



## Carbon Trust Foreword to UK Wave Resource Study.

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This study has been commissioned by the Carbon Trust to increase our understanding of the potential for wave energy generation in the UK. The report follows an equivalent assessment of UK tidal resource and economics, which was published in 2011 and uses the same approach of understanding the 'total', 'technical' and 'practical' resource. The technical resource is that which could theoretically be extracted from a particular area (or, more correctly, frontage) with optimised versions of wave devices currently under development. This is a function of wave resource and the extraction characteristics of rows of wave devices<sup>i</sup>. The practical resource also takes into account spatial constraints such as fishing, shipping and environmental restrictions. How much of any of these resource totals is eventually extracted depends ultimately on how much we are prepared to pay for wave energy, and the industry's success in bringing the cost of energy down.

This study has, for the first time, predicted *where* wave energy project developers will site their arrays. For the nearshore resource, this is a matter of identifying coastland that has high resource combined with coastal characteristics that make the deployment of devices possible. Offshore devices, on the other hand, could be sited anywhere from a few hundred meters to hundreds of kilometres offshore. To understand where future offshore arrays will be sited we have created a spatial model that identifies the optimum locations around the UK coast. The locational model uses wave resource data and data on depth and distance from shore to estimate the future attractiveness of every site in UK waters to offshore wave project developers.

The output of the locational model, shown in Figure 3.11 and the Executive Summary, clearly suggests that the most attractive sites for offshore devices are tens of kilometres offshore, both in Cornwall and off the North and West Coasts of Scotland. The frontages identified from this locational model, which can be thought of as long farms of wave energy devices many km long and a few km deep, are then fed into the energy extraction model (taking into account the directional, frequency and magnitude characteristics of the waves at each frontage).

The extraction model estimates the useful energy that can be removed from these frontages using multiple rows of farms. The extraction and locational models for offshore devices apply for both attenuator and point absorber type wave devices (for nearshore devices 'terminator' type devices are modelled)<sup>ii</sup>. Each row of farms extracts a proportion of the energy in the frontage, leaving less energy for each subsequent row. The assessment suggests that up to 95 TWh/yr of wave energy could technically be extracted from offshore sites in UK waters. This assumes very deep farms that capture a large proportion of the energy in the frontage. In reality the depth of farms will be limited by cost, as each additional row will capture less energy.

Cost modelling is based on assumptions about the economics and engineering of wave energy devices, drawing on previous cost of energy work by the Carbon Trust. The cost-resource curves in Figures 4.3 and 4.4 show the energy that could be extracted each year at different costs relative to the baseline of the cheapest sites. The graphs suggest that between 40 and 50 TWh of the 95 TWh could be extracted each year if we accept a cost of energy of two to three times the very

cheapest sites. Practical constraints such as space for shipping lanes and the impact on fishing were taken into consideration in estimating the practical resource at 32 to 42 TWh per year.

Our best estimate of the energy that could practically and economically be extracted from UK waters is therefore between 32 and 42 TWh per year which equates to an installed capacity of roughly 10 to 13 GW.

We believe this work is a significant advance on previous national assessments, as for the first time it identifies the location of the relevant wave frontages that are likely to be exploited. The results could be improved by more detailed work on the constraints (particularly the mitigation of effects on fishing and the environment), by improved resource data, and by updating the assumptions on both extraction and cost (location signals) as we learn more about how arrays of real devices actually interact. It is also worth noting that *risk* is not included in the locational model: we believe that the first commercial farms will most likely be developed nearer to the shore than Figure 3.11 suggests. The potential for wave energy in the UK is very significant; we hope that this report provides a useful resource to the industry showing the scale of potential market in the UK, and also to inform future innovation and spatial planning.

(October 2012).

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<sup>i</sup> The underlying energy data is the most recent available from the *Atlas of UK Marine Renewable Energy Resources*, published originally by the DTI in 2004.

<sup>ii</sup> Our thanks to Pelamis Wave Power, Ocean Power Technology and Aquamarine Power for instructive discussion and input, as well as to academics from Edinburgh University, Queens University Belfast, Heriot Watt University, and INETI in Portugal.

## Carbon Trust

## UK wave energy resource



AMEC Environment & Infrastructure UK Limited

October 2012

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## Document Revisions

No.	Details	Date
1	Draft for client comment	13/1/2012
2	First issue	2/3/2012
3	Minor revision	12/3/2012
4	Reissue with refined energy model	28/5/2012

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**Proposal for**

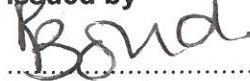
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Doc Reg No. B/C001/29603/003

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May 2012



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# Executive Summary

This study estimates the total wave energy resource in the UK. The majority of available energy arrives from the Atlantic to the west. Sheltering from Ireland reduces the wave energy resource in the Irish Sea and the energy levels in the North Sea are significantly lower than in the Atlantic. The total resource incident on our shores is around 230 TWh/y with the majority found in the deeper offshore parts of the UK's Exclusive Economic Zone.

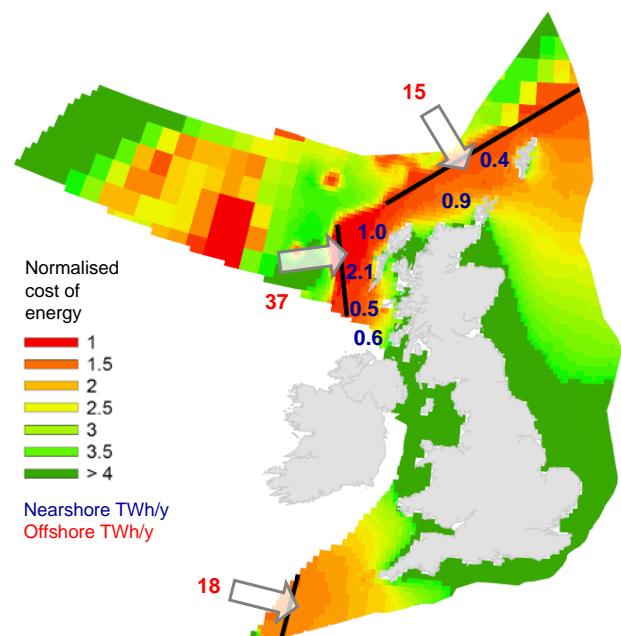
The offshore wave energy levels generally increase with westerly distance to shore. An analysis of the cost of energy at different locations in UK waters has shown that the least cost areas for offshore devices are found at the edge of the Rockall Trough to the west of Scotland and at the edge of the UK waters in the Southwest. These areas are around 100 kilometres from shore and in water a few hundred metres deep. Further offshore the resource increases marginally but the water gets considerably deeper, reaching several kilometres deep in places like the Rockall Trough and this greatly increases the cost of energy. The most attractive areas are shown in red on the map (see right). The available theoretical resource in these areas is around 146 TWh/y.

It is technically possible to extract a significant proportion of this energy at the attractive sites by using farms of wave energy devices. To do this many rows of long farms facing the Atlantic would be required. These might total around 1,000 km in length and average 180 km from shore. They need not necessarily be placed in a single continuous line. If all of these were built then around 95 TWh/y could be extracted from the offshore sites identified.

## Summary of resource estimates for offshore and nearshore wave energy farms

	Offshore		Nearshore	
	Annual energy [TWh/y]	Mean power [GW]	Annual energy [TWh/y]	Mean power [GW]
<b>Total</b>	230	26	230	26
<b>Theoretical</b>	146	18	133	15
<b>Technical</b>	95	11	10	1
<b>Practical</b>	70	8	5.7	0.6

## Offshore and nearshore practical resource distribution



The practical offshore resource (numbers in red) is spread along the frontages shown in black.

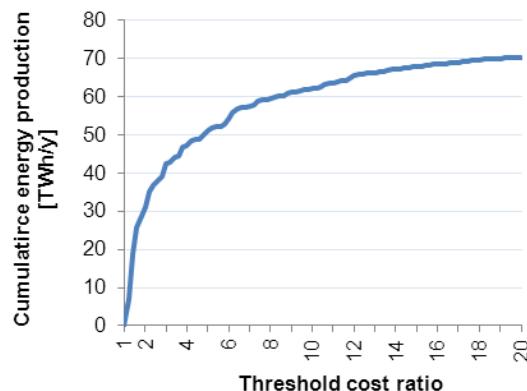
The offshore resource is sufficiently far offshore and dispersed that most of the fixed constraints, such as designated areas, can be avoided. The main constraints in these locations are shipping, fishing, cables and pipelines. In addition, large deployments of wave energy devices may cause environmental ‘barrier’ effects changing the behaviours of animals in the sea.

To mitigate these effects the farms would need to be positioned with space between them. This space can be used for more than one purpose—a shipping corridor might also mitigate the environmental barrier effect, for instance. Additionally, whilst in the theoretical case wave farms would be long and thin; in practice they could equally comprise blocks of farms without any great loss of energy. Accounting for these other sea users would leave around 70 TWh/y available for extraction.

The nearshore resource is also concentrated on the west coast. The total incident energy is similar to that for the offshore resource, but with some energy dissipated near to the shore. Unlike the offshore farms that can be positioned in a wide range of locations, nearshore systems are tied to particular conditions found near the coast. These seabed and technical conditions near the shore are highly variable meaning that the number of sites technically suitable for development is lower. This means that there is a much greater difference between the theoretical resource and the technical resource for nearshore systems than for offshore. The nearshore wave energy devices make an important contribution to the total practical resource of around 6 TWh/y.

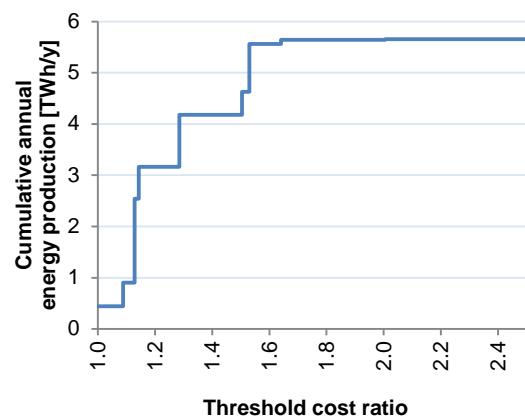
If new nearshore technologies can be found that increase performance then the technical nearshore resource would be proportionately higher. Likewise if new technology enabled the systems to be deployed in a wider range of conditions then the resource for nearshore systems could also be higher.

**Offshore practical resource cost curve**



All costs are normalised relative to the lowest cost part of the offshore resource

**Nearshore practical resource cost curve**



All costs are normalised relative to the lowest cost part of the nearshore resource

The resource can also be described by resource-cost curves that indicate the proportion of the resource available at or below a given cost of energy. The sensitivity of the resource available to the affordability of the power is shown by these curves. Around 42 TWh/y of offshore resource is available at or below three times the cost of energy at the cheapest location, and the nearshore is around 5.8 TWh/y.

## Acknowledgements

AMEC is grateful for the help received from Rosalind Hart, Ross Henderson and David Pizer at Pelamis Wave Power, and to Garth Bryans at Aquamarine Power for their help in defining suitable approaches to analysing the resource. We would also like to thank Denis Mollison, David MacKay, Jamie Taylor and Matt Folley for very useful discussions, help and input. In addition we would like to recognise the work by Jamie Moore and Michelle Moore at the Crown Estate using the MaRS system.

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## 1. Introduction

The United Kingdom with its long exposure to the Atlantic has some of the best wave resources found anywhere. This study considers the total resource available to the UK and the proportion that might usefully be captured. This study looks at the offshore wave energy resource and more briefly at the nearshore resource.

The area available offshore for exploitation is very large compared with the space needed to install wave energy devices and a simple cost of energy model can be used to identify least-cost locations. With preferred locations identified, energy estimates which include the impact of natural variations in wave energy due to sea state can be made together with a breakdown of energy availability at different cost-of-energy levels.

The nearshore resource is calculated differently using device-based analysis by Aquamarine<sup>1</sup>. This study considers a number of potential sites around the coast and uses finer-scale models to predict the wave conditions near the shore. From this, and using the power characteristics for the Oyster device, the energy output available at each coastline is calculated.

The overall wave energy resource is characterised in this study at four levels:

- **Total Resource (TWh/y):** The total resource arriving in UK waters. It is the total resource flowing over a single frontage (or group of frontages) that are arranged to give the highest overall energy availability to the UK. These frontages do not take into account potential location constraints such as water depth and distance to shore.
- **Theoretical Resource (TWh/y):** The maximum energy available from a set of frontages positioned in realistic locations based on areas likely to have the most competitive low cost of energy.
- **Technical Resource (TWh/y):** The energy available from the theoretical frontages using envisaged technology options.
- **Practical Resource (TWh/y):** The proportion of the technical resource that can be extracted taking into account locations constraints such as sea uses and environmental impacts.

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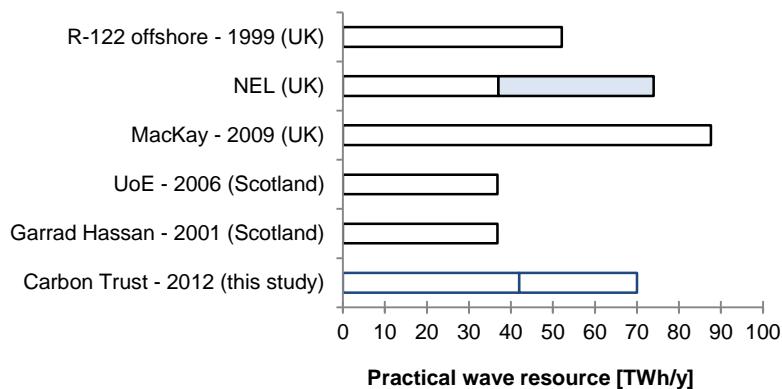
<sup>1</sup> The developer of the nearshore wave energy device called the Oyster.

## 2. Literature review

The UK wave energy resource has been estimated previously. Most estimates rely on a calculation of the wave energy flowing over a line around our coast. The total resource is most often defined as the total energy flowing across that line, whereas the accessible or practical resource is then the proportion of that energy that can be obtained using real technology and after taking into account competing sea uses. This is the same approach as taken in this study.

The estimates often depend on assumptions made by authors. These include the length of the resource frontage (see 3.2), the wave power levels in the sea, the extraction efficiency of the technology and the space available for exploitation. A summary of these estimates, their assumptions and references can be found in Table 2.1. The estimates of practical resource numbers are shown in Figure 2.1.

**Figure 2.1 Practical wave energy resource estimates for the UK and Scotland**



The R-122 figures include both nearshore and offshore. The grey bar represents a range of estimates. The bar for this study shows a mark at 42 TWh/y indicating the proportion of the resource available at or below three times the cheapest part (a cost threshold of 3).

**Table 2.1      Summary of previous wave energy resource estimates**

Source	Installed capacity [GW]	Mean power [GW]	Annual energy [TWh/y]	Level	Method
Wave power availability in the NE Atlantic, Mollison, Buneman, Salter					Provides a method and some mean power estimates for one location but does not provide an estimate of the total wave energy resource.
Scotland's renewable resource 2001, Garrad Hassan	14	4	37	Practical	Assumes 20MW per km <sup>2</sup> . The capacity factor for each location in the sea is based on a linear relationship between mean power level and capacity factor with 40% capacity factor at 55kW/m. The total resource is then estimated from a set of resource frontages. Two scenarios are used, seaward of the shipping lanes and facing the North Atlantic and landward of the shipping lanes facing the North Atlantic. Both give roughly the same result.
Matching Renewable Electricity, Generation With Demand 2006, University of Edinburgh	14	4	37	Practical	Estimates are based on the work by Garrad Hassan.
Future Marine Energy, 2006, Carbon Trust	19	6	50	Practical	As mentioned in Future Marine Energy.
Sustainable Energy - without the hot air, 2009, MacKay	33	10	88	Practical	This uses a resource frontage model. The total frontage is taken as 1000km based on access to the North Atlantic. The mean power, based on Mollison's work is 40kW/m. A reduction in frontage available for extraction is assumed to be 50% and the efficiency of extraction also 50%.
Wave climate and the wave power resource, 1986, Mollison	40	12	105	Practical	Based on a resource frontage model and assumed performance of various types of large (Salter Duck spines) marine energy devices.
Winter, A.J.B. (1980). The UK wave energy resource, Nature, Vol. 287, October 1980.	97	29	254	Technical	These assessments were for specific areas and gave no explicit indication of the general wave climate. Winter (1980) used two years of data from the Met Office depth-dependent wave-forecasting model to hindcast directional wave power climates around the western approaches to the UK from Land's End to Shetland and also in the Moray Firth. He found close agreement between the Met Office model and the IOS measurements made at South Uist.
	23	7	61	Practical	The overall average power level for all the lines considered was 29GW, of this he assumed that only 25% can be taken.
The development of wave power a techno-economic assessment, NEL	14 - 28	4 - 8	37 - 74	Practical	Uses a 1700 mile (2736km) contour 10 miles from the coast. After allowing for competing sea uses and restrictions and allowing clear ways through farms of devices the frontage remaining is 500-1000miles (805-1609km). Of this frontage an assumed 50% is exploited at an assumed 50% efficiency.
ETSU R-122 New and Renewable Energy: Prospects in the UK for the 21st Century: Supporting Analysis, 1999	228 - 266	68 - 80	600 - 700	Offshore technical	The offshore accessible resource is based on the Met. Office's wave prediction model at 15 locations around the west British Isles for the period from February 1983 to July 1986. The nearshore and shoreline wave energy resources were calculated using spectral analysis, refraction and energy dissipation models. 78 'hot spots' were identified and the effect of energy dissipation from sea bed friction was estimated for each using a ray model. The resource definitions cited differ from those in this report, the 'accessible' is quoted here as 'technical' and the 'practical' is quoted here as 'accessible'.
	38 - 53	11 - 16	100 - 140	Nearshore technical	
	19	6	50	Offshore practical	
	1	0	2	Nearshore practical	

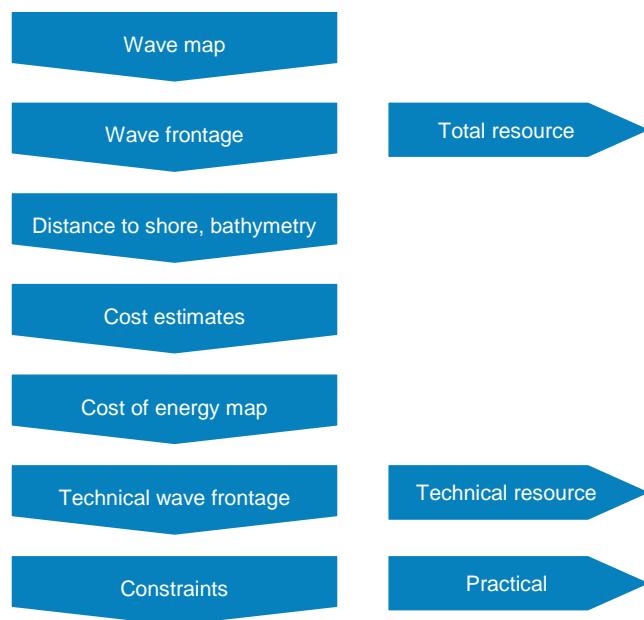
Shaded values are estimated from the estimates in each report using an assumed capacity factor of 30%. This is intended as a guide only.

