THE CROWN ESTATE

UK Wave and Tidal

Key Resource Areas Project

Technical Methodology Report

February 2013

Executive Summary

This report describes the technical methodology behind the analysis of the size and distribution of wave and tidal resources around the UK. The study, undertaken by The Crown Estate, aimed to improve understanding of the future potential for wave and tidal project development.

We conducted the study using our Marine Resource System, with support from Black & Veatch Ltd. and in association with the Marine Management Organisation (MMO), Northern Ireland Executive, Scottish Government and Welsh Government, as well as Regen SW. Whilst not the first study of the UK's resources, the study improved on previous publications in the production of a consolidated view of all the wave, tidal stream and tidal range resources and made improvements in spatial analysis to determine the geographic distribution of resources.

The methodology included the following steps:

a) Reviewing existing literature on UK wave and tidal resources and resource estimation methodologies;
b) Identifying seabed areas which may have future potential for project development, by virtue of the existence of appropriate levels of wave or tidal energy resources and water depths;
c) Estimating the electricity that might possibly be generated in these areas, if generation devices were deployed across them;
d) Summation of the results for each area by type of resource and region of the UK.

Contents

Executive Summary 1

1 Introduction 3

1.1 Overview 3

1.2 This report and study approach 4

2. Methodology 7

2.1 Literature review 7

2.2 MaRS Modelling 9

2.3 Analysis of Power Generation Potential 11

2.4 Final Outputs – Summation of Results 13

References 14

Appendices

Appendix A – Wave Literature Review and Resource Assessment

Appendix B – Tidal Stream Literature Review and Resource Assessment

Appendix C – Tidal Range Literature Review and Resource Assessment

1 Introduction

Thank you for downloading this report from The Crown Estate website. This section gives an overview of the UK Wave & Tidal Key Resource Areas study and outlines what the report covers, as well as the study approach.

1.1 Overview

This report describes the technical methodology used to develop new findings about the size and distribution of wave and tidal energy resources in areas of seabed around the UK. These findings come from a study that we, The Crown Estate, have undertaken to improve understanding of the future potential for wave and tidal project development.

We undertook the study in accordance with our remit to enhance the value and act as stewards of the marine estate[1]. We have shared the results in order to help develop a common view across the industry and government about the potential for wave and tidal projects, so that when the industry is ready to take up this potential, we can provide leases and other appropriate development rights.

As well as completing the study, we have recently undertaken an industry engagement exercise to invite views from project developers, other companies in the industry and stakeholders about our future approach to leasing wave and tidal projects[2]. The deadline for responses was 21st September 2012. We are currently updating our approach to wave and tidal leasing and will be making a further announcement in due course.

For more details of The Crown Estate's work in wave and tidal energy, see:
http://www.thecrownestate.co.uk/energy-infrastructure/wave-and-tidal/

Marine planning

In the UK, several organisations have statutory responsibility for marine planning, including the Marine Management Organisation (MMO) in England and the governments of Wales, Scotland and Northern Ireland. These organisations are developing marine plans, and at present, this work is at various stages of completion. The Crown Estate recommends that, when considering future wave and tidal projects, developers consider the marine plans under development by these organisations, obtaining information from and liaising with the organisations as appropriate.

[1] The Crown Estate's role and responsibilities are set out in The Crown Estate Act 1961 and rights to exploit the renewable energy zone and gas infrastructure storage zone under The Energy Act 2004 (and amendments in 2008). See The Crown Estate website for details.
[2] See http://www.thecrownestate.co.uk/news-media/news/2012/wave-and-tidal-industry-invited-to-shape-future-leasing/

1.2 This report and study approach

This report sets out the methodology behind the Wave and Tidal Key Resource Areas study. A separate companion Summary Report details the results and is also available to download from The Crown Estate website[3].

The study was conducted by The Crown Estate with support from Black & Veatch Ltd. Input was sought from the industry and the work was carried out in association with a number of government bodies. These included the Marine Management Organisation (MMO), Northern Ireland Executive (Department of Enterprise, Trade and Investment), Scottish Government (Marine Scotland), Welsh Government, as well as Regen SW. The study findings are informing work by organisations with responsibility for marine spatial planning[4], including the Northern Ireland Department of Environment.

The work is informed by the methodologies from several other recent studies, including the wave and tidal stream energy resource assessments by the Carbon Trust[5], both of which were co-funded by The Crown Estate and involved other organisations including Amec and Black & Veatch. Information and data on tidal range resources were provided by the Energy Technologies Institute (ETI), drawing on its project to model tidal energy resources on the UK continental shelf[6], also involving other organisations including Black & Veatch and HR Wallingford.

The technical methodology included the following steps:

a) Reviewing existing literature on UK wave and tidal resources and resource estimation methodologies. This is discussed in Section 2.1;
b) Identifying seabed areas which may have future potential for project development, by virtue of the existence of appropriate levels of wave or tidal energy resources and water depths. Section 2.2 gives details;
c) Estimating the electricity that might possibly be generated in these areas, if generation devices were deployed across them. Analysis methodologies were carefully considered and the resulting estimates necessarily include some assumptions about project locations and device spacing. See Section 2.3; and

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[3] The Crown Estate 'UK Wave and Tidal Key Resource Areas Project – Summary Report', October 2012, is available for download from http://www.thecrownestate.co.uk/media/355255/uk-wave-and-tidal-key-resource-areas-project.pdf
[4] The Scottish Government (Marine Scotland) is developing sectoral marine plans and regional locational guidance to facilitate sustainable development of wave and tidal projects in Scottish waters.
[5] In connection with the Carbon Trust's Marine Accelerator. Available to download at http://www.carbontrust.com/resources/reports/technology/accelerating-marine-energy
[6] This included a literature review of potential UK barrage options and model results for tidal lagoon projects. For further information on the ETI project, see http://www.eti.co.uk/technology_programmes/marine.

d) Summation of the results for each area by type of resource and region of the UK, as covered in Section 2.4.

