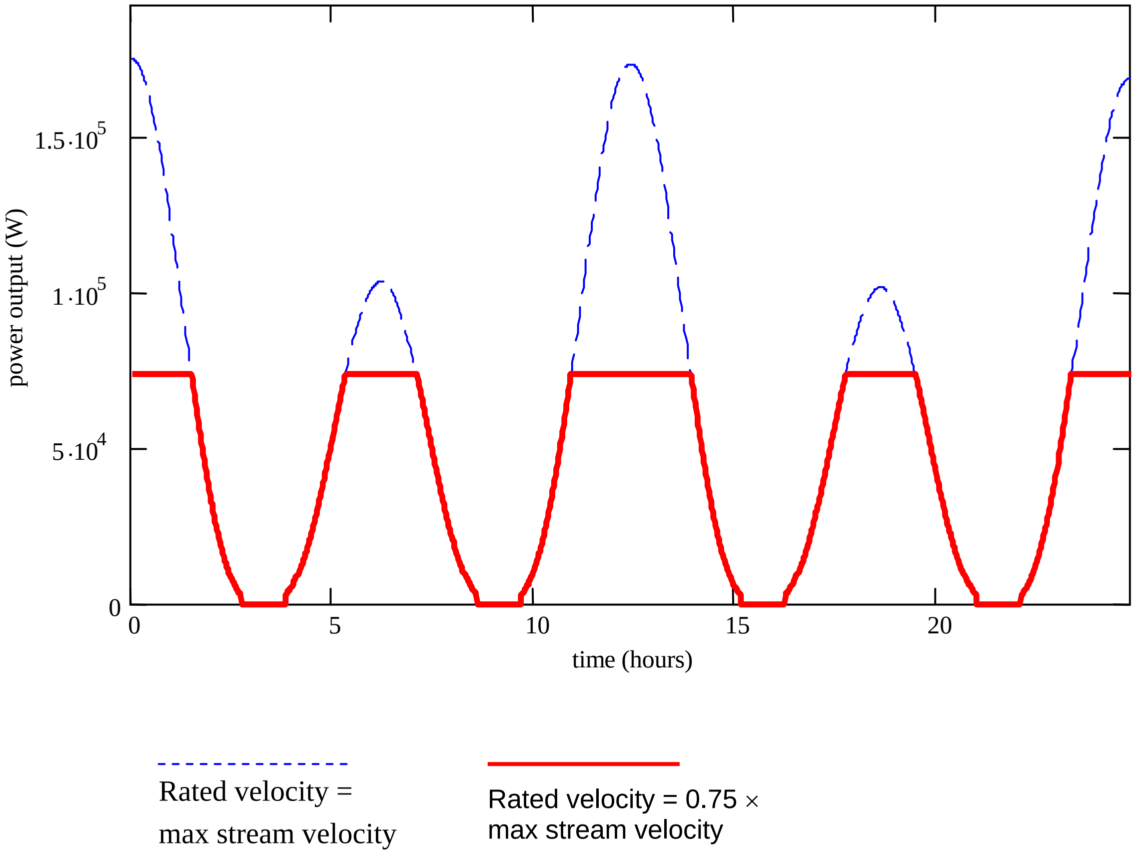
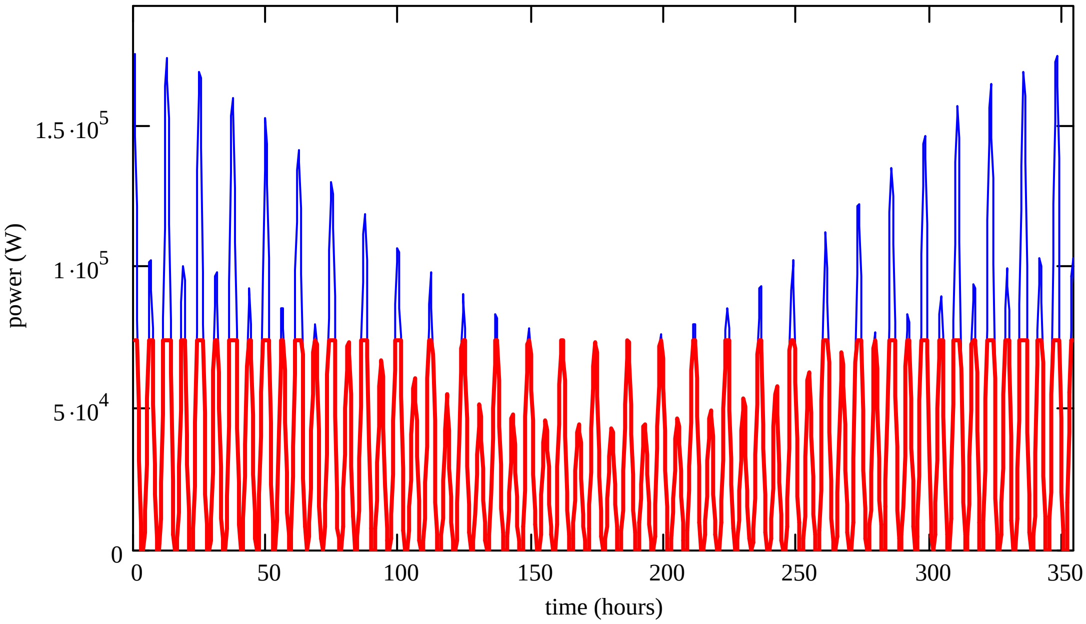