## 3. Methodology

### 3.1 Overview

This study estimates the wave energy resource in the UK using three main steps. The overall energy flux hitting UK shores is calculated by defining a series of frontages facing the Atlantic over which it is considered that all the energy flows. Then a simple cost model is used to identify areas of relative low cost. These are used to define some more realistic frontages over which the useful part of the resource flows—one set of frontages for offshore technologies and another for nearshore. Finally other uses of the sea, marine resources and environmental constraints are taken into account.

**Figure 3.1 Overview of the wave energy resource assessment methodology**



This wave energy resource assessment combines a number of different sources of data. These include maps of wave power levels, water depth and distances to shore, various spatial constraints on sea use and a cost model. The cost model uses the spatial physical data, such as distance to shore and water depth to estimate the cost of a wave energy farm. The wave map is then used to estimate the likely energy output of the farm. These two results are used to calculate the levelised at every location. This then produces a map of the UK waters ranked roughly by its financial attractiveness. From this map the UK's technical resource is derived.

There are several different types of constraints that affect where wave energy farms can be sited. These include environmental constraints, shipping lanes and other competing sea uses. Each of these constraints is applied to the costed resource map and areas of high constraint are removed or adjusted. From this map the UK's accessible wave resource is derived.

### 3.2 Nature of the resource

#### Wave crest and capture width

As the wind blows over the sea, energy is transferred to the water and forms waves. The faster the wind blows and the greater distance over which it passes (the fetch), the larger the waves become and the more energy they contain. As waves approach shallow water they begin to interact with the sea bed and lose some of their energy. Once the waves have broken on the shore they have lost most of their energy.

Wave energy is concentrated near the surface of the sea and the energy is spread out horizontally roughly perpendicularly to the direction of travel of the waves at any moment in time. The average power in the waves is measured per unit width of wave front (kW/m). The line over which this energy flows is termed here as the *frontage*.

The amount of energy extracted by a device can be expressed as a distance known as the capture width. The capture width is defined as the equivalent length of wave crest containing all the energy extracted by the device. It is calculated as the ratio of the mean power extraction and the ambient wave energy level. A more complete explanation can be found in Appendix F. The capture width is not necessarily related to the physical width of the device.

The capture width of a device varies with the frequencies of the waves arriving at a device. This is because devices are deliberately tuned to absorb energy from only certain types of waves. To capture very long low frequency waves, for instance, devices would need to be very large, and the additional cost of making such a machine may well outweigh the benefit. In other cases the device is designed to shed power to ensure that it survives in very energetic seas.

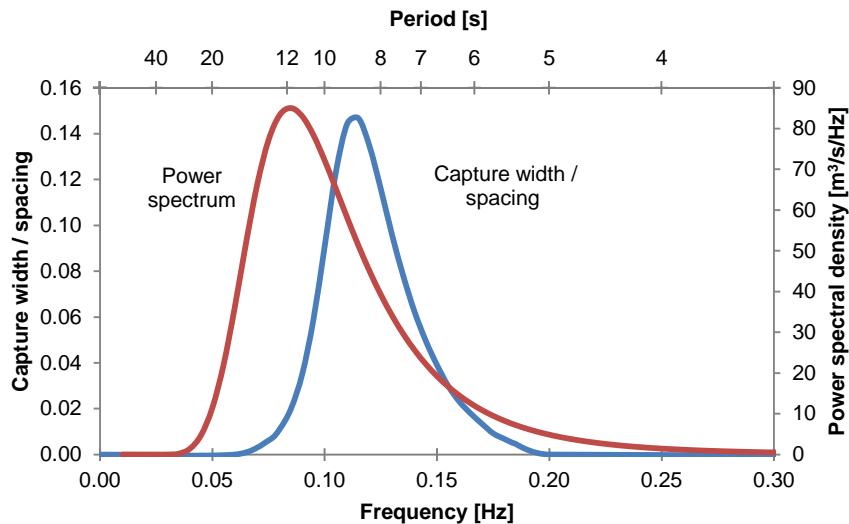
Figure 3.2 shows how the mean power in the sea is distributed over a range of wave frequencies (and equivalent periods). This is known as the power spectrum and peaks at about 0.8 Hz<sup>2</sup>. Also shown is the capture performance of a candidate device. This is shown as the dimensionless ratio of capture width and spacing. These show how this particular device aims to extract most power from the frequencies of about 0.06-0.2 Hz.

The capture performance shown represents an advanced device with the capability to produce power from the relatively large low-frequency waves. To do this the device would necessarily be physically larger and more massive than devices currently under development, but in most other respects it would be similar to current concepts.

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<sup>2</sup> Note that the power spectrum shown is the product of the energy spectrum and the group velocity.

**Figure 3.2 Absorption of energy in arrays at oblique angles to the incident waves**



**Figure 3.3 Changes to the power spectrum by multiple rows of devices**

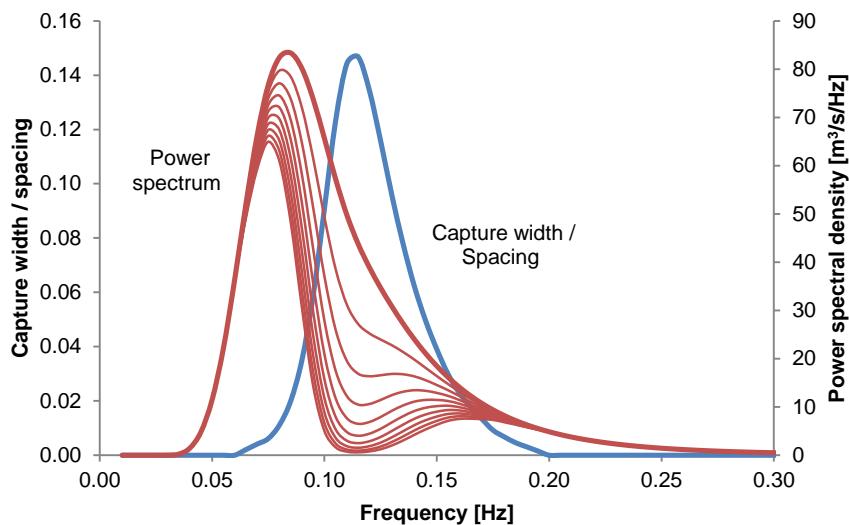


Figure 3.3 shows how several farms of devices combine to extract power from certain frequencies. It shows that most of the power in the frequency range of 0.1-0.15 Hz is extracted, whilst much of the power in the frequencies

0.03-0.06 Hz passes straight through unhindered. Some of these waves will continue to the shore where they may be available for capture by nearshore devices.

## Wave generation

The generation of waves of a certain height depends on the strength of the wind and the length of the fetch over which it blows. Holthuijsen provides a description of the growth of waves drawing on the following work (Holthuijsen 2007). Pierson and Moskowitz showed the final form of waves under long fetches by analysing waves in the Atlantic. This work provided a key description of those waves and also provided ‘universal constants’ that apply to any fully-developed deepwater waves. Such waves exist in the North Atlantic and many reach UK shores. However, in fetch-limited seas the waves do not develop fully. Sverdrup and Munk and Bretschneider analysed these fetch-limited conditions. Some empirical relationships between fetch and height and period were developed and combined by Young and Verhagen and modified by Breugen and Holthuijsen. From these it can be shown that a 1 m significant wave height with peak period of 4.6 s representing around 2 kW/m would take around 100 km of uninterrupted fetch to generate.

This means that in most practical cases, once all the energy is extracted from the waves in the UK Exclusive Economic Zone (EEZ) it cannot meaningfully be regenerated. Since this study investigates cases of very high levels of energy extraction from a single frontage, it is assumed that no significant regeneration between that frontage and the shore or other parts of the UK area of resource is possible.

## Directionality

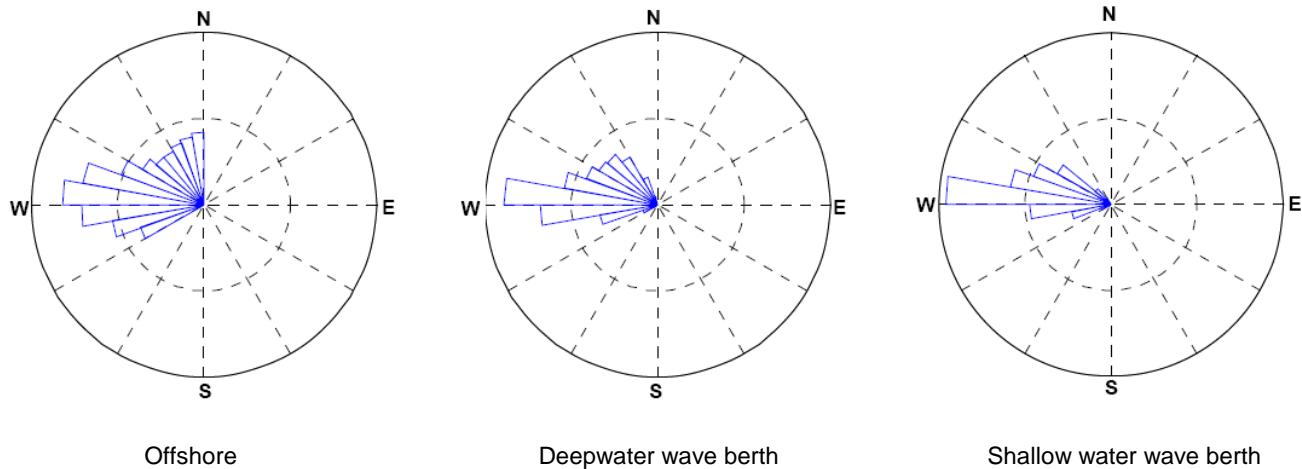
Wave energy comprises many different superimposed wave fields. These fields come from many different directions. For instance, a swell can arrive from one direction whilst a wind-driven sea can arrive from another direction at the same time. A given sea state contains both a mix of wave heights and periods and a mix of directions.

The many different wave energy device concepts under development have varying abilities to absorb energy from a range of directions and from different types of waves. Devices can also be directional or non-directional. For instance, a pure point absorber<sup>3</sup> device could theoretically extract energy equally well from waves from all directions. Other devices might try to increase their performance from narrower range of directions at the expense of the wider range. To compensate, they may instead be designed to turn to face (yaw) into the predominant wave direction.

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<sup>3</sup> Many of the terms in this section are explained in the Carbon Trust’s Marine Energy Glossary (Carbon Trust 2005).

**Figure 3.4 Observed wave directionality at different water depths and distances to shore at the European Marine Energy Centre**



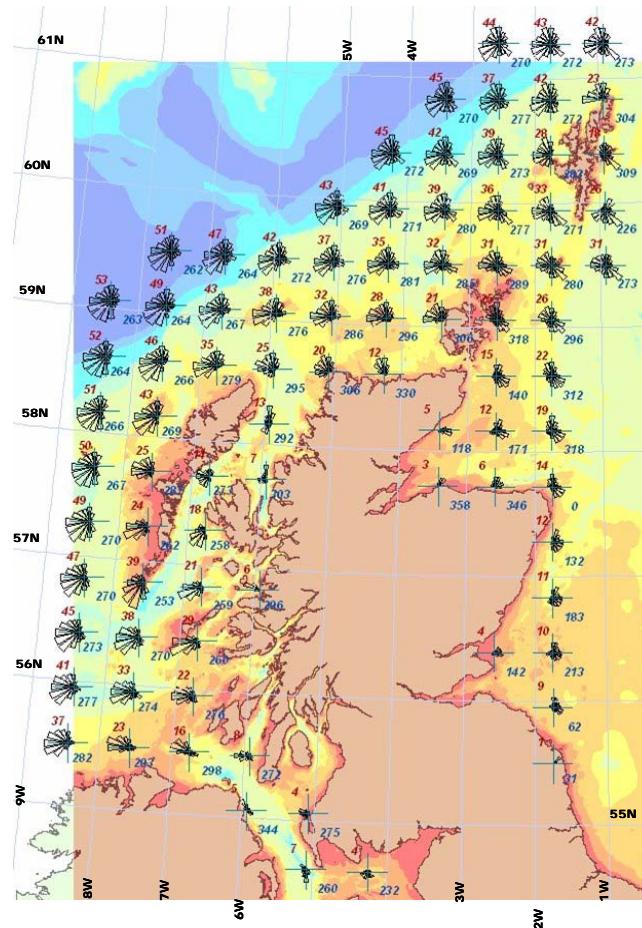
Reproduced with permission, Folley et al. 2009

As waves travel toward the shore their directional spread tends to narrow. This range is smallest near the shore where a large proportion of the energy arrives almost perpendicular to the coast. This is illustrated quite well by the observed wave resource at the European Marine Energy Centre in Orkney, Figure 3.4. This characteristic is seen in most of the energetic parts of the UK waters. In parts of the North Sea, which is on the whole far less energetic, there are often two dominant wave fields each coming from opposite directions.

All devices will have some ability to absorb energy from a range of angles, so that they can absorb some energy from sea states with an instantaneous mix of wave directions. The directional devices will also have some means of orienting themselves towards the predominant wave direction. The directional devices will perform best where the majority of the instantaneous energy is concentrated in a narrow range of directions. This energy will also lie within a band of wave frequencies the device can capture.

An illustration of the wave directionality around Scotland is shown in Figure 3.5. This shows the energy mainly comes from the west. Around the north coast less energy comes from the south due to the sheltering effect of the land itself. This means that waves nearer the shore are from a more northerly direction. Offshore they predominantly come from the west.

**Figure 3.5 Wave directionality around the Scottish coast**



Reproduced with permission, Taylor and Motion 2005

Where two wave fields arrive from two different directions at the same time, they may contain two lots of energy each at different wave periods. For instance, some energy might be contained in long-period swell waves from one direction, whilst some might arrive from short-period wind waves from another. The ability of a wave energy device to capture some of each of these waves is not only dependent on its ability to absorb energy from different wave directions but also to its ability to tune itself to different wave periods simultaneously.

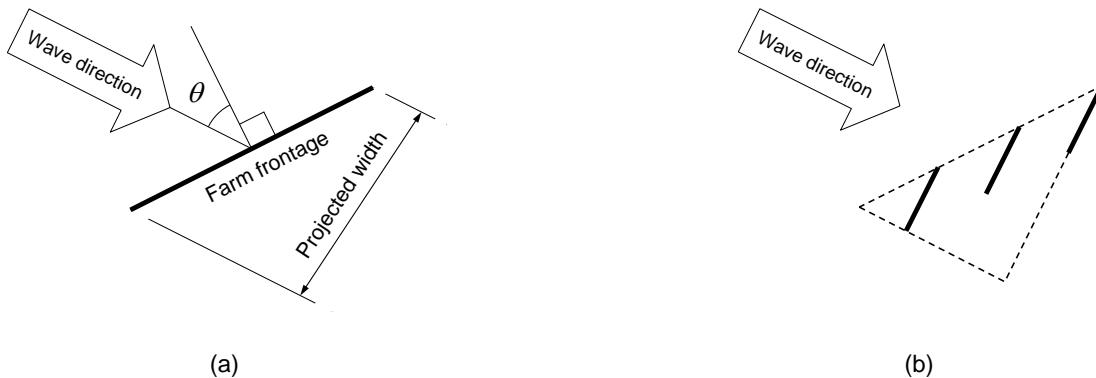
This study makes a distinction between the far-field long-frontage or farm-scale directionality effects and the in-farm near-field directionality effects. The in-farm effects are dominated by the ‘shadowing’ of one row of devices by another, whereas the total resource is dominated by the orientation of the frontage compared to the predominant wave energy direction.

The energy-weighted dominant wave direction has been calculated for several locations around the UK coast (see Appendix F). These directions are shown on several of the included offshore resource charts.