Figure 1 shows the process diagrammatically.

In parallel with the analysis, stakeholder engagement was vital to ensure information was incorporated from, and disseminated to, a number of organisations with interests in the project. It was also important for The Crown Estate to understand the range of criteria, technical and other, that influence wave and tidal project developers' assessments of site suitability.

While not the first study of the UK's wave and tidal resources (various data have existed for some years[7]), ways in which this study improved on previous ones include:

- The collaborative approach with marine spatial planning organisations;
- Improvements in spatial analysis to determine the geographic distribution of resources; and
- The production of a long term view of potential wave, tidal stream and tidal range resources.

Emerging nature of wave and tidal resource assessment

In this study we sought to use the latest available data and techniques. However, scientific understanding of wave and tidal resources is still emerging and at present, it is necessary to make a number of simplifying assumptions, some of which have a significant bearing on the results. For this reason, the results should be regarded as indicative of current understanding rather than conclusive. It is likely that the findings will be refined by further work in future.

[7] Including data associated with the Atlas of UK Marine Renewable Energy Resources, which was published last decade. See http://www.renewables-atlas.info/

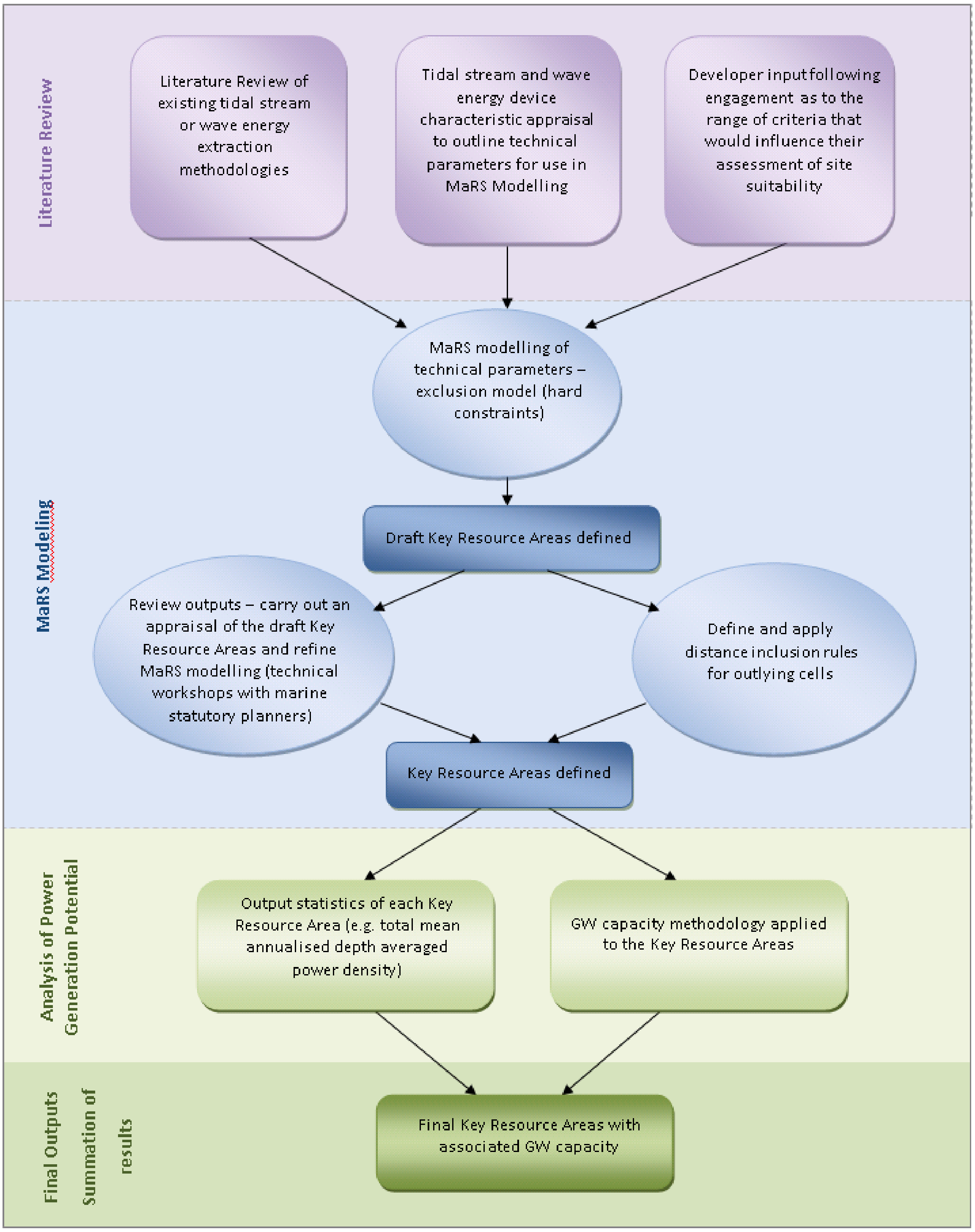

Figure 1: Study process

Source: The Crown Estate.

Notes:

- This describes the process conducted by The Crown Estate for wave and tidal stream resource assessment. For the tidal range results, we completed a literature review and the Energy Technologies Institute (ETI) provided data from their tidal resource modelling project. For further information on the ETI project, see http://www.eti.co.uk/technology_programmes/marine.

2. Methodology

This section gives an overview of the technical methodology used within the UK Wave & Tidal Key Resource Areas study.

2.1 Literature review

A literature review was undertaken to investigate the range of methodologies for estimating the energy extraction potential for wave, tidal stream and tidal range technologies. Three levels of resource assessments were reviewed; theoretical (considering resource constraints only), technical (considering resource and technical constraints) and practical (considering resource, technical and other practical constraints). From this, an understanding of the three levels of resource assessment was gained, along with the expected variation in resource estimates associated with each method. This review therefore informed our selection of criteria by which the theoretical and technical resources were defined. A practical resource assessment was not undertaken in this study.