Figure 20 below shows the same curve as in Figure 19 but plotted over the entire spring-neap-spring cycle. The blue and red curves have the same meaning as in Figure 19. If the device had a rated capacity greater than or equal to the maximum shown in Figure 20, and consequently produced the power output profile shown by the blue curve, then it would have a power factor of 23.6%. If it had a rated velocity equal to 0.75 times the maximum, then it would produce the power output profile shown by the red curve and would have a power factor of 46.4%.

- **Figure 20: Idealised Tidal-Current Power Output Profile Over Entire Period of Figure 18**

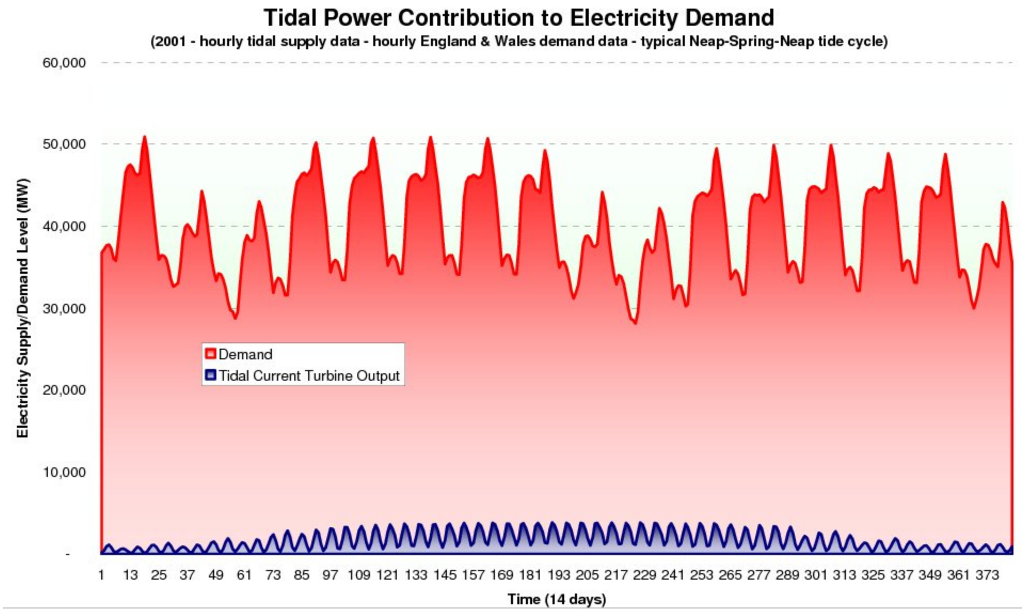


Identical devices, with the same rated capacity but installed at different sites with different velocity profiles, would achieve different power factors. The most economically advantageous combination of capture-surface size (rotor diameter, for horizontal axis turbines) and generator size (rated capacity) will differ from one site to another.

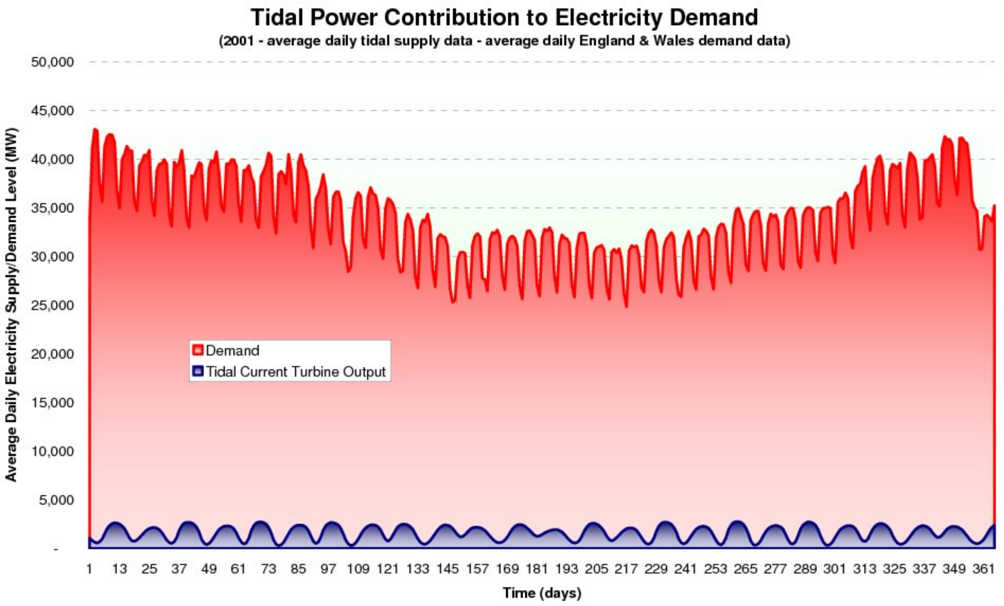
The above time variation does not correlate with energy demand, as the period of tidal output is different from that of electricity demand. Consequently, sometimes a tidal output peak will coincide with a demand peak, at other times with a demand trough and most of the time somewhere in between.