### Farm-scale effects

Wave farms are likely to comprise long rows of devices and whilst each individual device might be able to absorb energy well from a range of different directions the farm as a whole might not. Simplistically we might expect the energy across a line to be proportional to the cosine of the angle ( $\theta$ ) between the incident wave direction and the farm frontage, see Figure 3.6(a).

**Figure 3.6 Wave direction relative to a farm frontage**



The projected width of a farm is the length perpendicular to the predominant wave direction. This can also be considered as several perpendicular lines the total length of which is the same as the projected width of the farm. This is a highly simplified case that neither considers the true shape of the shadow behind the farm, nor the effect of the typical range of wave directions on the shadowing of the down wave farms.

Each frontage defined in this assessment is assigned a direction relative to the dominant wave direction in the region. This represents the case that the frontage cannot be arranged perpendicular to the predominant wave direction. An alternative description is shown in Figure 3.6b, where the farm frontage is broken into three sections, each arranged perpendicular to the incident wave direction.

Since waves come from a range of different directions the alternative arrangement might lead to greater shadowing of farms behind.

The assumed alignments relative to the predominant wave directions ( $\theta$ ) for each of the frontages considered in this analysis are listed in Table 4.2.

To account for the spread of directions in the sea we apply a spreading factor to some of the frontages. This spreading factor depends on the location in the sea. A derivation of the spreading factor can be found in Appendix F.

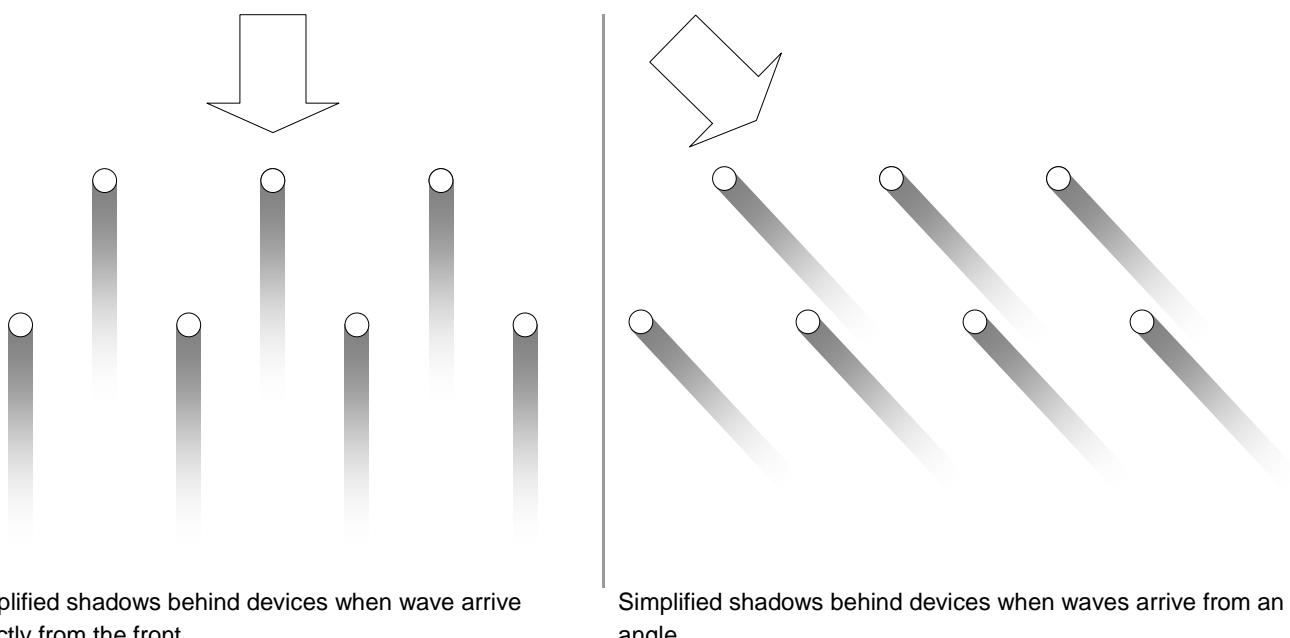
### In-farm effects

Each individual device will take some energy from the waves and leave a shadow behind. Assuming that devices have some ability to turn themselves towards the wave energy, as most do, these shadows will fall behind each individual device's frontage. In this case, the frontage is the capture width of the device, and not the physical width of the device.

Some good work is published that describes the shadowing affect for arrays. Some of these studies include Venugopal and Smith 2007, Beels et al. 2009, Troch et al.. These all depict the shape of shadows behind certain types of wave energy devices (mainly terminators<sup>4</sup>).

To illustrate the impact of direction on an array of devices we can consider a highly simplified case in which a shadow extends directly out behind the device as if a coherent beam. In this case, as the predominant wave direction changes the combined frontal area of the devices remains the same at most angles. Clearly there are angles where the rear row would be shadowed by the front row, but as a proportion of time this is likely to be relatively small.

**Figure 3.7 Illustrative model of wave farm shadowing**



Simplified shadows behind devices when wave arrive directly from the front

Simplified shadows behind devices when waves arrive from an angle

The diameters of the circles represent a device capture width that is constant in all directions.

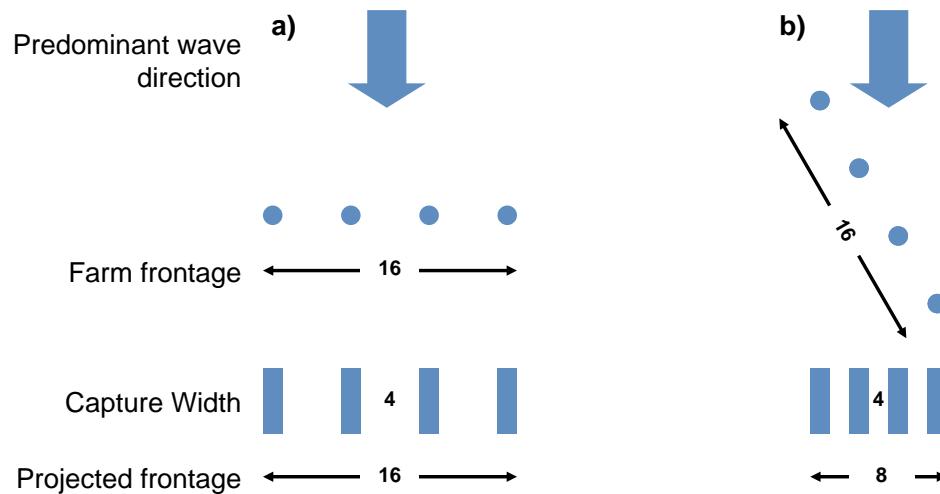
Whilst the projected frontage of the farm may reduce at oblique angles the energy absorption may not reduce quite as much. This is because when viewing a farm at an oblique angle the gaps between the devices appear narrower, whereas the total capture width of the devices appears the same. This means that the absorption of the incident wave at oblique angles is often higher than in direct waves. So, whilst the projected frontage reduces at oblique angles, the proportion captured increases. The extraction model used here takes this into account.

Figure 3.8 illustrates this effect. Two farms each of the same number of devices, spacing and length are laid out. One is positioned perpendicular to the predominant wave and the other at 60°. The projected frontage of the first farm is equal to its width, whereas for the second farm it is half. Each device is represented as a circle of diameter

<sup>4</sup> Terminators are devices that are generally long and thin and arranged perpendicular to predominant wave direction, see also Carbon Trust 2005.

equal to its capture width. If we calculate the total capture width of the farm, we find that in both cases they are the same. This illustration shows only one row of devices but a similar effect is seen on multiple devices. This effect is described mathematically in Appendix F.

**Figure 3.8 Absorption of energy in arrays at oblique angles to the incident waves**



This case also does not consider the diffraction or scattering of the energy around the devices which may diminish the strength of the shadows by allowing waves to curve into and then regenerate the shadow. Also devices that interfere with the waves will also cause shadows to be projected in front and to the sides of the devices, these are known as side-lobes in radio theory where they are often a nuisance.

Devices may interfere with each constructively or destructively too. It is also possible that device behaviours might be controlled such that otherwise individual devices work together to increase the overall performance of the farm (like a phased-array radio station), though there are significant engineering challenges in doing this.

When the devices are very close together and more numerous the impact of the shadowing will be much greater, since the shadows will more often impinge on devices behind.

The capture width used here is an approximated average condition. In some seas the capture width will be much greater leading to greater occlusions and in other seas the capture width would be less. For instance in very high seas when the device deliberately sheds power to minimise loads, the capture width would be smaller than average. The value of the capture width used in this study was derived from discussions with wave energy device developers.

The extraction model simplifies the directionality performance of individual devices by including it in average capture width of the device (see Section 3.4). Any inefficiencies in siting, such as due to occasional shadowing, are then spread evenly across all devices in the array. This assumption is necessary to ensure that the extraction model is realistic but not dependent on a particular wave energy device type.

It is to be expected that at very high numbers of rows of devices this approximation will break down. It may be that a combination of lower energy, greater occlusion and other siting efficiencies disproportionately affects the performance of rearward rows.

In nearshore regions where the spread of wave directions is much smaller there is less need for devices to be able to yaw to face the predominant waves (see Figure 3.4). The Aquamarine Oyster device, for instance does not yaw, and yet can still extract a significant proportion of the incoming energy in the shallow nearshore regions for which it is designed.

### Wave heights, periods and capacity factor

Each sea location will have energy distributed over a range of wave heights and periods. There is a range over which the long-term wave resource is distributed and there is another range appropriate to any given instant. This latter spread is termed here as the instantaneous ‘spectral bandwidth’. To account for this effect the performance characteristics of the device are dependent on incident wave frequency (see Appendix F).

Where the instantaneous bandwidth is wide, devices need to either have a wide natural hydrodynamic spectral response, or be able to tune very quickly to the new waves. The North Atlantic is likely to have a relatively wide bandwidth, compared to say the west coast of Africa. This means that devices need to be more sophisticated in the way that they are controlled and in their natural hydrodynamic performance for use in UK waters (Smith and Venugopal 2006, Smith *et al.* 2005).

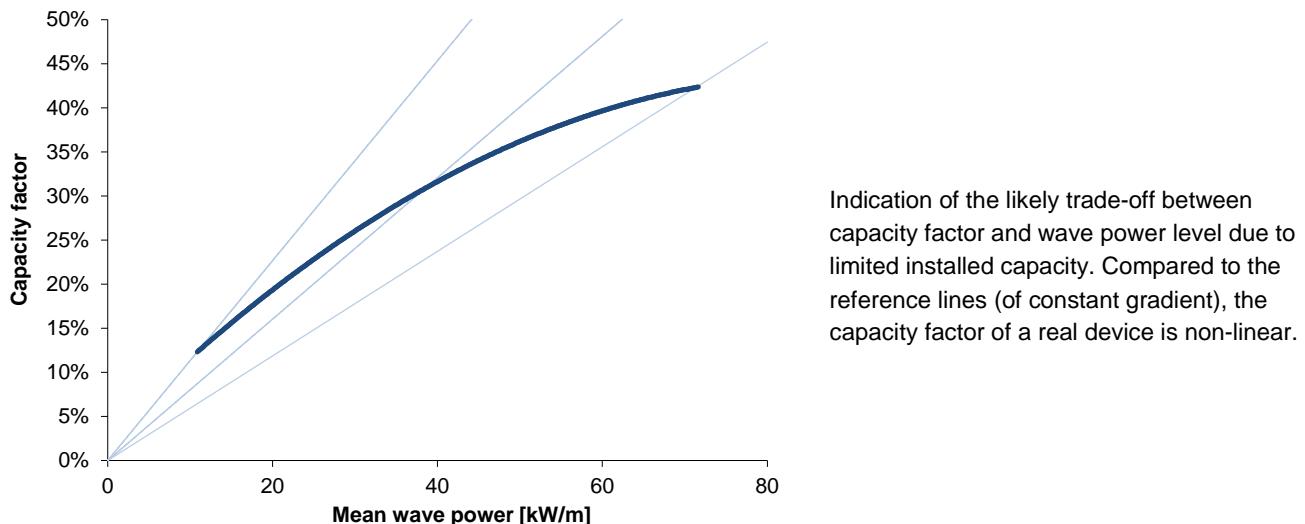
The rated capacity of a device will also limit its overall performance. Designing the rated capacity requires a techno-economic judgement on the appropriate size of generator for the expected range of sea conditions. This means, for instance, that the device may choose not to absorb all the energy in very large seas, but rather to let these waves pass. In so doing, the capital cost might be lowered at the expense of wave conditions that only occur rarely. A similar limitation might also arise from the survival mode of the device, where the device deliberately sheds power to avoid high, potentially destructive, loads on the device.

This means that a device designed for a moderate wave energy climate might have a relatively low installed capacity. If that same device was installed in higher wave energy seas then the capacity limitation would shed a greater proportion of the power. An illustration of this is shown in Figure 3.9. This illustrates for example that a device designed for a capacity factor of say 30% in moderate waves of 40 kW/m would have a significantly lower capacity factor in low seas, but in higher seas the gain in capacity factor would also not increase as much of the energy is shed.

A higher rating to improve the performance in higher seas would require changes such as a larger onboard electrical generator, or more extensive changes to the physical size of the device to accommodate the higher forces and larger motions. This means that in all likelihood wave devices will be designed for specific conditions so as to avoid power losses as far as possible<sup>5</sup>.

<sup>5</sup> Some wind turbine models are available in a range of sizes to suit different wind regimes. A low wind turbine might have a larger rotor for the same size generator than the high-wind equivalent, for instance.

**Figure 3.9 Representation of the effect of limited installed capacity on capacity factor in a range of different wave climates**



### 3.3 Wave resource model

The total wave energy resource in the UK is calculated in several stages. The first stage estimates the amount of energy that passes through UK waters—mainly this derives from the wave energy arriving from the Atlantic. To do this a series of frontages over which the energy flows are chosen. The total resource is calculated as the amount of energy crossing these lines. However, these frontages may not necessarily be positioned in the most practical of locations, for instance they may be far offshore or in very deep water.

The offshore and nearshore technical resources are then calculated by defining a set of more realistic frontages. The proportion of this energy that can be extracted using a farm of real wave energy devices is then calculated. The method of choosing these frontages differs between the offshore and nearshore. The offshore frontages are identified by using a cost model that ranks different parts of the sea in order of their likely levelised cost of energy – taking into account energy levels, distance to shore, water depth and so on. The nearshore resource is identified by considering technical constraints, such as suitable water depths and seabed conditions.

The following section provides an explanation on how each of these estimates is made.

#### 3.3.1 Resource data

##### Offshore

The primary reference wave energy data used in this study is from the Atlas of UK Marine Renewable Energy Resources (DTI 2004). This contains estimates of the annual mean wave power level at all locations in UK territorial waters. The Atlas is developed from the UK and Global Waters wave model developed by the UK Met

Office. The average power levels are calculated based on seven years of data (June 2000 to May 2007) (DTI 2004ii).

The Atlas has good spatial resolution and gives a good overall estimate of the resource around the UK coast. It does, however, have a few limitations. Wave energy levels vary significantly each year. The seven-year-long record might not capture the full variability of the resource over time. It is also possible that the seven years used were different to the long-term average. The underlying model also loses accuracy near the shore, where, as the waves interact strongly with the seabed, modelling becomes significantly more complex and uncertain.

The wave resource varies seasonally too, with higher energy levels in the winter compared to the summer. For this study a few of the underlying model data were extracted at a few representative locations. These comprised joint probability distributions of wave height and period. From these the spectral content of the waves throughout the year was calculated. This in effect ensured that the seasonal variability is weighted correctly in the power calculations (see Appendix F).

Some concerns have been expressed by the industry that the Atlas mean power levels are too low. Some developers have formed their view from their own resource assessments in certain locations. Taylor and Motion studied the accuracy of the Met Office hindcast model and found that it is likely to be up to 15% low compared with buoy measurements in some places, though they do not give an overall accuracy figure (Taylor and Motion 2005).

The Irish Wave Atlas also appears to predict significantly higher energy levels for the Irish waters bounding the UK waters (SEI 2005). This difference can be observed on the published charts. As with the UK Atlas the Irish model also contains some limitations on accuracy and it is not possible to say without more detailed study and long-term data which is more accurate.

The total wave energy resource for the UK is strongly dependent on the real wave energy levels found in the sea. To address this uncertainty, a set of sensitivity analyses is included for the total and accessible resource estimates.

This study uses directional wave roses for twenty reference sites around the UK. These were obtained from the UK Met Office and are derived from the wave resource model used in the UK Atlas. For each the dominant energy-weighted direction is calculated (see Appendix F). These predominant directions are shown on the charts throughout this report.

## Nearshore

The DTI Atlas is less accurate very near the shore and in very shallow water. The resource near the shoreline varies significantly with local features and conditions. A more accurate model with a finer resolution is needed for these areas. Aquamarine has produced a set of wave resource models for different coastlines in the UK. These have been modelled with various levels of detail depending on the commercial attractiveness of the site to Aquamarine.

For the sites studied in most detail, a MIKE21 wave model is constructed with a high local spatial resolution and the National Oceanographic and Atmospheric Administration Wave Watch III used at the boundaries. Some of the sites have also been calibrated using data from Acoustic Doppler Current Profilers. These fine-resolution models are used to derive an average power level for a particular stretch of coastline.

The models also produce time-series of wave energy data that can be used with an energy model of the Aquamarine Oyster device to predict the likely annual energy production from a farm. This time-step calculation takes into account many of the complex interactions between the Oyster and the real sea conditions. This complexity has been simplified to a capacity factor in this study.