In particular, the literature review emphasised that we were using the most up to date information available, but research is still required into understanding the complex hydrodynamics of the wave and tidal resource, and the added complexity of the impacts of energy extraction from the systems. In addition, the review identified that previous resource reports have different interpretations of the constraints applied to a theoretical, technical or practical assessment and consequently, the results of different resource assessments are not necessarily comparable. Careful consideration of the constraint criteria is required when looking at any resource assessment results.

The tidal stream literature review specifically provided insight into the potential resource that could be extracted in UK waters and the variety of previous selection criteria used to generate a range of potential resource assessment results. It is evident that some tidal stream resource assessments fail to consider the flux of energy available, which should be considered in any technical resource assessment, and use only a practical/spatial assessment of constraints. The literature also shows that resource estimations vary widely, depending on the constraints assumed (i.e. an economic factor, a technical limitation of depth or tidal velocities) and therefore, as described above, this impacts the results of any resource assessment.

In terms of wave energy, the review highlighted that wave energy extraction is likely to be constrained by environmental or (project) economic factors. However, further work is needed to understand the likely impact of such constraints on a broader, UK-wide basis. In terms of resource reports, it is important to include an assumption for these constraints in order to avoid overestimation of the UK resource; some reports have assumed all the resource can be extracted.

The tidal range literature review and modelling outputs provided by the ETI confirmed that there are extensive options for tidal range deployment in UK waters and that the tidal barrage options in particular have been investigated in detail.

The literature review included the most up to date work completed by the Carbon Trust[8] on the UK wave resource (2012) and the 'UK Tidal Resource and Economics' study published in July 2011. Both were used to identify and implement selection criteria appropriate for this particular UK wide assessment of wave and tidal resource. Note that these studies are not considered suitable for a local scale assessment (see Appendices A – C for the literature reviews).

The research into the site selection criteria (which define the boundary cut offs for the Key Resource Areas) indicated that, for wave and tidal stream, there is a potential for significant energy extraction when presenting a future view, based on the latest understanding of resources and devices. The physical boundary conditions on area selection were set in such a way that gave benefit of doubt to device designs and device-resource interactions for financial viability, given the science in the former, and engineering in the latter, are still in the process of being understood. This consideration is most important for tidal stream technology where substantial niche areas, such as shallow locations or low velocity sites, add considerably to the potential area of analysis in the technical resource.

As a result of the literature review, the Key Resource Areas aimed to encompass all potential technology characteristics, including potential future developments, to ensure that the locations selected incorporated all the possible resource which may be commercially viable, allowing us to understand the total theoretical opportunity across the marine estate.

In order to ensure that the analysis provided a good description of commercial opportunity, it was important that the technical factors influencing the analysis were considered from an industry viewpoint. The research therefore included developer engagement, to ensure that the range of criteria selected incorporated developers' knowledge. Views were invited through the trade associations RenewableUK, REA and Scottish Renewables through a technical parameters consultation. Responses were collated and fed into the technical analysis.

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[8] In connection with the Carbon Trust's Marine Accelerator. Available to download at http://www.carbontrust.com/resources/reports/technology/accelerating-marine-energy

2.2 MaRS Modelling

The Crown Estate's Marine Resource System (MaRS) was used to identify areas of seabed considered as being most technically suitable for potential wave and tidal stream development. The MaRS system is a GIS tool which analyses many layers of spatial information, combining them to help answer key resource planning questions. Spatial layers can be prioritised and combined in different ways to support a variety of studies, including the identification of areas most technically suitable (e.g. Key Resource Areas) or identifying areas where other users or interests might limit access to given resources.

The methodology for establishing development potential for wave and tidal stream energy using MaRS is formed by selecting criteria based on an up to date understanding of each resource, the technical characteristics of emerging technologies and foreseeable evolution of these technologies gathered during the literature review phase. Development opportunities were then categorised though the analysis of physical conditions (e.g. resource levels, water depths, sediments, distances etc.) that combine to create differing levels of opportunity and constraint. It is important to note that non-technical parameters (those arising from other sea users, interests and sensitivities) that may preclude wave or tidal development were not considered during this analysis of the technically suitable theoretical resource.

In some instances the presence or absence of appropriate physical condition thresholds were considered to be incompatible with wave and tidal development and so the area was excluded from the MaRS model. In other instances, physical conditions, such as suboptimal resource levels, were considered to represent a partial restriction on the activity that diminished the suitability of that area, and its relative influence is given a weighting. In the identification of Key Resource Areas, only the exclusions were considered to ensure that the resource areas identified encompassed a broad range of potential wave and tidal technologies.

Following the appraisal of existing wave and tidal technologies (Appendices A-C), as well as a review of developer inputs subsequent to engagement, a model was developed to ensure that all areas with unsuitable technical parameters for wave and tidal stream development were excluded. For example, at present, tidal stream technology is not predicted to be deployed within water depths of less than 15m (LAT); however the physical boundary conditions on area selection were set in such a way that gave benefit of doubt to device-resource interactions and device designs for financial viability and therefore, options to extract to 5m water depths were included. The parameters that were used within the technical exclusion model for identification of both wave and tidal stream resource can be found in Table 1.