Figure 21 and Figure 22 below show a comparison between the output of a tidal device array and electricity demand, over two different timescales.

- **Figure 21: 14 Days Tidal Power Output**[36]



- **Figure 22: Tidal power output and electricity demand over a 1 year timescale**



The peaks and troughs in tidal elevations and currents do not occur simultaneously across the British Isles, and to a certain extent the output from widely separated tidal current facilities, such as, say, one in the Pentland Firth and one in the Bristol Channel, could achieve a degree of smoothing if combined together.

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[36] "Variability of UK Marine Energy resources", University of Oxford Environmental Change Unit for the Carbon Trust, 2005

A.3 Wave

Variability of the Wave Resource

Ocean waves are an essentially random phenomenon and are usually treated using statistical techniques.

Waves exert a force on a wave energy collector that oscillates with a period of between 1 and 10 seconds. However, the power take off mechanisms of many devices, especially those with hydraulic systems, smooth this out, so that when the wave power density is constant, the power output will be constant. Even where the individual device’s power take off is not able to do this, the outputs of the individual devices in an array will be uncorrelated on a second by second timescale and the combined output of the array will be smooth.

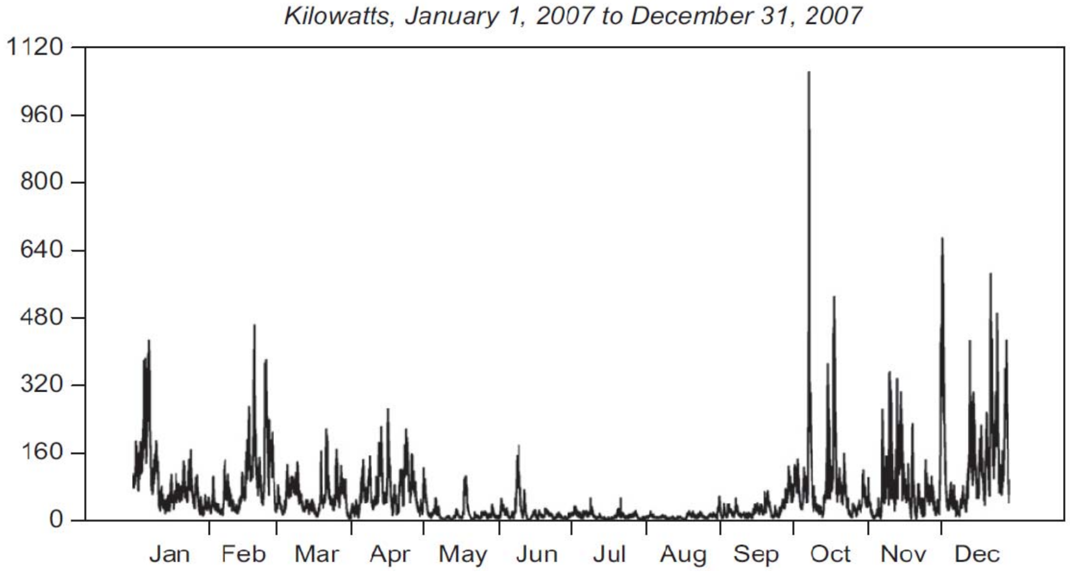
The average period and height of the waves at a particular point vary quite slowly so that over the course of, say, twenty minutes to half an hour, the power density is roughly constant. Over longer periods these parameters can vary quite widely.

Wave power density is proportional to the 5th power of wind speed, which means that a small change in wind speed will result in a large change in power density. On a timescale of several days, the output of a wave energy facility can exhibit large peaks and troughs corresponding to storms and the quiet periods between them. On this timescale, the output is essentially random.