This calculation is potentially biased toward Aquamarine technology. To address this, the results presented here show the estimated mean power at each coastline after the fine-resolution modelling and before conversion by the Oyster device. The Oyster will then be used as a proxy for other near-shore shallow-water devices. This will allow the reader to substitute performance figures for alternative devices as needed. Testing of the Oyster and many other devices is still ongoing and the true performance is not yet known. Thus this approximation is considered reasonable and in line with the high-level simplified analysis of the offshore resource.

### 3.3.2 Total energy resource model

The total wave energy resource for the UK is the total amount of wave energy passing through the UK Exclusive Economic Zone (EEZ). This is especially difficult to define because the result is dependent on a judgement on the energy flows. In this study a set of flux lines is defined over which the majority of energy in the UK is expected to flow. The resource is then defined as the product of the length of the flux line and the mean power level along the line [kW/m].

The geometry of the UK's EEZ complicates matters. This is because, whilst the mean wave power increases further offshore, the flux line gets slightly shorter. This analysis has sought the line which has the highest combination of flux, i.e. the product of length and mean power level. The chosen lines are perpendicular to the predominant wave direction based on the wave roses from the model used for the UK Atlas and obtained from the Met Office.

Two sets of frontages are chosen; one north of Ireland and the other south (see Chart 1). These lines are shorter than they might be since the energy arriving at Ireland and France could also be included. However, if Ireland or France were to extract this energy then it would not be available to the UK. Similarly, if the Faroe Islands were to install marine energy in its EEZ, then the energy arriving at Shetland would be lower. This is unlikely since the Faroe Islands with an estimated demand of 0.25 TWh/y<sup>6</sup> would have difficulty absorbing large quantities of electricity or exporting it to another country, such as Scotland or Iceland. The nearest likely export location would be Scotland in any case since Iceland already has a renewable energy surplus (CIA 2011).

### 3.4 Energy extraction model

At the time of writing the energy extraction performance of different technology types are not known with certainty. However, understanding is growing and there is now sufficient understanding to estimate the likely overall level of the performance of some good candidate wave energy devices. This analysis makes some simple assumptions about the energy extraction potential of a farm. These assumptions are based on advice from technology developers but are intended to be generic.

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<sup>6</sup> 2008

## Offshore

The offshore wave model assumes wave energy devices are arranged in rows perpendicular to the predominant wave direction. It is approximated that the performance of each device can be described by a frequency-dependent capture width (see Appendix F). This in effect assumes that each row of devices extracts a certain proportion of the energy from each frequency wave, leaving less for the line behind. A relationship between the number of rows in a farm and the overall extraction is developed.

Each farm is assumed to have three rows and farms can be sited next to or immediately behind other farms. The frontages identified by the cost model may not be well aligned compared to the predominant wave direction. To account for this a set of relative directions are assumed for each (see Appendix F).

**Table 3.1 Offshore performance assumptions**

An average frequency-dependent capture width is sufficient to describe all wave conditions.	The performance of wave energy devices in the real sea is not yet proven and a higher level of precision is not justified at this stage. The capture width used in the study combines both an assumption on the correct rating of the machine for a given wave climate and on the likely efficiency that could be achieved in practice. This implies that machines will be adapted for high wave climates to avoid excessive power shedding.
The power spectrum at the reference site can be applied to all relevant locations	The average power spectrum developed is based on a single deepwater location. It is assumed that the spectral spread is similar to all locations of interest (see Appendix F).
The device capture width includes all operational features of the device.	The device capture width includes an allowance for instantaneous directional spread and includes the ability to yaw devices as needed to face the predominant wave direction. It allows for all losses in the system, such as power conversion losses. It also includes an allowance for bimodal frequency and multidirectional seas.
The wave atlas represents the long-term wave resource in the UK.	The atlas model is the only model available covering the whole resource. The potential 15% under-prediction noted by Taylor and Motion 2005) will be treated as an uncertainty and used as a potential high case in the results. The short length of the wave record used is considered representative of the long-term average.

## Nearshore

The nearshore wave resource estimate is based on Aquamarine's energy extraction technology. Their yield model converts the predicted resource levels from their nearshore fine-resolution wave models into a yield estimate. Whilst this result is specific to the Aquamarine device, it can still be used to give a general description of the technical resource near the shore. Several other methods of shoreline energy extraction can be conceived to extract energy from the shore with similar levels of efficacy. There may be differences in costs of energy between the technologies but these need not strongly influence the assessment of the overall resource. In other words, whether or not Aquamarine's Oyster technology proves to be the ultimate nearshore technology, it still serves as a useful proxy for this study. We do not believe that reliance on the work by Aquamarine will distort the overall assessment of the resource. In the following chapters we assign a mean wave power level and capacity factor to each coastline and others can recalculate the results based on a capacity factor of their own.

**Table 3.2 Nearshore performance assumptions**

The Aquamarine Oyster is a good candidate device for nearshore resource estimates	The Aquamarine device's energy capture mechanism is conceptually very simple. It has the ability to absorb a proportion of the energy incident on a particular line of devices. The device will have certain unique characteristics, such as a particular balance between its physical size and rated output. The capacity factor assumption is stated for each coastline allowing others to repeat the calculation with other capacity factors representing their devices.
The wave modelling for the nearshore locations is sufficiently accurate	Aquamarine has used a pragmatic balance of wave measurements and modelling at each location depending on the commercial attractiveness to them. Modelling in coastal zones is difficult and so even with the best modelled areas estimates are likely to be uncertain.  Some sites will be less accurately modelled than others. However, we expect the overall resource estimates to be good.

### 3.5 Cost as a location signal

The resource frontages could be positioned in many different places in UK waters, with some locations more practical than others. A review of the different offshore wave energy generating options concluded that devices with minor modifications could be installed in wide variety of locations—in deep water, far from shore, in differing seabed conditions. This would imply that farms could be placed far offshore where the wave levels are highest. In practice there will be balance between the cost of operating in certain areas and the energy generated there.

The success of the marine energy industry will be judged on the levelised cost of energy produced by the farms. The cost of energy is dependent on the cost of the device, the water depth, the energy levels and most of the relevant siting parameters. The cost of energy is a good way to distinguish between the attractiveness of different sites. This study uses a simple cost model that takes into account the main cost drivers to produce a cost of energy estimate at different locations in the sea. From this, the geographic areas with the lowest costs of energy can be identified. These are then used to estimate the overall technical resource. A summary of these calculations is shown in Figure 3.1.

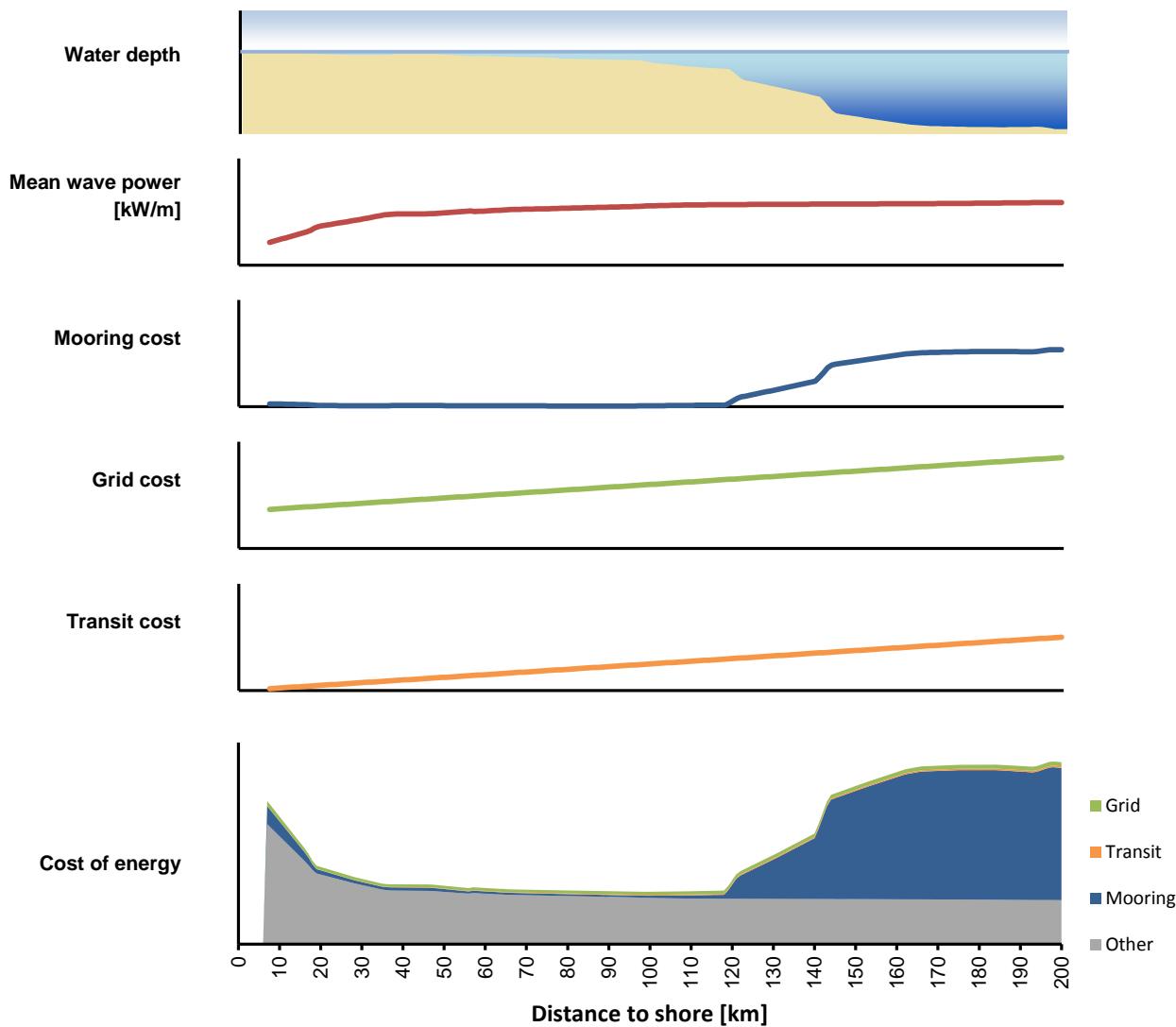
It is important to note that this study is not primarily about costs, but it uses costs as a guide to location. The cost of energy used in the study is based on work by the Carbon Trust Marine Energy Accelerator programme and has been extended to include site-specific conditions such as water depth and distance to shore (Carbon Trust 2011). It is clear that the areas of highest resource are well offshore and often in very deep water. The purpose of the cost model is to map the trade-off between areas of highest resource and areas of low cost.

## Offshore

The offshore cost model assumes that each farm is approximately 50 MW in scale and experience of installing 250 MW of that technology has been gained. The model takes into account the cost of installing, maintaining and decommissioning the system. It makes allowances for cable costs which increase with distance from shore, the additional transit time for ships servicing distant farms, the likely lower availability of remote systems, and the mooring cost (a function of water depth). The details of the cost model are contained in Appendix C.

Figure 3.10 illustrates the trade-off between distance to shore, wave energy levels and water depth and wave energy resource levels. This example represents a straight line drawn from the coast of Lewis into the Atlantic. It shows that the increasing energy levels drive the cost of energy down until the edge of the trench when the mooring costs begin to dominate. This shows in this particular case that the cost of energy varies little between 40-120 km from shore with the least cost at around 120 km.

**Figure 3.10 Illustration of the trade-off between cost of energy and distance to shore**



## Nearshore

The nearshore cost model is simpler. The devices are assumed to operate only in a fixed depth of water. Sites with particularly difficult seabed conditions, such as large numbers of rocks, are avoided. The costs are assumed in the first instance to vary little with location. This means that the variation in cost of energy in the nearshore resource depends only on the available resource.

The nearshore resource contains far more variability than offshore and these will undoubtedly affect the cost of each individual site. However, the way these costs vary will depend greatly on how each device is designed. This study does not consider such complexity since to do so would tie it too closely to a particular concept, and that is not the intention of the study.

### 3.5.1 Calculation of the cost of energy

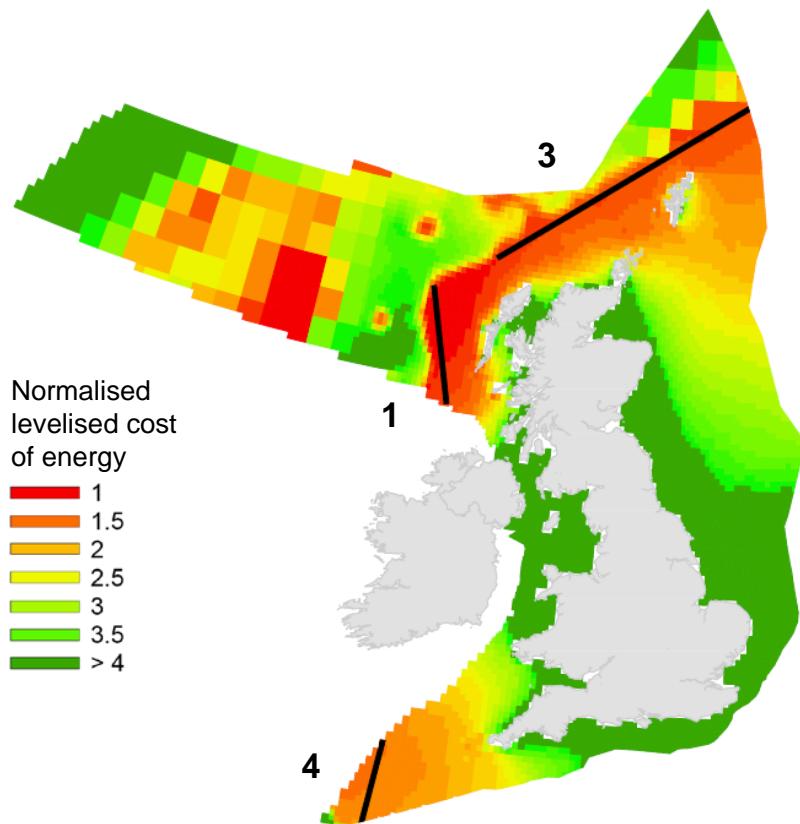
In keeping with other Carbon Trust work, a cost of energy model is constructed for a candidate wave energy device (Carbon Trust 2006). This model includes estimated costs for all capital items, including structural costs, installation, and project management. It also includes operating costs such as operations, maintenance and insurance.

Some of these costs are sensitive to location. For each a relationship between the cost and the physical characteristics of the site is made. In the case of floating offshore devices, this model is assumed to relate only to the distance to shore and the water depth.

Whilst the approach is informed by detailed discussions with wave energy device developers, it is intended to be generic. The main underlying assumption therefore is that the relative sensitivity of the cost of energy to location is the same for different floating devices. This is justified since the grid connection costs are likely to be similar and all floating devices will have some kind of mooring that's cost is dependent on depth. They will also need to be transported to site and maintained once there.

A highly simplified discounted cash-flow analysis is used to estimate the cost of energy (£/kWh). All farms are assumed to last for 20 years. The capital expenditure is in the first year and decommissioning in year 20. The base-case discount rate used is 15% and represents the cost of financing proven technology in early commercial-scale farms. A description of the parametric cost model is contained in Appendix C. This model is broadly the same as that used in the Carbon Trust's Marine Energy Accelerator. The costs included in this report are normalised rather than actual, to protect the commercial interests of the technology developers.

**Figure 3.11 Offshore wave cost-of-energy model**



Results of the cost of energy analysis identifying areas of least cost of energy and the numbered resource frontages chosen to represent the offshore resource. The normalised levelised cost of energy is intended to show areas of relative high and low cost.

### 3.6 Constraints

The practical resource is that proportion of the resource that is still available once all other non-technical sea-use and environmental issues have been taken into account.

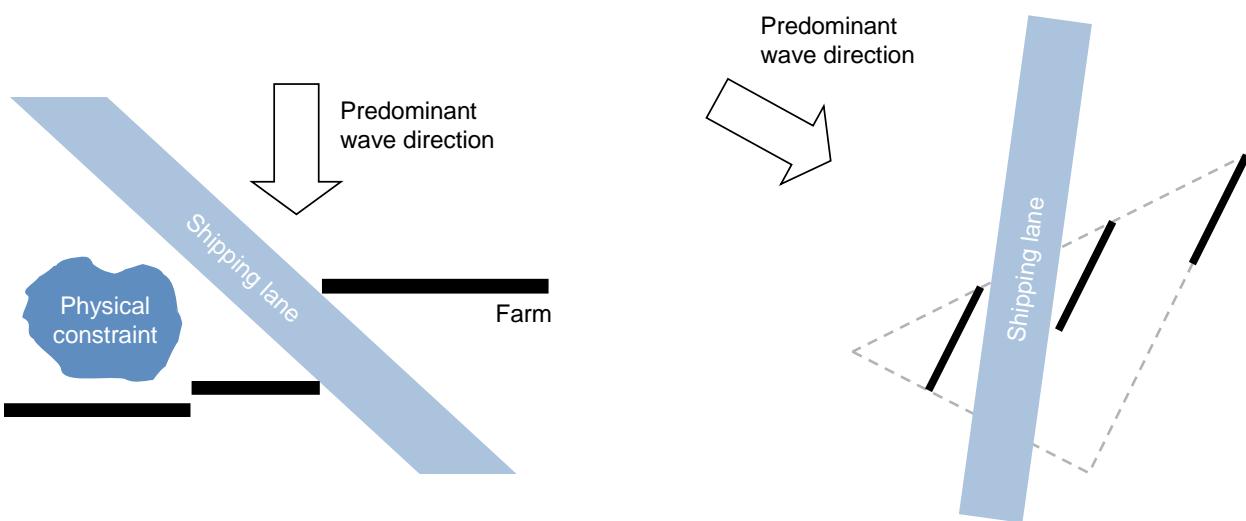
#### Offshore

The offshore wave farm model assumes that devices are laid out in wide farms that are only a few rows of devices deep. A 50 MW farm, for instance, might be 5-10 km long but only 1-2 km horizontally deep. Farms need not be placed along the same line, as proposed in the maps here. The resource extraction can still be maximised so long as

the non-occluded total frontage remains the same (see Figure 3.6 and Figure 3.12). This means that farms can be sited to avoid certain local features, and gaps between farms can be left with minimal loss of resource.