	Exclusions	Criteria	Justification
Tidal Stream Energy	Tidal Resource (Mean Spring Peak Current, m/s)	Minimum: 1.5 Maximum: n/a	The tidal resource thresholds were investigated through literature review and consultation with industry and technical experts. A Mean Spring Peak current of 1.5 m/s represents the lower end of resource considered potentially viable in future for commercial extraction. This threshold has been used to encapsulate this broader view of future opportunity within the Key Resource Areas.
Tidal Stream Energy	Water Depth (m)	Minimum: 5 Maximum: n/a	Some sources quote that sites with water depths (LAT) of less than 15m are generally not economic for tidal stream technology in large scale commercial array development. In this project, however, we set a minimum depth threshold of 5m (and no maximum threshold) to ensure that all potential future niche tidal stream technologies targeting shallow sites were included within the analysis.
	Category	**Criteria**	**Justification**
Wave Energy	Wave Resource (Annual Mean Power Density, kW/m)	Minimum: 20 Maximum: n/a	The literature review and expert judgement identified that a minimum power density threshold of 20kW/m would represent the likely minimum cut-off for commercial scale resource. This was explored further at the technical workshops with statutory marine planning bodies and was also broadly supported following consultation with industry. It is noted that some technology developers believe that future technological advancement will allow commercial opportunity to be supported in lower resource sites.
Wave Energy	Water Depth (m)	Minimum: 10 Maximum: 200	Some evidence assumes that sites with water depths (LAT) of less than 15m should be excluded based on the likely required depth for near-shore technologies. Following the technical workshops with the statutory marine planning bodies discussed in the Review (c) Section, and consultation with the industry this parameter was amended to 10m to take account of the broad range of wave technologies and future potential. The most constrained depth was taken as 200m since this represents approximately the edge of the UK Continental Shelf, beyond which the depths increase dramatically.

Table 1: Parameters used within the technical wave and tidal stream exclusion models

To ensure that the defined areas encapsulated all of the likely commercial resource, the boundaries were extended to include adjacent model cells where viable resources could have been overlooked due to the coarseness of the model (1.8km for tide and 12km for wave).

The MaRS analysis for Key Resource Areas is potentially restricted by the extent of available data sets. Cells/regions where input data was incomplete were removed from the analysis. This largely related to areas close to the shore where, for example, there is limited resource data available. The modelling results, therefore, only covered cells where there was full data coverage (i.e. all input datasets are present). This had only minor impacts on the results as the majority of significant wave and tidal resource for the Key Resource Areas was represented by the data. The outputs of the MaRS modelling provided a draft output of the UK Key Resource Areas that was taken forward into a review process with the marine statutory planning authorities.

The appraisal undertaken aimed to establish whether the Key Resource Area outputs encompassed all potential future locations for commercial wave and tidal stream development based on current understanding of resources and technology. The review took the form of a number of technical workshops with the marine statutory planning bodies to discuss the results, in relation to the previously agreed technical parameters and thresholds applied.

Following this appraisal, the final Key Resource Areas were defined as per the criteria outlined in Table 1.

2.3 Analysis of Power Generation Potential

Following the definition of the Key Resource Areas, an analysis of power generation potential was undertaken. This section describes the methodology used to analyse the generation potential for UK wave and tidal stream resources, as well as the methodology applied by the ETI for the UK tidal range resource assessment. As noted earlier, the analysis of power generation potential considered only the theoretical resource within the Key Resource Areas and no economic or practical constraints were evaluated.

The wave installed capacity for the Key Resource Areas was calculated using the Carbon Trust 2012 model since this is the most up to date methodology available, as described in Appendix A. It is important to note that some of the boundary-defining constraint data, used within this resource assessment, are different to those used in the Carbon Trust 2012 report and this resulted in minor variations in the outputs. The differences are described in full in Appendix A. The methodology, at a high level, considered wave frontages around the UK aligned with the Key Resource Areas and energy extraction per row of converters from the base case resource. Theoretical rows of converters were assumed in order to calculate the energy extraction. In practice, it is likely that shorter and higher numbers of lines of converters would be deployed instead of the very long lines assumed in the analysis. This is because, in reality, long lines would not be possible due to a number of other considerations including other sea users, sensitivities and interests. A potential next step would be to undertake a practical resource assessment, by incorporating all the areas to be avoided and thus breaking up the long lines into shorter lines. For this technical resource assessment, it was assumed that energy can be extracted from the resource, up to the point the resulting resource drops below 20kW/m. This minimum power threshold was used as it was agreed to represent the likely minimum cut-off for installation of commercial-scale wave energy converters. For further details of this methodology, see Appendix A which describes the process in detail.

As described in Appendix B, the method for assessing tidal stream resource used both a farm (spatial consideration of resource) and a flux (available energy consideration of resource) assessment. The lower of the two calculation results was considered to limit the technical resource (due to either space limitation or total energy – flux – limitation, respectively). The literature review highlighted the importance of using both methodologies for the initial technical resource assessment. Site selection criteria applied in this assessment were broader than previous studies in the literature and were set in such a way that gave benefit of doubt to device-resource interactions and device designs for financial viability, as well as a consideration of the present technical potential. Some of the installed capacities for the Key Resource Areas would not, given present technology, be economically viable to develop at this time because some of the larger areas have low average depths (10m) and low mean power densities (0.5kW/m^2). Development in these locations would result in high numbers of very low rated (small) converters. Long term, nevertheless, it is conceivable these areas could be utilised by certain technologies.

As already described, the technical opportunity for tidal range presented within this project was derived in a different way. The Energy Technologies Institute (ETI) identified tidal range sites as part of its Tidal Resource Modelling project and provided a licence to The Crown Estate to use the results of this. A literature review in the ETI work identified tidal range options of over 100MW within UK waters, along with their associated installed capacities. The barrage options have been studied in detail previously and a full literature review can be found in Appendix C. Options for new lagoons were identified from specific criteria. The lagoon options previously identified in the DECC Options Definition[9] (located within the Severn Estuary) were also included. Lagoons were deemed to require a mean tidal range greater than 4m and a depth of 25m for location of the impoundment (as this is approximately the submergence depth below mean sea level required for conventional turbines). The ETI Continental Shelf Model (CSM) was then used to model the tidal range locations to provide a pre-feasibility view on the likely annual energy yield from each scheme. For more information, see Appendix C.