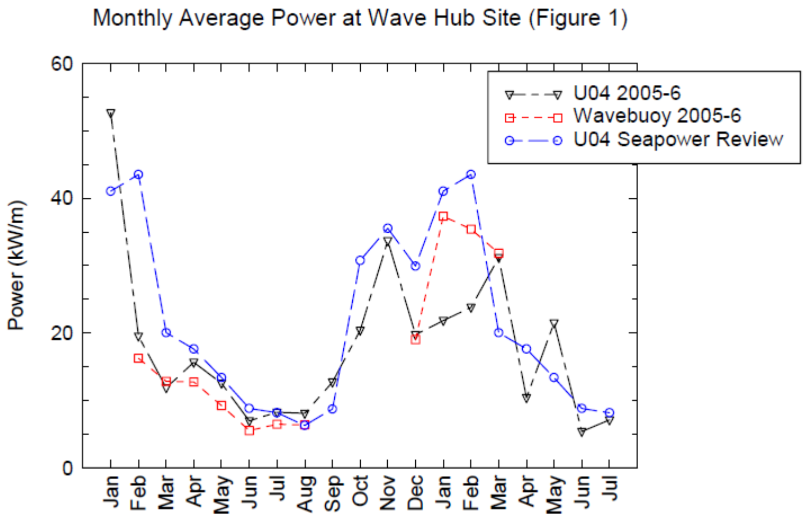
On a timescale of months to a year, wave energy output follows a seasonal pattern, with high power in the winter, low power in the summer and gradual change from one to the other during autumn and spring.

Figure 23 below shows the time variation of wave power density over the course of 2007 at a site on the West Coast of the USA. Figure 24 shows the wave power densities at SWRDA’s Wave Hub site off North Cornwall.

- **Figure 23: Wave Power Density in kW / m at Aberdeen**[37]**.**



- **Figure 24: Energy Density by Month at the Wave Hub Site**[38]



These graphs clearly bring out the random, peaky and seasonal nature of wave energy density.

Depending on the level of data available for a given site and device, the device output can be calculated using either a simple capture width or capture efficiency, which essentially regards

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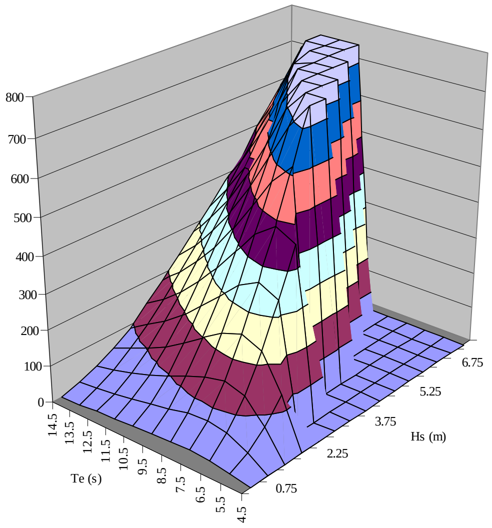
[37] G Reikard, Ocean Engineering 36 (2009) 348–356.

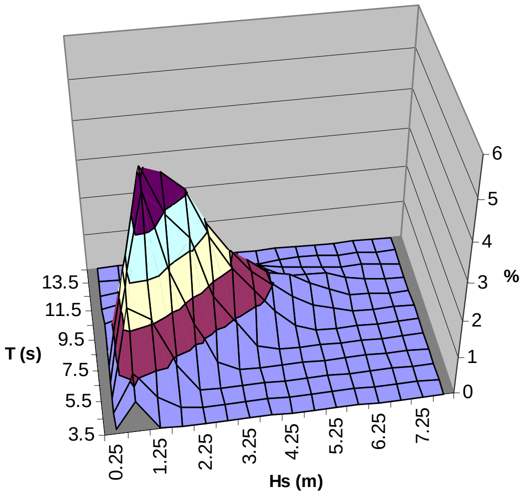
[38] Applied Wave Research, The wave power climate at the Wave Hub site, 7 November 2006, downloaded from http.//www.wavehub.co.uk/, accessed 31 July 2009.

output as proportional to input, or else the method of scatter diagram and power matrix can be used. These are illustrated graphically in the two figures below.

- **Figure 26: Wave Power Density as a Function of Wave Height and Period**



- **Figure 25: Device Power Output as a Function of Wave Height and Period**



The annual energy output of a facility can be estimated by multiplying the power matrix by the scatter diagram.

A.4 Correlation Between Wind and Wave Output

Figure 27 below is Figure 3.7b from the report "Matching Renewable Electricity Generation With Demand", produced by the University of Edinburgh for the Scottish Executive in 2006. It shows wave and wind power density at 59.06°N, 8.42°W, a site 120 km north-west of Lewis during February 2002. There is a clear correlation between wind and wave output which is to be expected given that waves are in general due to wind. However there are points at which the outputs do not correlate, the example used in the report is the 23rd of February when the waves must be caused by more distant winds that do not affect the wind turbine.

- **Figure 27: Wind and Wave Output Comparison**