This is unlike other forms of energy extraction that rely on the availability of a plan area of space, such that when less space is available the resource is also reduced accordingly. It is inevitable that there will be some inefficiency in siting when trying to avoid constraints, but these can be relatively minor.

**Figure 3.12 Siting wave energy farms to avoid local constraints**



a) Farms can be arranged to accommodate other sea uses, or to avoid difficult siting conditions without necessarily greatly affecting the total resource.

b) Gaps left between farms could be used to align individual farms closer to the wave's direction whilst at the same time accommodating other sea uses.

Wave energy farms will however compete with other users of the sea for space. They will also affect the local environment. To account for this the likely constraints on siting were analysed in the UK EEZ. The constraints were derived from spatial datasets of resources, sea uses and environmental conditions. These were combined using the Crown Estate's Marine Resources System (MaRS).

The constraints data were divided into two groups, exclusions and restrictions. Exclusions are either areas in which marine energy deployment cannot take place or are areas that are removed from the analysis for convenience (see below). Restrictions are areas where marine energy farms could be sited but there would be some effect on other users of the sea, the environment or other marine resources.

This study is not intended to compare the benefits of marine energy extraction with those of other sea uses, nor is it intended to assess whether the effects of marine energy on the environment are acceptable. Nevertheless, some judgement is needed on how much of the resource would be available once these considerations are taken into account. In this study, a factor is applied to each issue in each area to estimate the proportion of the technical resource that would be available in practice. Below we discuss the issues and how each factor was derived.

To simplify this assessment each potential constraint was assessed as to whether it would likely have an effect on the economic marine energy resource. If the effect was likely to be minimal, say because its does not conflict with marine energy locations, then it was treated as an exclusion. This in effect ensures that such constraints are treated with the utmost importance. This does not mean that marine energy is necessarily incompatible with such areas, just that they are not significant in this high-level analysis.

Some of the most sensitive locations are to be found in Special Areas of Conservation (whether existing, draft or proposed). These have been treated as restrictions with a relatively high weight. This means that areas within SACs are identified as less likely candidate sites. These have most effect on the nearshore resource and are shown as dark on the constraints maps (see Appendix B). This assumption does not mean that wave energy is incompatible with the aim of these designated areas, just that there is a higher chance that they would be.

Two of the main considerations that do affect the siting of offshore marine energy devices are the location of shipping routes and fishing activity. Both can be described well using available spatial data. International shipping routes, such as traffic separation schemes, are treated as exclusions, as are areas of high shipping activity, notably the shipping route from the Western Isles toward the west coast of Ireland. The fishing activity is based on the fishing value by area. This estimates the economic value of fishing at each location in the sea and can be used to identify areas of high resource.

There remain other potential considerations such as the effects on birds, mammals and other environmental conditions, but these are currently not well mapped.

### *Fishing*

The fishing value maps show that some of the best areas are at the edge of the near continental shelf. This might well be because of the greater abundance of fish that feed there on the nutrients rising from the Rockall Trough. A particularly well resourced area is found to the north of the Western Isles and to the west of Orkney. Farms of devices could affect fishing by hindering activity in some areas, perhaps by restricting the commuting routes to fishing. It is possible that the farms would not affect the number of fish available but may affect the ease with which they can be caught. As we will show in the later sections, some of the most attractive offshore wave energy resources are also near the edge of the continental shelf.

### *Military areas*

Much of the west coast of Scotland is designated as military practice and exercise areas (PEXA). These cover very large areas and the Ministry of Defence do not state publicly how they are used. They have not been included in this study although it can be expected that there would be some conflict with military uses, though it is not possible to say to what extent or whether the effect could be mitigated.

### *Potential environmental barrier effects*

If farms were to be laid out in rows along the edge of the UK's continental shelf, as we depict in this report, there may be some other effects on the environment. This is more difficult to assess since it is not yet known how significant these effects from such large deployments might be.

To illustrate this, consider the case of marine mammals. Mammals may be affected by the noise of the devices or the presence of their moorings, for instance. If farms do affect the behaviour of the mammals such that they avoided farms, then a long line of farms would represent a barrier to them. This may prevent mammals taking their normal routes or lead to them to other areas.

This assessment does not comment on the likelihood of this happening, but instead recognises that if large quantities of wave energy devices were deployed then there may be significant environmental barrier effects that would need careful management. This consideration is included in the ‘cumulative impact mitigation’ factor listed below (see Table 3.3).

### *Cables and pipelines*

Many areas of the UK EEZ already have cables and pipelines running through them. A large number of the transatlantic communication cables run from Cornwall and there are many communication links to Ireland and France. Marine energy farms could theoretically be placed on top of such routes, since the moorings could straddle the lines. There is a risk of damage to the cables from anchoring operations which may dissuade operators from doing this. Also if cables are damaged then the farm may be in the way of the vessels sent to repair them. This need not necessarily be a problem since the devices could be removed temporarily whilst the repairs take place.

The cable routes themselves are relatively narrow, assumed here to be around 1 km wide. They could be avoided through careful siting, but this will introduce some inefficiency in siting leading to some loss of resource.

### *Overall effect*

The main common mitigation to the above effects is to ensure that farms are not too large (whatever that may mean) and that spaces are left between farms. The accessible resource is calculated from the practical by applying a factor to each broad location in the UK EEZ. This factor combines together a number of considerations as follows:

**Table 3.3      Allowances for offshore farm non-technical constraints**

<b>Issue</b>	<b>Allowance</b>
Shipping routes	Corridors are left around areas of relatively high shipping density
Fishing areas	Gaps in farms are left to allow fishing and fishing vessel transit
Cumulative impact mitigation	Gaps in farms are left to mitigate any ‘barrier’ effect, for example on mammals. These gaps may combine with those left for fishing areas.
Cable corridors	A siting efficiency factor to allow for the possibility that farms cannot always be sited conveniently around cables and pipelines

The gaps left in the line may serve more than one purpose. Gaps left for navigation, may also be used for fishing, gaps in fishing areas may benefit mammals and so on. Additionally in certain areas where the frontages are not well aligned to the predominant wave direction gaps could be left in any case to avoid one farm shadowing another. This means that the overall impact of constraints on the resource might not be as great as it first appears (Figure 3.12b).

The estimates for each resource frontage are shown in Table 3.4. The frontages are as numbered in Chart 2. The constraints factors are based on a judgement of the impact that each issue might have on the technical resource. The overall effect is another judgement of the likely impact of these effects in combination and recognising that the constraints are not purely additive. Table 3.5 shows the equivalent factors for the nearshore resource.

**Table 3.4 Offshore constraints factors**

Frontage	Constraints				Overall
	Fishing	Environmental	Shipping	Cables	
1 West	80%	85%	95%	100%	75%
3 North	75%	85%	98%	98%	71%
4 Southwest	80%	85%	95%	95%	74%

These factors are applied to the technical resource to estimate the practical resource. The 'overall' factor takes into account that the combination of the individual factors is not purely additive.

**Table 3.5 Nearshore constraints factors**

Region	Overall
Orkney	60%
Shetland	60%
Lewis	60%
Uist	60%
Barra	60%
Tiree	60%
Islay	60%
Colonsay	15%
Cornwall	15%

## 4. Results

### 4.1 Total resource

The total resource is estimated as the total energy crossing the flux lines shown in Chart 1. These lines total 670 km in length. A directional spreading factor of 70% is applied, as explained in Appendix F. The total resource is approximately 230 TWh/y.

### 4.2 Theoretical resource

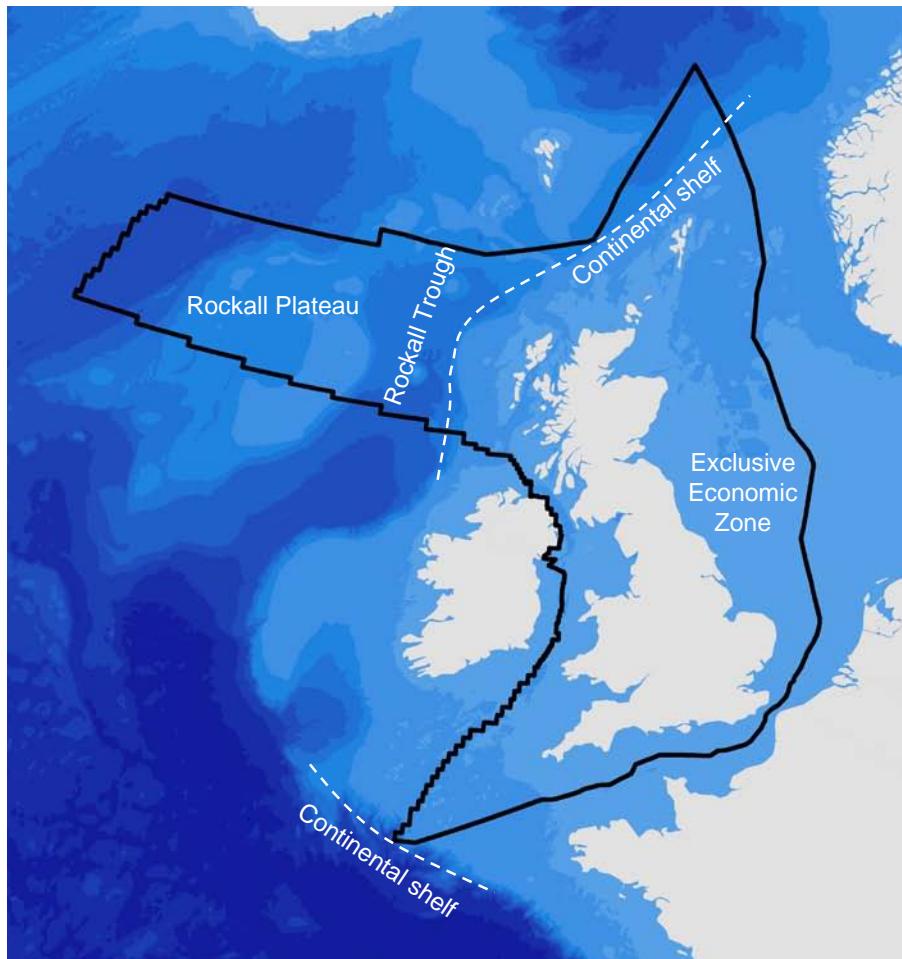
#### Offshore

The cost of energy analysis identifies that the least-cost locations are off the west coast of Scotland. This is illustrated in Chart 2 and Figure 3.11 on page 22. This area is high in resource with mean power flux levels of 35 kW/m near the shore to over 70 kW/m far offshore. Moving offshore the water gets steadily deeper, reaching a few hundred meters deep at the edge of the Rockall Trough. The trench then shelves away steeply and reaches depths of several kilometres in places.

The least-cost locations are found near the edge of the Rockall Trough about 100 km offshore. These locations have mean power levels of around 50 kW/m and are a few hundred meters deep. Further offshore is the Rockall Plateau, which is of a similar depth to the nearshore shelf. At its centre the island of Rockall pierces the surface. This area also appears relatively low cost. However, it is significantly further offshore and would require a cable that traverses the deep Rockall Trough. It is possible that it would be developed, but given that it is not significantly cheaper than the nearshore shelf areas it is unlikely. It is not included any further in this analysis.

In the Southwest, the resource gets cheaper towards the west. This is because the resource levels are relatively modest at the coast and increase towards the Atlantic. This part of the Exclusive Economic Zone ends at the edge of the UK's continental shelf and before the water becomes very deep. Thus it is likely that the most cost effective resource would be sited well offshore. There are opportunities to export the electricity to either Ireland or France as well as to the UK. The farms may well benefit from combination with either country's assets.

**Figure 4.1 Key features in UK waters**



## Nearshore

The nearshore flux levels calculated by Aquamarine are similar in many places to that estimated from the UK Atlas but in the Western Isles (Lewis, Uist, Barra, Tiree, Islay) the estimated flux is significantly higher. This means that the nearshore resource is higher than might have been predicted using only the relatively low resolution Met Office model.

The nearshore resource is likely to be more constrained than the offshore resource and the devices are less footloose. Consequently, the technical suitability of the sites is much lower. This is accounted for by the estimates suggesting that only between 30-70% of sites might be suitable for deployment, perhaps due to rocky seabed conditions. The theoretical nearshore resource is estimated as approximately 133 TWh/y.

## 4.3 Technical resource

### Offshore

The technical resource is calculated from up to fifteen rows of farms (45 rows of devices). At about this size of farm the energy extraction model suggests that the addition of more rows does not greatly increase the resource (this can be seen in the resource cost curves in Figure 4.3). At large numbers of rows the extraction model probably also does not describe the overall resource well (see Section 3.2). The figures quoted here for the technical and practical resources are those for a cost ratio threshold of 20 and a maximum of 15 three-row farms<sup>7</sup>. This results in an offshore technical resource of about 95 TWh/y.

### Nearshore

The nearshore technical resource is estimated based on the work by Aquamarine. This work used high resolution models of the resource and also the seabed conditions. The technical suitability and constraint factors listed in Table 3.5 are then applied. This gives a nearshore technical resource of approximately 10 TWh/y.

## 4.4 Practical resource

The practical resource is derived from the technical resource by applying the constraint factors estimated earlier. This reduces the practical resource from the technical to 70 TWh/y for the offshore resource and 5.7 TWh/y for the nearshore resource.

## 4.5 Summary

The practical resource is summarised in Table 4.1 and Figure 2.1. These results are not strictly additive; since if it were possible to extract all of the offshore resource then none would be left to arrive at the shore. However, it is possible for the two to coexist in several different ways. For instance, perhaps only part of the resource frontage would be exploited leaving unhindered waves to arrive at the shore. Alternatively, the offshore farms might only extract a proportion of the incident energy, say only the high-frequency waves, leaving plenty for the shoreline devices to use.

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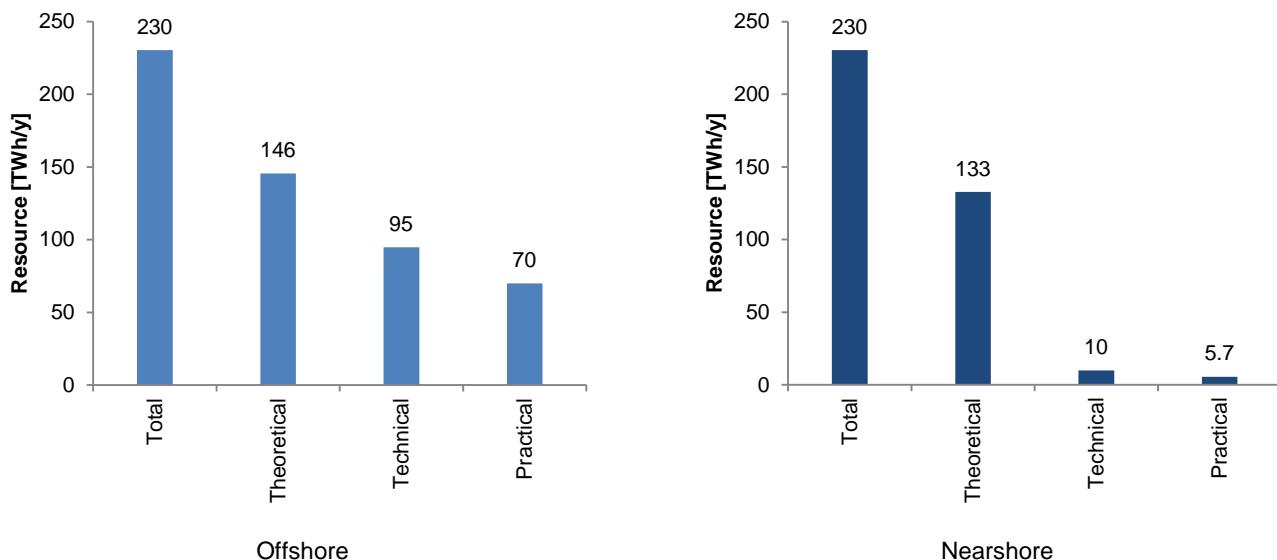
<sup>7</sup> The choices of a cut-off at 15 farms and a cost threshold of 20 are somewhat arbitrary. It is chosen because it represents the vast majority of the resource and it is clear from the charts that the resource at this point is approaching an asymptote.

**Table 4.1 Summary of resource estimates for offshore and nearshore wave energy farms**

Offshore		Nearshore			
	Annual energy [TWh/y]	Mean power [GW]	Annual energy [TWh/y]		
<b>Total</b>	230	26	<b>Total</b>	230	26
Theoretical	146	18	Theoretical	133	15
Technical	95	11	Technical	10	1
Practical	70	8	Practical	5.7	0.6

The power listed is mean power and not installed capacity. The total resource is the same for both nearshore and offshore.