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[9] DECC Severn Tidal Power Strategic Environmental Assessment of Proposals for Tidal Power Development in the Severn Estuary. Options Definition Report. Version 3, April 2010. Available to download at http://www.decc.gov.uk

2.4 *Final Outputs – Summation of Results*

Following the analysis of power generation potential, the final outputs were analysed to provide a summation of the results. There were a number of considerations when analysing the results in relation to the total potential capacity outputs. These included the following:

- In some places, it may be possible to exploit the resource using more than one technology option, or a combination of technologies could exist. For illustration purposes, the results reflected the technology option(s) considered in this project which in theory would generate the largest amount of electricity. This is not to imply that these projects are in any way preferable or more likely to be built than others in practice. In some cases projects could co-exist; selection may be based on hydrodynamic modeling to optimise the resource available, the practical constraints and the project economics.

- Where either lagoon or barrage options were located within areas of seabed between administrative borders (e.g. Severn Estuary or the Solway Firth), the energy and power figures were split equally between regions.

- The potential installed capacity for each technology type has been calculated independently, in each case imagining the other technology types are not deployed. Since in practice the resources cannot be used in all ways at once, the results should not be summed.

For a full summary of the UK Wave and Tidal Key Resource Areas Project and its findings, see the Summary Report available from our website: (http://www.thecrownestate.co.uk/media/355255/uk-wave-and-tidal-key-resource-areas-project.pdf)

References

1. UK Tidal Current Resource and Economics assessment (CTC799), Carbon Trust, July 2011, http://www.carbontrust.co.uk/Publications/pages/publicationdetail.aspx?id=CTC799
2. UK Wave Energy Resource, Carbon Trust, October 2012, http://www.carbontrust.com/media/202649/ctc816-uk-wave-energy-resource.pdf
3. DECC Severn Tidal Power Strategic Environmental Assessment of Proposals for Tidal Power Development in the Severn Estuary. Options Definition Report. Version 3, April 2010. Available to download at http://www.decc.gov.uk

Appendix A – Wave Literature Review and Resource Assessment

THE CROWN ESTATE





Appendix A - UK Wave Resource in The Crown Estate's Key Resource Areas

December 2012

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Document issue details:

Contract Name:	The Crown Estate Technical Support				
Project Number:	121901				
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22.03.12	1st Issue	0	SW	AB	AB
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01.05.12	3rd Issue	2	SW	CL/JM	AB
20.12.12	4th Issue	3	SW	AB	AB

CONTENTS

1 INTRODUCTION 4

2 BACKGROUND 5
2.1 MaRS GIS 5
2.2 Literature Review 5
2.3 Methodology 9

3 CONSIDERATION OF ALL MARINE ENERGY SOURCES 12

4 REFERENCES 13

TABLES

Table 1 Carbon Trust 2012 UK Wave Energy Resource Results (GW) 7

1 INTRODUCTION

The Crown Estate is currently identifying Key Resource Areas for wave, tidal current and tidal range development as part of a larger scope of work to better understand their assets. Black & Veatch (B&V) is providing technical support to The Crown Estate in three aspects:

- The provision of 'engineering criteria', along with their associated scoring and weighting, for application into The Crown Estate's GIS Marine Resource System (MaRS) - which is being used for constraint mapping and as a means of identifying the potential Key Resource Areas.
- A methodology for assessing the potential future installed capacity of wave and tidal current developments within the potential Key Resource Areas, including a literature review, and the results from the application of this methodology.
- Analysis of the Pentland Firth and Orkney Waters Strategic Area to generate an estimated potential future installed capacity using the data output from a hydrodynamic model developed by ABPmer under a separate contract with The Crown Estate.

The Crown Estate identified Key Resource Areas, where wave and tidal current energy technologies could potentially be deployed in the future. The 'engineering criteria' for identification of the Key Resource Areas are defined in the UK Wave and Tidal Key Resource Areas Project – Technical Report which summarises the output of this work.

This report summarises the literature review and the associated methodology and results of analysis for the potential future installed capacity within Key Resource Areas. We believe the methodology applied is the most up-to-date and appropriate methodology to assess the resource based on existing data sets, as required for this work, and that this method has not been superseded (Section 2.2).

The analysis of the Pentland Firth and Orkney Waters Strategic Area in terms of installed capacity is also provided in this report. The Crown Estate required the analysis to consider the total potential future installed capacity within the Key Resource Areas. This includes the potential installed capacity using envisaged technology options and restrictions, without undue impact on the underlying hydrodynamic environment. This resource has been termed the 'Technical Resource' for the purposes of this report, and does not include any practical constraints or economic considerations.

2 BACKGROUND

The estimation of the potential for wave energy extraction in UK waters has been completed by various organisations over several decades. Each study uses a slightly different methodology, or slightly different inputs, which has resulted in a range of estimations which are not directly comparable and some of these key references are discussed in Section 2.2.

This is, to some extent, to be expected as the understanding about the resource and the technical potential for energy extraction improves, and the methods to estimate the potential are improved.

The behaviour of wave energy is, comparatively to other forms of energy source, complex and therefore a full understanding of various aspects is lacking (for instance in the incorporation of seasonal variability into the mean power estimations), primarily due to lack of widespread data.

This study has focussed on the 'offshore resource', i.e. that resource which enters the Key Resource Areas, and the study has not assessed the 'nearshore resource', because this is considered to be a part of the management of any future leasing. It is expected that this management of the Key Resource Area will also maintain future opportunity for any later Strategic Areas identified further offshore.

2.1 MaRS GIS

The Crown Estate's GIS tool, known as the Marine Resource System (MaRS), was utilised to overlay resource and constraint data, which was restricted, weighted and scored using recommendations from B&V on envisaged technology options, in combination with strategic decisions by The Crown Estate (informed by industry engagement).

The Key Resource Areas were established by a power density > 20kW/m (based on data from the Marine Energy Atlas and the ABPMer hydrodynamic model for the Pentland Firth and Orkney Waters Strategic Area), along with a maximum water depth of 200m.