**Figure 4.2 Summary of resource estimates for offshore and nearshore wave energy farms**



**Table 4.2 Offshore resource by region**

Region	Directionality ( $\theta$ )	Length [km]	Theoretical		Technical		Practical	
			Annual energy [TWh/y]	Mean power [GW]	Annual energy [TWh/y]	Mean power [GW]	Annual energy [TWh/y]	Mean power [GW]
1 West	10°	243	77	9	50	6	37	4
3 North	80°	600	29	3	21	2	15	2
4 Southwest	0°	162	39	5	25	3	18	2
<b>TOTAL</b>		<b>1,005</b>	<b>146</b>	<b>17</b>	<b>95</b>	<b>11</b>	<b>70</b>	<b>8</b>

**Table 4.3 Nearshore resource by region**

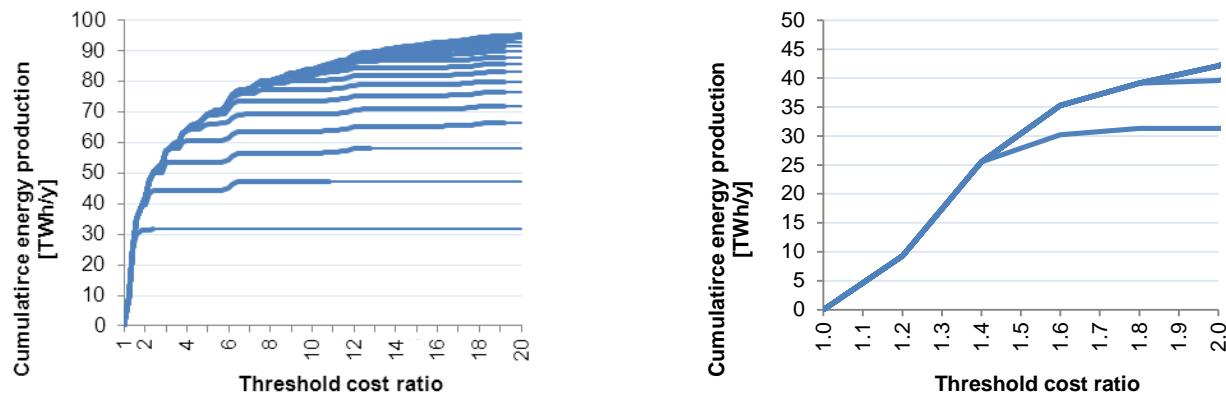
Region	Incident wave power [kW/m]	Length [km]	Theoretical		Technical		Practical	
			Annual energy [GWh/y]	Mean power [MW]	Annual energy [GWh/y]	Mean power [MW]	Annual energy [GWh/y]	Mean power [MW]
Orkney	24	64	13,680	1,562	1,559	178	935	107
Shetland	28	72	17,660	2,016	748	85	449	51
Lewis	36	60	19,169	2,188	1,700	194	1,020	116
Uist	41	84	30,015	3,426	2,734	312	1,640	187
Barra	50	20	8,751	999	744	85	446	51
Tiree	44	26	10,053	1,148	760	87	456	52
Islay	38	32	10,764	1,229	1,031	118	619	71
Colonsay	18	16	2,523	288	74	8	11	1
Cornwall	25	92	20,148	2,300	521	60	78	9
<b>Total</b>		<b>466</b>	<b>132,763</b>	<b>15,156</b>	<b>9,871</b>	<b>1,127</b>	<b>5,654</b>	<b>645</b>

## 4.6 Resource cost

### Offshore

The resource can be broken down further by its cost. To do this the assumed frontages are broken down into small lengths using a geographic information system. For each segment the cost of energy is known. From this the total amount of energy at or below a given cost of energy can be calculated. This calculation is then repeated by assuming that a second row of farms is placed immediately behind the first. For simplicity, this second row is assumed to have same costs as the first but is exposed to less energy. The cost of energy produced by the second row is therefore proportionately higher than from the first row. This process is repeated for a large number of farms rows. The results are shown in Figure 4.3.

**Figure 4.3 Offshore technical resource cost curve**



All costs are normalised relative to the lowest cost part of the offshore resource. The right-hand chart is provided to enhance the clarity of the low-cost resource. The bands shown represent individual rows of farms (i.e. three rows of devices). The transition from thick lines to thin lines for each farm show the point at which that row stops contributing to the total resource.

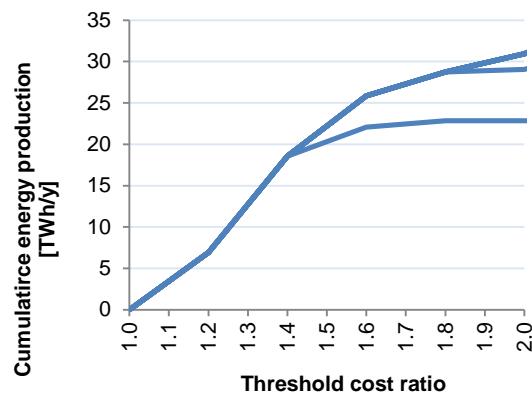
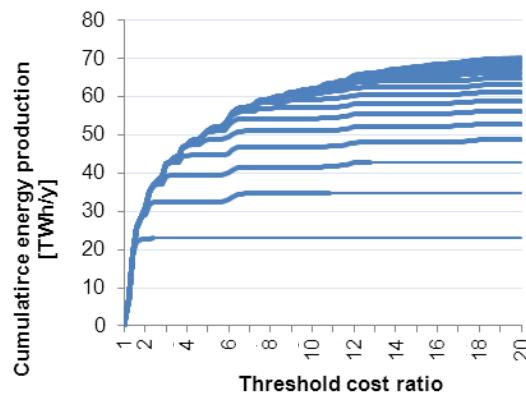
These curves show the impact of adding additional rows behind the front row. If a great many farms were added (15 are shown here) then the resource extracted by each additional row diminishes. The resource approaches an asymptote. Very high levels of energy extraction are unlikely since they are difficult to achieve and, as can be seen, increasingly less cost-effective.

The simplistic resource-extraction model used here also begins to break down with very large numbers of rows; destructive in-farm effects and shadowing are likely to become more significant. Also, farms with greater numbers of rows might also be more cost effective, benefitting from their economies of scale.

Figure 4.3 also shows how if the affordable part of the resource was constrained to be perhaps between one and two times the cheapest part (the threshold cost ratio), then it would still be beneficial to have several rows of farms before exploiting lower energy resources. For instance at a threshold ratio of 2 it is more cost-effective to add up to three rows of farms in some places before exploiting some lower-energy parts of the resource. This means that in the most energetic parts of the resource, farms will be deeper than in less energetic regions.

The resource cost analysis can also be applied to the practical resource as shown in Figure 4.4.

**Figure 4.4 Offshore practical resource cost curve**

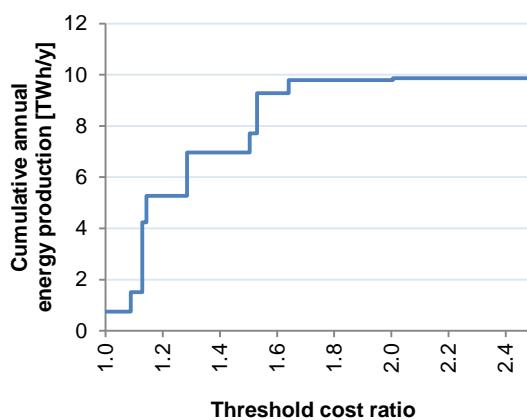


All costs are normalised relative to the lowest cost part of the offshore resource. The right-hand chart is provided to enhance the clarity of the low-cost resource. The bands represent individual rows of farms (i.e. three rows of devices). The transition from thick lines to thin lines for each farm show the point at which that row stops contributing to the total resource.

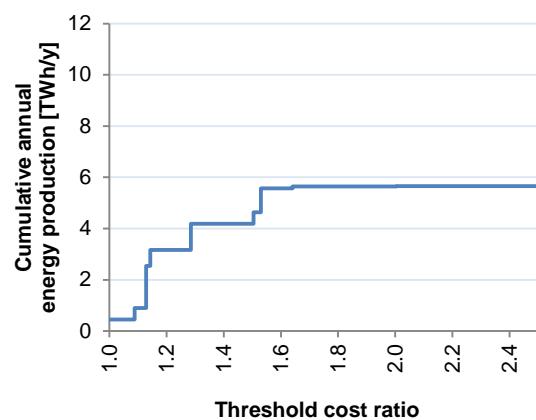
## Nearshore

A similar process was applied to the nearshore resource. The resource is broken down into broad regions and consequently the resource cost curve contains a number of discrete steps. These results for the technical and practical cases are shown in Figure 4.5 and Figure 4.6 respectively.

**Figure 4.5 Nearshore technical resource cost curve**



**Figure 4.6 Nearshore practical resource cost curve**



All costs are normalised relative to the lowest cost part of the nearshore resource

## 4.7 Sensitivity tests

This section tests some of the assumptions contained and considers how sensitive the result are to them. The model applied here is not linear and so each sensitivity needs to be tested a different way. The results are shown in Table 4.4.

### Underlying resource map is low

There are concerns that underlying data in the Met Office wave map are low compared to the long-term average (see Section 3.3.1). Some have estimated that in certain locations the model may be low by around 15%. The work by Aquamarine has also shown that the Met Office model nearshore is also not accurate. The total resource is directly proportional to the underlying resources. The first sensitivity test increases all the levels of resource by 15%. This may be too generous to apply to the overall resource since the differences found were only for certain locations.

The nearshore resource estimates do not share the same parent data and so are not assumed to be 15% low.

### Cost of energy is more strongly related to distance to shore

The cost of energy model drives the offshore resource frontages to the edge of the UK's first continental shelf. This is because the benefits of the higher wave power levels there are assumed to outweigh the costs. To test this, all items related to distance to shore were doubled in the model. This included doubling the transit costs and doubling the cabling costs.

Inspection of the cost of energy map showed that the least cost locations identified did not change. This means that the frontages (1, 3 and 4) defined for the theoretical, technical and practical resource levels do not change.

### Higher performance of devices

#### *Offshore*

Wave energy technology is likely to improve. However, improving the performance of the offshore devices does not necessarily increase the total practical resource. The effect of increasing the performance of individual devices (by improving the capture width, see Appendix F) is to reduce the number of devices or rows that are needed to deliver the same amount of energy. Reducing the number of rows may mean reducing the depth of each farm but not their width. The farms described in this report are long, but not very deep. The main limitations on siting are more to do with the farms' widths—whether they form a barrier to other sea users—rather than their depth. This means that even though the high-performance farms would take up less space it is unlikely that any more frontage would be deployed as a result.

If the performance of devices in lower-frequency waves was increased then less energy would pass through the farm unhindered (see Section 3.2). This would increase the technical and practical resources. It is not known how

much of this resource can be extracted with current technology given the requirement to balance power performance with cost and survivability.

Of course, since the performance has improved, the overall cost of energy would also probably reduce. As with all other cost reductions this would increase the proportion of the resource available at or below a given cost of energy. The sensitivity of the resource to this threshold cost of energy can be seen on the resource cost curves.

### **Nearshore**

The nearshore resource is calculated from a set of capacity factors and spacing for a particular nearshore concept, the Aquamarine Oyster. This model implicitly assumes that 28 MW per kilometre can be installed and depending on the resource level the capacity factors are in the range 18-36%. Improving the capacity factor by 20%, i.e. a range of 22-43%, would also increase the technical and practical resources by 20%. Similarly increasing the packing density of the farms by 20% to 34 MW per kilometre without any loss in performance would also lead to a 20% increase in technical and practical resource.

**Table 4.4 Sensitivity tests**

Case		Total		Theoretical		Technical		Practical	
		TWh/y	GW	TWh/y	GW	TWh/y	GW	TWh/y	GW
<b>Offshore</b>	Base	230	26	146	17	95	11	70	8
	Underlying resource map is low	265	30	167	19	109	12	81	9
	Cost of energy is more strongly related to distance to shore	230	26	146	17	94	11	70	8
<b>Nearshore</b>	Base	230	26	133	15	10	1.1	6	0.6
	Higher performance devices	230	26	133	15	12	1.4	7	0.8

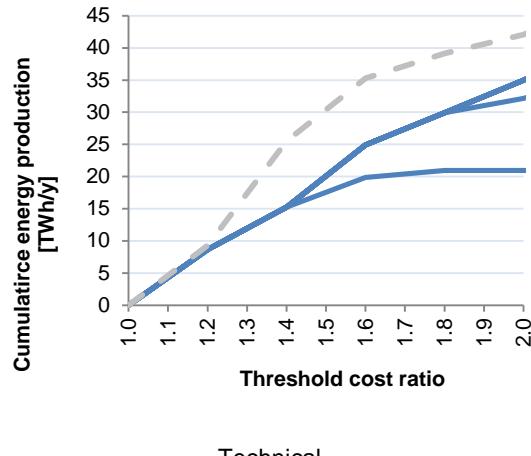
Some sensitivity cases shown do not result in any changes from the base case.

### **Directionality model**

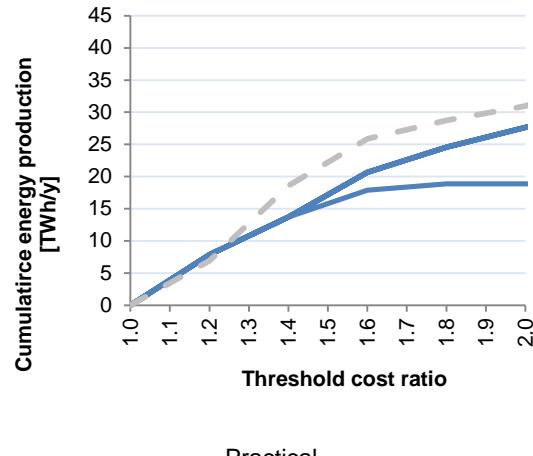
The extraction model assumes that the farms can absorb different proportions of energy at different angles of incidence. This is discussed in Section 3.2. This model is probably correct for individual farms with relatively few rows. It may be though that it does not describe the total resource well. For instance it may be that in practice farms will be laid perpendicular to the predominant wave front with gaps left between them, as shown in Figure 3.6b. To account for this, a simplified extraction model has been applied to the resource, this model described by equation E10 in the Appendix F. This shows that main effect is to change the quantity of resource at or below a given cost threshold.

Figure 4.4 shows a comparison between the two models for cost thresholds below two. They show that both the technical and practical resources are lower meaning that, in the base case, a greater proportion of the resource is available at lower cost.

**Figure 4.7 Offshore resource cost curve**



Technical



Practical

The grey line shows the base case. All costs are normalised relative to the lowest cost part of the offshore resource.

## 5. Conclusions

This study estimates the total wave energy resource in the UK. The majority of available energy arrives from the Atlantic to the west. Sheltering from Ireland reduces the wave energy resource in the Irish Sea and the energy levels in the North Sea are significantly lower than in the west. The total resource incident on our shores is around 230 TWh/y with the majority found in the deeper offshore parts of the UK's Exclusive Economic Zone.

The offshore wave resource generally increases with westerly distance to shore. An analysis of the cost of energy at different locations in UK waters has shown that the least cost areas are found at the edge of the Rockall Trough to the west of Scotland and at the edge of the UK waters in the Southwest. These areas are around 100 kilometres from shore and in water depths of a few hundred metres. Further offshore the resource increases marginally but the water gets considerably deeper, reaching several kilometres deep in places and this greatly increases the cost of energy. The available theoretical resource in these areas is around 146 TWh/y.

It is technically possible to extract a very high proportion of this energy by using farms of wave energy devices. To do this many rows of long farms facing the Atlantic would be required. If all of these were built then around 95 TWh/y could be extracted from offshore. However, taking into account other sea users, shipping, fishing, cables and pipelines, would leave around 70 TWh/y available for extraction. Of this around 42 TWh/y would be available at or below three times the cost of energy of the cheapest site (i.e. a cost ratio of 3).

The wave energy available at each level of resource is summarised below:

**Table 5.1 Summary of resource estimates for offshore and nearshore wave energy farms**

	Offshore		Nearshore	
	Annual energy [TWh/y]	Mean power [GW]	Annual energy [TWh/y]	Mean power [GW]
<b>Total</b>	230	26	230	26
<b>Theoretical</b>	146	18	133	15
<b>Technical</b>	95	11	10	1
<b>Practical</b>	70	8	5.7	0.6

The impact of distance to shore and corresponding increasing water depth on the cost of energy is not great (up to the edge of the continental shelf). This implies that the target areas in the longer term for well-developed offshore wave energy devices are likely to be near the edge of the UK's first continental shelf.

However the cost of energy does not vary significantly in these areas meaning that farms could be sited closer to shore without a significant cost of energy premium. This would allow farms to be sited nearer shore to minimise the capital requirement for the projects, to minimise operations risks and inconvenience, or for other reasons.

For maximum energy extraction offshore wave energy devices would be sited in relatively long farms. The main impact of such farms might be in making barriers to other sea users, such as fishing vessels or barriers to the movement of fish, mammals and others. These barrier effects can be mitigated by careful siting and in some cases without affecting the overall available resource. If the energy extraction levels are high in certain locations then there may be other environmental effects due to the lower wave climate behind the farm, but these are not established or discussed in their report.

The resource cost curve analysis indicates that in high resource areas it is likely that it will be beneficial to have fairly deep farms comprising many rows of devices before moving to lower-resource areas. There may be practical and commercial reasons why farms are first sited nearer the shore and then move farther as they become more developed. However, once established in a high resource area, it makes sense to growth the farms there before moving to lower resource areas.

An important route to cost of energy reduction for offshore wave energy devices is to move farther offshore and into the higher resource areas. This requires finding ways to minimise the transit time, maximise availability despite the distance to shore and to maximise production to minimise the cost of farm-to-shore cabling. Whilst not trivial, these are entirely possible.

The nearshore resource is highly technology dependent. The UK wave energy atlas is not reliable in shallow water near to the shore. The local wave conditions are harder to predict and require more detailed modelling suited to the technology concept under investigation.

The seabed and technical conditions near the shore are highly variable meaning that the number of sites technically suitable for development is lower. This means that there is a much greater difference between the theoretical resource (133 TWh/y) and the technical resource (10 TWh/y) for nearshore systems than for offshore.

Unlike offshore wave if new nearshore technologies can be found that increase performance then the technical nearshore resource would be proportionately higher. Likewise if new technology enabled the systems to be deployed in a wider range of conditions then the resource is for nearshore systems then potentially the resource could be higher.

# Appendix A

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## **Appendix B Charts**

**Chart 1: Total resource**

**Chart 2: Offshore resource**

**Chart 3: Nearshore technical resource**

**Chart 4: Offshore resource sensitivity test**

**Chart 5 Offshore constraints – UK**

**Chart 6 Offshore constraints – Southwest**

**Chart 7 Offshore constraints – West**

**Chart 8 Offshore constraints – North**

**Chart 9 Nearshore constraints – UK**

**Chart 10 Nearshore constraints – Western Isles**

**Chart 11 Nearshore constraints – Orkney**

**Chart 12 Nearshore constraints – Shetland**

**Chart 13 Nearshore constraints – Cornwall/Southwest**

**View Appendix B: Charts at**

**<http://www.carbontrust.com/media/205619/ctc816-appendix-b-charts.pdf>**

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## Appendix C

# Levelised cost of energy model

This study is not intended to comment on the absolute cost of energy, but rather to investigate its sensitivity to location. Consequently all the cost of energy figures in this report are normalised relative to the assumed least cost location found in the UK waters. This approach is intended to show the spread of resource with cost rather than to explain the costs themselves. Nevertheless, the costs are based on detailed cost reduction work done by the Carbon Trust on the Marine Energy Accelerator. They are derived from real or estimated costs and have been discussed with industry members to check that they are reasonable.

### Offshore

The cost of energy is assumed to vary with location. Each location has different costs and energy resources. The costs are related to the physical characteristics of the location, such as the water depth and the distance to shore. The energy resources are taken from the wave resource Atlas.

The capital and running costs will vary separately with location. For instance mooring capital costs might be related to water depth, whereas running costs might be driven by transit times. The balance between cost centres shifts the location of the least-cost resource.

The discount rate used in the levelised cost estimates (see Appendix C) also affects the importance of operational costs relative to capital costs. High discount rates emphasise capital costs, whereas low discount rates raise the importance of operations costs. Since capital and operating costs also vary differently with location, the discount rate will drive siting preference too.

The cost of energy model includes estimates for real devices for all major cost centres. These include—

#### Capital costs

- Structure
- Foundations/moorings
- Control/instrument
- Power Take-off
- Grid connection
- Installation surveys
- Installation of structure
- Installation of mooring
- Installation of grid connection
- Commissioning
- Management and other

## **Operating costs**

- Planned maintenance
- Monitoring/Control
- Unscheduled repair
- Site rent
- Insurance

The costs are intended only to be sufficiently accurate to ensure that the sensitivity of the cost to location is approximately correct. For this, it is not necessary for each individual cost to be completely accurate.

The costs centres include both technical and non-technical site development costs. This is intended to ensure that the cost of energy fairly reflects the true mix of costs likely in a real commercial farm. If, for example, costs like project management and surveys, were neglected then the results would be skewed towards operations and maintenance costs and the answers would be misleading.

The overall costs are normalised to the capital cost and presented in Table C.2. This shows for instance that, in 150 m water depth the mooring would comprise around 4.6% of the capital cost. Similarly, the total annual operating costs are equivalent to approximately 4.5% of the capital cost.

**Table C.2 Normalised costs**

Cost	Base	
<b>Capital costs</b>		<b>100.0%</b>
Fixed capital		89.1%
Mooring	150m depth	4.6%
Grid connection	50km to shore	6.2%
<b>Operating costs</b>		<b>4.5%</b>
Fixed operating		4.3%
Transit	50km to base	0.2%
<b>Decommissioning</b>		<b>0.7%</b>

All costs are normalised based on 150 m water depth and 50 km distance to shore. The operating and decommissioning costs are expressed as a proportion of the total capital cost.

The base case cost split shown above is for a site 150 m deep and 50 km to shore. The mooring, grid connection and transit costs are all variable. The variable costs are presented below relative to this base site.

## Mooring costs

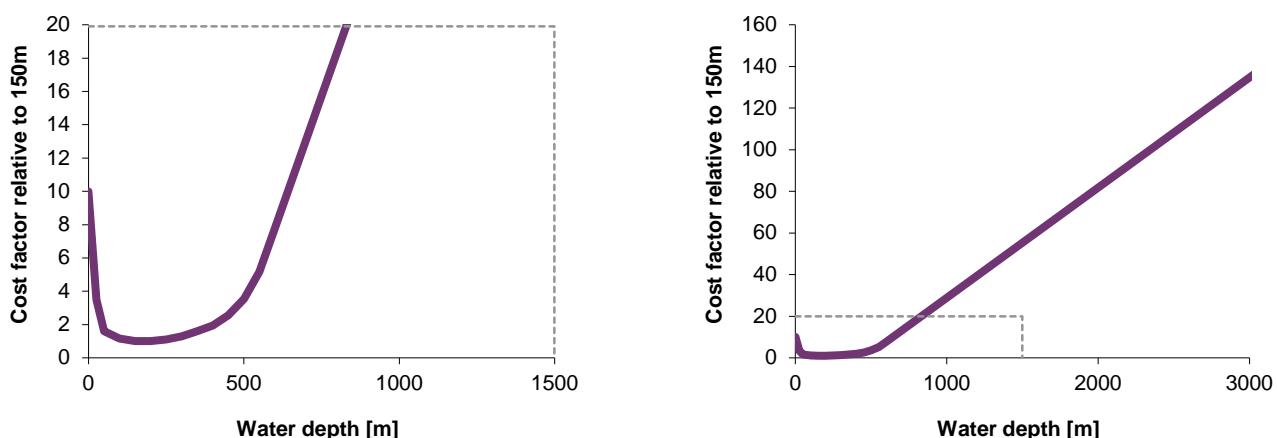
The mooring costs are assumed to vary primarily with water depth. In very shallow water the conditions are difficult—due to steeper and more complex wave interactions—and the mooring loads become very large and expensive to withstand. As the water gets deeper the cost increases with the length of the mooring primarily because of the increased cost of the mooring line itself. It is expected that the cheapest moorings will be for floating devices in water around 150 m deep, where the balance of mooring line cost and loads reaches an optimum. In very deep water (kilometres deep) it is probably more likely that another form of mooring would be used, perhaps where entire farms are moored rather than mooring each individual device. This assumption is however useful since the results show that operation in very deep water might not even be necessary.

Figure C.1 shows how the mooring cost might vary with depth. In deep water the costs rise from the cheapest level at 150 m deep. These data are taken from estimations of costs from an offshore wave device developer.

The cost of anchoring might also vary with location. The local seabed conditions might require different types of anchor, such as drag-embedment anchors in soft locations and gravity foundations in hard. The costs of these might also vary. This study does not take into account seabed conditions. This is for a number of reasons.

There are numerous anchoring and foundation options available to suit all different types of seabed. It is assumed that for any location a fixation system can be found at some cost. It is also assumed that the technology is relatively footloose, meaning that particularly problematic locations can be avoided. The moorings themselves can be moved around slightly to avoid local obstacles. The farm can be moved a few kilometres if needed too, without affecting the overall resource. This means that in all likelihood a cost-effective mooring solution can be found for most locations, either by choosing an appropriate anchoring technology, micrositing anchor points or repositioning the farm to more favourable seabed conditions.

**Figure C.1 Mooring cost variation with depth**

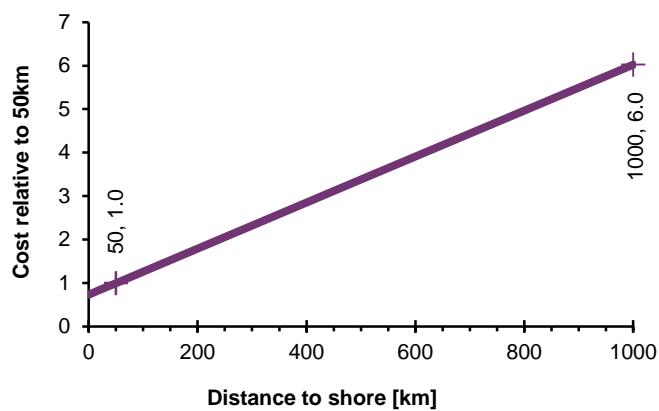


Both charts show different views of the same data, with the left-hand chart showing a more detailed view of the costs at shallower depth.

## Grid connection

The grid connection costs are estimated using a variety of sources, including from the Carbon Trust Offshore Wind Accelerator. It is set so that the cost increases with distance to shore so that the cost of venturing into higher resource areas are tempered by the increased infrastructure required doing so. This postulated relationship represents a relatively lower sensitivity to distance to shore. There are plenty of estimates that would put the cost much higher but these tend to be driven by the costs of much shorter connections with a greater proportion of the cost in trenching and other protection measures required nearer the shore.

**Figure C.2 Variation of grid cable cost with distance and installed capacity**



Grid costs are normalised relative to 50 km distance to shore

The distance to shore is also not necessarily the best distance to measure since there may not be a suitable grid connection point there. This means that the cable would need to be routed to another point along the coast. When devices are very close to the shore this extra distance can be quite significant compared to the distance to shore itself. However, the developer has the option to bring the cable to shore and then take it over land, or to take the longer distance offshore.

This additional distance becomes relatively less important as connection distances increase, since a small change in direction of the cable can extend its reach along a coast line quite considerably without greatly increasing its length.

This study looks at high levels of deployment where offshore hubs and networks would possibly be an option. Such hubs might be located on islands that are already well offshore. The distance to shore calculation does not treat small islands ( $<500 \text{ m}^2$ ) as ‘shore’ meaning that they are ignored in the distance to shore calculation.

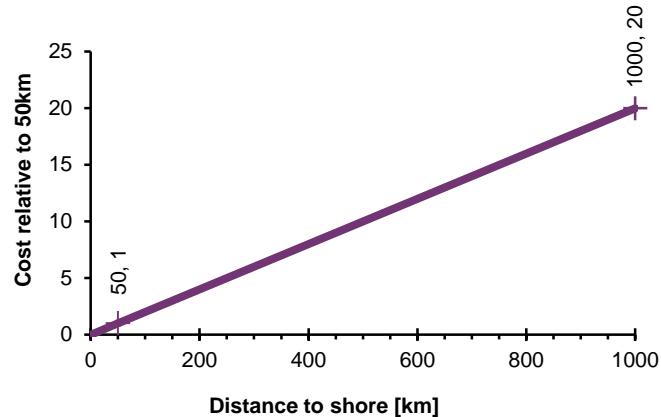
This study makes the approximation that distance to shore is adequate to estimate the impact of distance on the part of the cost associated with grid connection.

The grid costs include costs up to and including the connection equipment on shore. They do not include either shallow or deep reinforcement of the grid.

### Transit costs

The cost of moving vessels around inside the farm to maintain devices is included in the operation cost. However, the cost of travelling between the farm and the shore is modelled as below. This is derived from estimated vessel hire costs and fuel costs provided by developers.

**Figure C.3 Variation of transit costs with distance to shore**

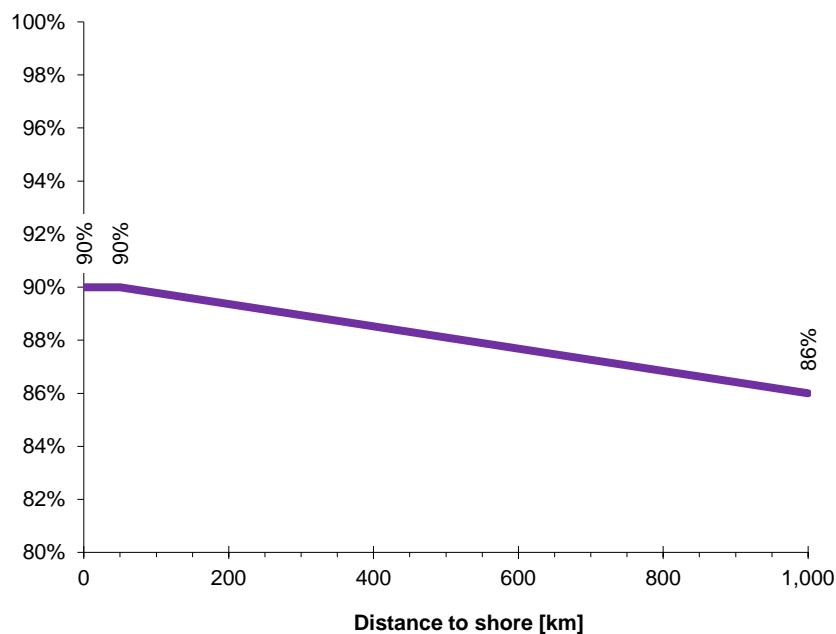


The transit costs are normalised relative to 50 km distance.

### Availability

As devices are moved offshore they will be less convenient to service. When transit times are long it becomes more difficult to schedule work in good weather windows. This will inevitably lead to some loss of availability. The resource extraction model assumes that the farm will be 90% available near the shore, but as deployment distances increase this will drop, assumed here to around 86%. This is illustrated below.

**Figure C.4 Availability as a function of distance to shore**



## Nearshore

The nearshore costs of energy are assumed to vary only with the energy resource. The costs are derived from previous Carbon Trust work and are assumed to be:

**Figure C.5 Normalised costs**

Cost	
Capital	100%
Operating	4%
Decommissioning	10%

All costs are normalised based on 150 m water depth and 50 km distance to shore. The operating and decommissioning costs are expressed as a proportion of the total capital cost.

## Appendix D

### Cost of energy

#### Cost of energy

The cost of energy is defined as the constant cost unit electricity cost that would be required to give a return equal to the discount rate (Carbon Trust 2006). This is based on a simplified discounted cash flow analysis, which assumes that the capital is spent in year 0, the operating costs run for the life of the project and the decommissioning costs are incurred in the final year. The costs are spread over the operating life of the farm.

$$coe = \frac{C + O \left( \sum_{i=1}^L (1+R)^{-i} \right) + D(1+R)^{-L}}{E \sum_{i=1}^L (1+R)^{-i}} \quad E1$$

Where

$C$  = capital cost [£]

$O$  = operating cost [£]

$D$  = decommissioning cost [£]

$L$  = project life [f]

$E$  = annual energy output [kWh/y]

$R$  = discount rate

This formulation gives the same result as a conventional discounted cash flow analysis, though its form may not be immediately recognisable. This form is simpler to implement in the models described in this report.

## Appendix E Constraints

The spatial datasets listed overleaf are divided into two types; exclusions, which are areas avoided in this analysis, and restrictions, areas where marine energy may compete with other sea users or environmental conditions. Some areas are buffered and the distance used in each case is shown in the buffer column.

**NOTE: Areas defined as exclusions are not necessarily incompatible with wave energy development. Some, like Ramsar sites, are treated as exclusions simply because they are not located near to likely wave energy deployment locations so whether they were included or excluded they would not change the overall resource estimations. This is done to simplify the process and focus debate on the areas where incompatibility may arise.**

Category		Nearshore			Offshore		
		Type	Buffer [m]	Weight	Type	Buffer [m]	Weight
Designated areas	Areas of Outstanding Natural Beauty (AONB)	Exclusion	-	-	Exclusion	-	-
	Heritage Coast	Exclusion	-	-	Exclusion	-	-
	Important Bird Areas	Restriction	-	900	Exclusion	-	-
	Local Nature Reserves (LNR)	Exclusion	-	-	Exclusion	-	-
	Marine Nature Reserves (MNR)	Exclusion	-	-	Exclusion	-	-
	Maritime Cliffs and Slopes	Exclusion	-	-	Exclusion	-	-
	National Nature Reserves	Exclusion	-	-	Exclusion	-	-
	National Parks	Exclusion	-	-	Exclusion	-	-
	National Scenic Areas	Restriction	-	900	Exclusion	-	-
	Ramsar Convention Sites	Exclusion	-	-	Exclusion	-	-
	Scheduled Ancient Monuments (SAM)	Exclusion	-	-	Exclusion	-	-
	Sites of Special Scientific Interest	Exclusion	-	-	Exclusion	-	-
	Special Areas of Conservation (dSAC) (existing, candidate and draft)	Restriction	-	1,000	Exclusion	-	-
	Special Protection Areas (SPA)	Restriction	-	1,000	Exclusion	-	-
Hazards	World Heritage Sites	Exclusion	-	-	Exclusion	-	-
	All offshore cables and pipelines	Restriction	500	500	Restriction	500	500
	Designated Wrecks	Exclusion	100	-	Exclusion	100	-
	Disposal Sites	Exclusion	-	-	Exclusion	-	-
	Munitions Dumps	Exclusion	-	-	Exclusion	-	-
	Navigation Obstructions	Restriction	100	700	Restriction	100	700
	Protected Wrecks (buffered)	Exclusion	-	-	Exclusion	-	-
Recreation	Wreck Points	Exclusion	100	-	Exclusion	100	-
	Royal Yachting Association Cruising Routes	Restriction	100	600	Restriction	100	600
	Royal Yachting Association Racing and Sailing Areas	Restriction	-	600	Restriction	-	600
Resource extraction	Aggregate Dredging Areas	Exclusion	2,000	-	Exclusion	2,000	-
	Aggregates Dredging Options	Exclusion	2,000	-	Exclusion	2,000	-
	Aquaculture Leases	Exclusion	-	-	Exclusion	-	-
	Bivalve Harvesting Areas	Exclusion	-	-	Exclusion	-	-
	Existing wind farm sites or lease areas	Exclusion	-	-	Exclusion	-	-
	Fish Value (Non-VMS and VMS) Combined for all Gear Classes	Restriction	-	900	Restriction	-	900
	Fishery Orders	Exclusion	-	-	Exclusion	-	-
	Gas Storage Leases	Exclusion	-	-	Exclusion	-	-
	Offshore Wind Activity	Exclusion	-	-	Exclusion	-	-
	Oil and gas Surface, Subsurface equipment and Wells	Exclusion	500	-	Exclusion	500	-
	Oil and Gase Safety Zones	Exclusion	-	-	Exclusion	-	-
	Oil Fields	Restriction	-	900	Restriction	-	900
Shipping	Anchorage Areas	Exclusion	-	-	Exclusion	-	-
	International Maritime Organisation IMO Routeing and Traffic Separation	Exclusion	1,852	-	Exclusion	1,852	-
	Navigation Aids	Restriction	250	700	Restriction	250	700
	Shipping Density	Restriction	-	700	Restriction	-	700
	Shipping Density - Exclusion Areas	Exclusion	-	-	Exclusion	-	-

## Appendix F

### Extraction model

#### Directional spread on long frontages

The UK wave energy atlas contains some directional information. It shows how much time waves arrive from each direction. Unfortunately, this does not explain how much energy arrives from each direction. To address this data for twenty points around the coast were purchased from the Met Office. These data are derived from the Global Waters Wave model that sits behind the UK wave atlas. From these, twenty wave energy roses were created. From these a predominant wave direction was calculated. These directions are shown on the charts in Appendix B.