2.2 Literature Review

The literature review is focussed on a selection of previous studies to estimate the potential UK wave resource in order to allow an agreed methodology to be derived for this study and to provide comparison to the figures presented in this report. The literature review highlights the variations in each methodology which means that it is difficult to compare the results as they cannot be considered as 'like for like' comparisons. Some of the differences include the type of analysis (theoretical, technical or practical), the location of the wave fronts, the consideration of directional spread and refraction, the incorporation of economic and environmental constraints (and the specific variables associated to weight their importance).

The only reports to provide a technical resource, which in theory should be comparable to the technical resource provided in this assessment, are the Winter 1980 paper, the ETSU 1999 report and the Carbon Trust 2012 report. The remainder of the reports all provide a practical resource with varying aspects of economic and practical constraints incorporated into the assessments, in addition to the impact from varying wave fronts and directional spread.

2.2.1 Carbon Trust, UK Wave Energy Resource (May 2012)

The Carbon Trust report and its methodology have been focussed upon in this review because it is the most recent estimate for the UK, and it is the methodology selected as the basis for this study. Black & Veatch was also involved in early scoping of the work and the outline methodology, as well as revisions to the report to its final (May 2012) version.

The Carbon Trust 2012 analysis produces two sets of results; one for offshore resource and the other for nearshore resource. Only the offshore resource is considered in this study for The Crown Estate. In the Carbon Trust report, the resource estimates are divided into:

- Total (Flux measurement of resource entering UK waters);
- Theoretical (Flux measurement of resource in areas of most promising economics);
- Technical (Theoretical resource considering potential technical extraction);
- Practical (Technical resource considering all sea uses and constraints).

The report assumes no regeneration following wave energy extraction around the UK. This is because previous studies have identified the nature of wave resource in that, for example, a 2kW/m wave resource would take approximately 100km of uninterrupted fetch to be regenerated and therefore, any energy that is extracted in the UK Exclusive Economic Zone (EEZ) could not be significantly regenerated inshore of the extraction.

Total Resource is affected by the far field effect of directionality, i.e. the orientation of the frontage compared to the predominant wave direction. The report estimates this from a flux model to provide the energy available based on the directionality, following extraction of data from 20 locations provided by the Met Office from model outputs. The directionality was estimated, on average across the sites, to result in a 30-40% reduction on the Total Resource. The near field effect (instantaneous directional spreading) is taken account of within the assumed capture width. The capture width, which has been estimated through discussions with wave technology developers, incorporates all power conversion losses in the system as well as bimodal frequency and multidirectional seas.

The Theoretical Resource uses the same method as the Total Resource; however, the areas are reduced to encompass only those which are considered the most economically attractive.

The Technical Resource considers rows of wave energy converters (WECs) in lines which are perpendicular to the predominant wave direction, and considers the energy that may be extracted.

The performance of most WECs remains unproven over the entirety of the design wave spectrum; therefore an assumption for a generic performance has been used.

Most of the WECs in development at this time focus their energy extraction on a fraction of the wave frequency spectrum. This means that there will be waves at higher and lower frequencies which will not be particularly well absorbed, therefore allowing these waves (as well as 'residual' waves from the frequencies which are well absorbed) to propagate towards the shore. WECs that could absorb well from all parts of the wave energy spectrum would require further economic optimisation. This means that not all wave energy can be absorbed.

These technical aspects are incorporated into the assumed capture width (following modelling by an offshore wave technology developer) along with all losses, including conversion losses.

There are also a number of resource effects which are described and incorporated into the overall capture width of the technology. They are:

- Farm scale effects, which take into account the overall direction of the waves and therefore the resulting energy available in relation to the entire farm (rather than specific devices which may be able to account for some of the directionality). To account for this effect, a spreading factor is applied to the frontage depending on the location.

- Shadow effects, which are created as each WEC absorbs energy. If the angle at which the devices are aligned is oblique to the wave frontage then these shadows are closer together. The overall effect is that more energy is absorbed from the same length line of converters than if the wave direction was perpendicular. This effect is accounted for within the average capture width assumed for the study.

The Carbon Trust report also recognises the more complex factors, required for detailed site assessments, of diffraction, scattering and constructive/destructive interference but does not include them in the high level resource assessment.

The conversion efficiencies (assumed to be 80%) are included into the overall calculation of the annual energy production. **Table 1** presents the Installed Capacity and Mean Power in GW.

Table 1 Carbon Trust 2012 UK Wave Energy Resource Results (GW)

	Total Resource	Theoretical Resource	Technical Resource	Practical Resource
Mean Power	26	18	11	8
Installed Capacity*	86	60	37	27

* estimated based on a 30% capacity factor

It is noted that the wave frontages have been reduced in length to account for energy which could be extracted within Irish and French waters and therefore for the resource that could potentially not be available for UK waters. The Faroe Islands are also highlighted but it is predicted that wave energy generation is unlikely on a commercial scale due to the lack of proximity for energy evacuation to either Iceland or Scotland. These resources are therefore excluded from the Carbon Trust study.

2.2.2 Marine Renewable Energy Strategic Framework, Approach to Sustainable Development. Report by RPS to the Welsh Assembly Government, March 2011.

The report establishes how the target of 4GW of installed capacity for wave and tidal current, as set by the Welsh Assembly Government (12), can be achieved (the 4GW is stated as 10% of the total resource available – therefore assumed to be 40GW, but the methodology for this calculation is not provided). It also investigates the potential constraints and how they could impact achieving this target. Low, medium and high energy yield scenarios are therefore provided; however, the split between wave and tidal for the final estimates is not clear, but it appears that the vast majority (>90%) of the resource estimate is based on wave energy.

The report is based on a farm methodology for device siting and consideration of the practical constraints within each area. The spatial farm methodology goes into considerable detail about which types of technology can be installed in specific areas within the Welsh territorial waters and it considers the potential overlap of technology types and wave/tidal area overlap. The constraints (practical constraints are ranked in order of their likelihood to preclude development) are overlaid to understand how they would impact the area available for development.

The aspect that appears to be missing from this farm methodology is the consideration of the energy that is actually available in the Welsh territorial waters and how much of that resource can technically be extracted (with or without causing environmental and/or economic impacts).

2.2.3 Offshore Renewables Resource Assessment and Development (Technical report), South West Regional Development Agency, 2010.

The aim of this study was to estimate the potential capacity for the South West region to develop wind, wave and tidal technologies. The process was to map the 'realisable resource' from 2010 to 2030, apply hard constraints and other constraints such as navigation, and then assess the potential capacity that could be installed in the areas with low constraints.

The report covers South West marine waters from the Bristol Channel to Bournemouth, out to the extent of the UK Marine Renewable Energy Zone (REZ). Limitations of the reporting were set as 50km offshore and 15kW/m power density. The report concludes that 1.2GW of practical installed capacity could be delivered in the development scenario for the specific region.

The methodology used in this report was a spatial farm methodology with overlaid constraints (IMO routes, wind farm licences, wrecks, anchorages, PEX-D locations, MOD areas, aggregates and dumping sites) similar to the hard constraints applied for the Commercial Resource. The methodology does not therefore consider the flux of the energy resource available in the study location for extraction (or that a large proportion of the energy in the South-West arrives through Irish Waters) or the limit, either economic or environmental, to the energy extraction. There is no information on the detail of the technology or energy extraction efficiencies (for example, impact of directional spread of energy, the power conversion losses and electrical losses).

The outputs from this assessment are therefore not directly comparable with these results.

2.2.4 Mackay, "Sustainable Energy — without the hot air, 2009.

This report includes an estimation of the UK wave resource. A 1000km wave frontage is selected with an average mean power density of 42kW/m. The assumption is made that wave devices have an overall power conversion of 50% and that a line of devices along 500km of the frontage may be developed. This results in c.10GW mean power (33GW Installed Capacity). We note that this approach would result in c.20kW/m power density behind the frontage which is still technically extractable.

2.2.5 Garrad Hassan, Scotland's Renewable Energy Resource 2001

The aim of the study was to develop resource maps, resource estimates and generation costs (2010 and 2025) for Scotland for a range of technologies including tidal current and wave. Only resource predicted by models to be available at less than 7p/kWh was considered to be technically and financially viable within 10 years (i.e. by 2010).

The methodology uses a flux method of wave frontages to assess the energy available in Scottish territorial waters. The methodology applies a Cost of Energy limitation (7p/kWh) in addition to a timescale limitation of deployment by 2025.

The installed capacity estimated for Scottish Waters was 14GW based on a practical assessment. The complete practical resource with the cost of energy and the timescale limitations means that the result is not directly comparable to the methodology applied in this assessment.

2.2.6 ETSU reports, 1985, 1992, 1999

The ETSU 1985, 1992 and 1999 reports are often quoted as the most relevant references on the UK wave energy resource. As a high-level summary:

- ETSU 1999 added no new information, referring to the 1992 Whittaker report for the total resource (600–700 TWh/year) and ETSU 1985 for the achievable resource (50 TWh/year).

It did not refer to ETSU 1992 for the achievable resource, worth noting as both were written by the same author.

- ETSU 1992 referred to the 1992 Whittaker for the total resource (600–700 TWh/year) and developed an achievable annual average power (7–10 GW) based on installed capacity and load factors. This would suggest a potential future installed capacity of c. 20-35GW.
- ETSU 1985 contained a detailed assessment of the UK wave energy resource. It estimated the wave resource by assuming an annual average wave power density and multiplying by the expected capture width (length of Atlantic-facing UK coastline). This produces the total power available. Other factors such as directionality, device spacing, absorption efficiency and conversion efficiency are then used to calculate the annual average power to the grid. This is multiplied by 8760 hours to produce the wave energy resource. As discussed in the 1999 report, the achievable resource was estimated at c. 50 TWh/year, which would equate to c. 20GW of installed capacity.

2.2.7 Mollison, Wave climate and the wave power resource, 1986

Mollison estimated a practical mean power extraction of 12GW which, when converted to installed capacity using an assumed 30% capacity factor, gives c. 40GW potential future installed capacity for UK waters. Wave frontages similar to those used in this study, and a net available energy (accounting for directional spread), are assumed.

2.2.8 Winter, The UK Wave Energy Resource, *Nature* **287**, 826 - 828 (30 October 1980)

Winter provides an estimated Total Resource mean power of 29GW which is compiled from a series of selected wave frontages around the UK (similar to the wave frontages associated with the Key Resource Areas in this study). The installed capacity, estimated with 30% capacity factor, gives c.100GW as the total potential future installed capacity. This Total Resource estimate does not account for technical aspects such as spacing and power conversion losses. Once these are included into the estimation, Winter provides a Technical Resource mean power of 7GW, which is equivalent to 23GW installed capacity. Practical constraints are not considered.

2.3 Methodology

The Key Resource Areas, as identified by MaRS, are used to create the wave frontages, and the underlying Carbon Trust 2012 methodology for calculating the mean power is then applied (with some limited changes as discussed below). The Carbon Trust model is used to estimate the technical resource using The Crown Estate defined wave frontages.

The Marine Energy Atlas resource data source provides a gross average power density. This is simply the sum of all the energy that is available at a single cell (from the complete multi-directional spectrum). Some wave technology types (e.g. point absorbers) can absorb wave energy from any direction. However, some technologies (e.g. some terminators and attenuators) are direction sensitive and then the gross average power density overestimates the resource available to them. A more accurate consideration would therefore be the net average power density resolved to a particular direction(s) from the directional spread for a particular technology. The Marine Renewable Energy Strategic Framework (9) assessment of Welsh Resource incorporates consideration for specific technology types; however, the Carbon Trust report (10) does not, although it does account for this directional spread within the capture width of the technology. This Carbon Trust method is applied as it is suitable for this UK wave resource assessment.