The predominant wave direction is calculated using a simple flux model. This is slightly different to the energy extraction model. The extraction model recognises that relatively porous farms of well spaced devices can absorb significant proportions of the energy from a wide range of angles. The flux model assumes that absorption remains constant at all angles. This means that the energy flux is proportional only to the projected width of the line. (This is equivalent to assuming that  $cw(f)/Z = 1$  at all frequencies, where  $cw(f)$  is the anticipated frequency dependent capture width of a device and  $Z$  [m] is the likely spacing between devices, see below).

Using the directional frequency information in the UK wave energy atlas a directionality factor  $\lambda$  can be calculated. This indicates the proportion of the energy that can be obtained given the directional spread of the waves.

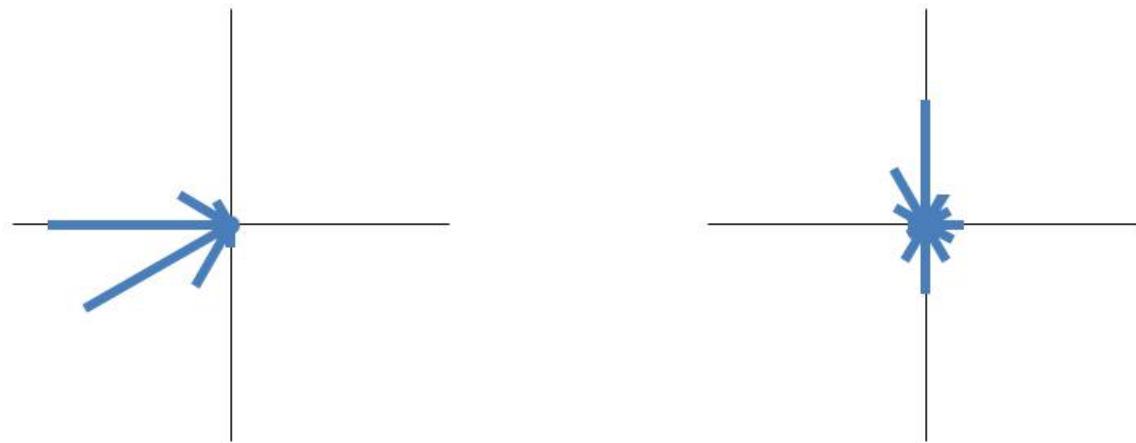
Each farm is assumed to have a frontage placed at a particular angle. It is possible for any given rose to then find the angle of the farm frontage that gives the highest factor  $\hat{\lambda}$ .

The energy  $E$  passing over a single frontage position with a heading of  $\beta$  can be calculated from the energy coming from each direction  $\alpha$  as follows.

$$\lambda = \sum_{\alpha=0^\circ}^{360^\circ} E\{\alpha\} \cos(\alpha - \beta) \Delta\alpha \quad E2$$

This approximation assumes that the wave farm can accept energy equally well from any angle. However, an alternative assumption is that the farm cannot accept energy at all from certain directions. A second comparative case then assumes that the farm can only accept energy from wave directions  $-90^\circ < (\alpha - \beta) < +90^\circ$ .

**Figure F.6 Comparison of two wave roses**



#### **Site 20 South Uist**

Directionality factor	unidirectional case	$\hat{\lambda} = 83\%$
	limited direction case	$\hat{\lambda} = 82\%$

#### **Site 12 North Sea**

Directionality factor	unidirectional case	$\hat{\lambda} = 78\%$
	limited direction case	$\hat{\lambda} = 49\%$

The average  $\hat{\lambda}$  for the twenty sites is 80% in the uni-directional case and 68% in the constrained direction case. These values change little if sites of 20 kW/m or less are excluded from the average. The most directional sites are in the North Sea and the least are in the Atlantic. Conveniently these are also the most energetic sites. A comparison of two sites, one highly directional site in the Atlantic and one bidirectional site in the North Sea are shown in Figure F.6.

The impact of wave direction spread on long wave frontages compared to short frontages is estimated to be a reduction of 30-40%. A corresponding directional spreading factor of 70% is applied only to the results of the total available energy (it is not applied to the farm energy extraction calculation since the spreading factor is included in the capture width, see below).

## Energy extraction by farms of devices

### *Mean power extraction from devices*

One way to express the power absorption of a wave energy device is to consider its capture width. The capture width is defined as the mean power absorbed before losses  $\bar{P}_A$  [kW] as a proportion of the mean energy flux  $\bar{P}_I$  [kW/m]. Since the units of flux are kW/m, the result is a length. This length is not necessarily related to the width of the device and, depending on the operation of the device, can be wider or narrower than the device itself (Falnes 1997, Falnes 2002, Rainey 2001)

Most devices are able to capture energy only over a finite range of wave frequencies. This means that their capture width differs depending on the frequency of the waves arriving. The energy extraction technique used here takes an

assumed power spectrum for the sea and an assumed frequency-dependent capture width for a candidate device. The power spectrum is calculated for a particular representative site. The mean power from the device is then calculated first by assuming that it was installed at the reference site and then by scaling to local conditions using the ratio of the mean powers at the reference and actual sites. This step was necessary as spectra for only a few locations in the sea were available for use in this analysis.

### *Mean power spectrum*

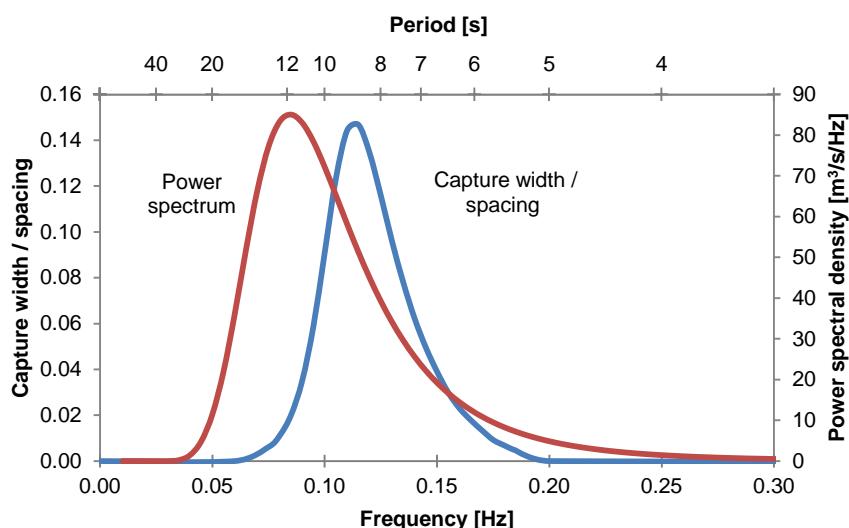
The mean power spectrum  $S(f)$  is calculated from a joint-probability distribution in significant wave height and energy period obtained from the Met Office wave model at a reference site  $D$  which is Point 2 on Chart 1. This is a deep water location and is roughly representative of the deep conditions found along the frontages chosen from the cost of energy analysis (see Figure 3.11).

### *Mean power absorption*

On the advice of floating wave energy device developers we have taken a view on the anticipated frequency dependent capture width of a device  $cw(f)$  and the likely spacing between devices  $Z$  [m]. For the purposes of this study, the capture width is an average condition that describes the performance of devices in arrays, in seas of varying directional spread, crossed, mixed and multi-modal seas. It includes all the features of the performance of the devices in an array including any constructive or destructive interference. It is also independent of the mean power in the sea. Note that this means that the directional spreading factor described above is not applied to the absorption model, it is implicit in the capture width used.

The sample power spectrum and the frequency-dependent capture width are shown in Figure F.7.

**Figure F.7 Average power spectrum and capture width**



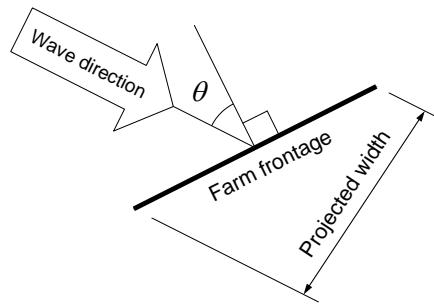
In arrays oblique to the predominant wave direction, a further allowance is made. In oblique arrays the effective spacing between devices becomes smaller. The proportion of the energy extracted at a particular frequency  $f$  [Hz] from a single row of devices spaced at  $Z$  [m] at an angle of  $\theta$  to the predominant wave direction is calculated as:

$$\varphi(f) = \frac{cw(f)}{Z \cos \theta} \quad E3$$

The fraction of the energy remaining behind the first row is then:

$$\phi(f) = 1 - \frac{cw(f)}{Z \cos \theta} \quad E4$$

**Figure F.8 Wave direction relative to a farm frontage**



The fractional power extraction for an array of  $R$  rows of absorbers in oblique regular waves is then:

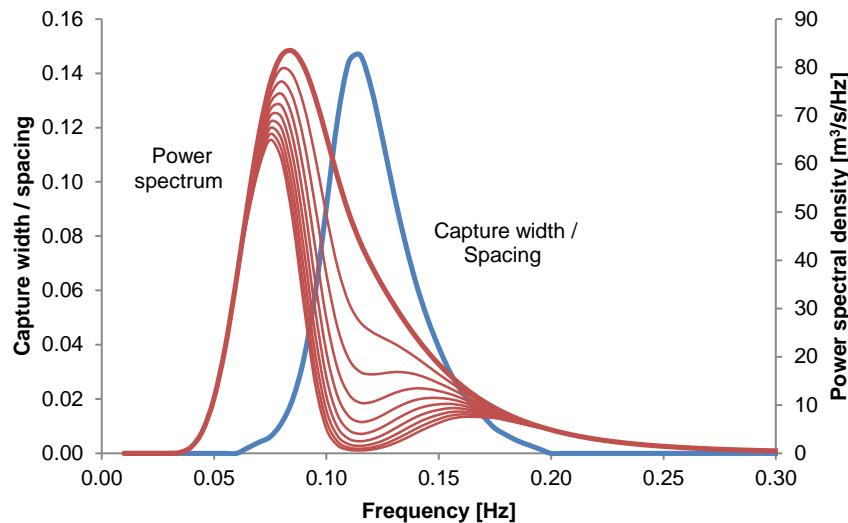
$$\varphi_{R,\theta}(f) = \sum_{r=1}^R \frac{cw(f)}{Z \cos \theta} \phi^{r-1} = \sum_{r=1}^R \frac{cw(f)}{Z \cos \theta} \left(1 - \frac{cw(f)}{Z \cos \theta}\right)^{r-1} \quad E5$$

And likewise for the energy produced by any set of consecutive rows starting at row  $R_1$  and ending at  $R_2$  inclusive is:

$$\varphi_{R,\theta}(f) = \sum_{r=R_1}^{R_2} \frac{cw(f)}{Z \cos \theta} \left(1 - \frac{cw(f)}{Z \cos \theta}\right)^{r-1} \quad E6$$

This can be illustrated by considering the effect on the original power spectrum by multiple rows of extracting devices, see Figure F.9.

**Figure F.9 Illustration of the effect on the power spectrum of frequency-dependent energy extraction for multiple rows of devices**



The power absorbed  $\bar{P}_{AD}$  per unit frontage  $F$  at the reference site  $D$  is calculated from the power spectrum as follows:

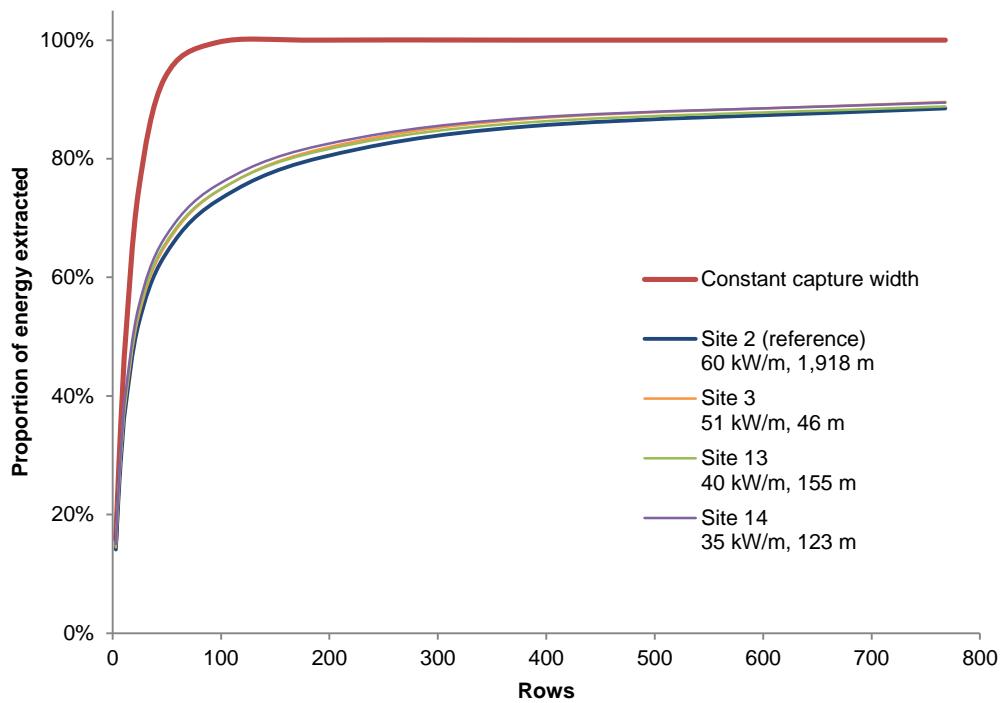
$$\frac{\bar{P}_{AD}}{F} = \rho g \cos(\theta) \sum_{j=1}^N \varphi_{R,\theta}(f_j) S(f_j) \Delta f \quad [\text{kW/m}] \quad \text{E7}$$

The power absorbed at the actual site  $E$  is calculated based on the incident powers  $\bar{P}_I$  at the reference and target sites. The mean power at reference site  $D$  is 60.3 kW/m.

$$\frac{\bar{P}_{AE}}{F} = \frac{\bar{P}_{IE}}{\bar{P}_{ID}} \cdot \frac{\bar{P}_{AD}}{F} \quad [\text{kW/m}] \quad \text{E8}$$

This approach assumes that the spectral spread of the power at the reference site is similar to all other sites. To test this assumption, three additional locations were used. These each had different mean power levels and water depths. The impact on the total absorption of multiple rows of devices is shown in Figure F.10. The sites used are numbered on Chart 2.

**Figure F.10 Impact on energy extraction of different reference site power spectra**



The water depth and mean power at each location is shown in the key.

The effect of using spectra from each of these different sites is limited to less than 3%. The reference site gives the lowest of all extraction suggesting that the candidate device used here might be better suited to the less energetic and shallower locations found at Sites 3, 13 and 14. The reference spectrum from Site 2 is used throughout and changes due to the use of different spectra are neglected as small.

The net power output delivered is then calculated. This assumes an absorbed-energy-to-wire efficiency of  $\eta = 80\%$ , appropriate to technologies ready to be deployed at this scale. The availability ( $A$ ) is location dependent (see Appendix C). This would give the annual energy production as:

$$E = \bar{P}_{AE} A \eta .8760 [\text{kWh/y}] \quad \text{E9}$$

### *Sensitivity tests*

Section 4.7 discusses some sensitivity tests on the model. One of these tests is to assume that the extraction model does not take into account the ability of the farm to extract different proportions of energy at different incident wave angles. The formulation for that sensitivity test is below.

$$\varphi_{R,\theta}(f) = \sum_{r=R_l}^{R_2} \frac{cw(f)}{Z} \left(1 - \frac{cw(f)}{Z}\right)^{r-1} \quad E10$$