The conversion efficiency (mechanical input power to electrical power) of the technology is assumed by the Carbon Trust 2012 study to be 80%, however, we believe that this is too optimistic for present technologies and our base case uses 70% (with upper and lower bands of 50% and 80%).

The Carbon Trust 2012 report's final results assume no limitation on extraction. However, the report also assesses economic limits on the installation of wave technology and, depending on the cost threshold selected, the extraction limit varies accordingly. The 20kW/m constraint in this study could be considered to reflect a similar economic constraint, but the nature of the constraint application is different between the two studies and the Carbon Trust 2012 study has the potential to extract energy to well below the 20kW/m cut-off used in this study.

To explain the extraction limit used in The Crown Estate method further, once the extracted/absorbed energy has been established for each line of WECs, the remaining wave energy is considered and if there is a remaining resource > 20kW/m then a further line of WECs is assumed to be installed. In an assessment of wave energy extraction on a UK scale, the offshore resource can always be extracted to the lower limit of 20kW/m used in this study as a primary technical constraint, before the available space is filled with farms, i.e. a spatial study of extraction alone is likely to provide an over-estimate because of the vast space available (in regional and nearshore studies this is different because of technical limitations and practical constraints). The energy flux (20kW/m) should therefore be used to provide the limiting factor for offshore wave energy extraction because the point at which one would stop extracting wave energy in such an assessment will either be an economic or an environmental limitation. The economics have been investigated in various studies (7, 10) but are not considered in this study because The Crown Estate's interest is a longer-term view of resources available on the marine estate. The resulting cumulative hydrodynamic impacts of energy extraction will be researched in regional and UK wide hydrodynamic modelling as the industry progresses.

Various studies (7, 8, 9) have reviewed practical constraints to a high level of detail, ranking particular constraints with the level of likely impact on wave energy installations. Practical constraints will limit the amount of space available for installations, but appear unlikely to impact the total resource available for extraction unless (as mentioned above) the study is a regional or nearshore assessment where a high proportion of the space is more likely to be removed due to practical constraints.

The extracted mean (electrical) power produced from the Carbon Trust model for this study is then converted into an installed capacity based on an average assumed capacity factor of 30%, to be consistent with the literature (10).

As the Pentland Firth and Orkney Waters Strategic Area already exists, and hydrodynamic modelling of that area has been completed by ABPmer, this data is used to assess the area. The associated power density data has been used for this specific area (rather than the Marine Energy Atlas data) to refine the installed capacity.

The results for the Pentland Firth and Orkney Waters Strategic Area using the Marine Energy Atlas were compared to the results when using the ABPmer Pentland Firth and Orkney Waters Strategic Area model, and there is a c. 15% variation further to the error we have assumed for the Marine Energy Atlas model. This is deemed acceptable given the 15% standard error assumption is in relation to the total UK resource and therefore could vary on a site by site basis.

2.3.1 Uncertainties:

The data used in this assessment has uncertainties. This has an impact, along with the assumptions used in the methodology, on the overall accuracy of the outputs. These impacts are estimated as:

Resource: The power density data is from the 2008 version of the Marine Energy Atlas. This data set covers the study area; however, is at a coarse resolution (c. 12km x 12km grid cells) and based on modelling of a restricted number of years, with limited validation data. Based on experience we have estimated the error band for the long-term mean power density as ±15%.

Conversion Efficiency: Overall power conversion efficiency is assumed to be 70%. This includes the wave energy losses associated with the structure being present in the water, as well as conversion losses from mechanical input energy to electrical energy. There are wave technologies in development that have lower overall conversion efficiency and it is also possible that technologies will improve their overall efficiency in the future. We have therefore used a range for the conversion efficiency from 50% to 80% to account for this variation (i.e. an error band of +14%/-28%).

Capture Width: As per the Carbon Trust 2012 methodology, the capture width has been assumed for all sea states that occur in the long-term resource data. This is necessary due to (a) lack of data on the actual annual average wave resource (e.g. Hs/Te scatter diagrams) across the frontages, (b) lack of data on WEC performance. It is likely that WECs will be 'tuned' to the predominant wave characteristics (e.g. Hs/Te) and thus, the assumption is likely to be reasonable for the majority of the actual wave resource/scatter diagram and therefore, the wave occurrence. However, very small and very large waves, and to a lesser extent very short and long period waves, will be generally captured less efficiently by WECs. Therefore, the energy remaining for the shore-ward lines of WECs will tend to be concentrated in waves at the margins of the scatter diagram, reducing the actual capture width that these lines of WECs will be able to deliver in practice. This reinforces the need for a technical resource limit applied within a farm (offsetting the lower incremental costs of adding a further line to an existing farm compared to the costs of installing a first line in a resource). No uncertainty has been estimated for these effects.

Excluded resource: Where resource arrives in the UK's territorial waters from territorial waters outside the UK (France and Ireland) it is assumed that there is the potential for this energy to be extracted before it reaches UK waters and this therefore has, conservatively, been excluded. This excluded resource is provided separately as an indication of the additional potential resource from these areas.

Nearshore resource: The methodology developed for this assessment is only applicable to the offshore resource. However, the nearshore technical resource will be a fraction of the offshore technical resource, and be a smaller fraction of the offshore commercial resource, due to the increasing impact of practical constraints on the limited areas in the nearshore zone. We consider it unlikely that any nearshore technologies would target the residual wave resource of < 20kW/m remaining behind any offshore farms assumed by this methodology, especially as this resource would be reduced by the time it reaches the nearshore zone, and a significant proportion of the remaining resource will likely consist of sea states that are unsuitable for efficient energy conversion (see 'capture width' above).

An important consideration for the on-going management of the wave energy resource around the UK will be the planning of wave energy developments to maximise the overall future potential and avoid the 'best' offshore or far offshore resource being "blocked" by nearshore or offshore developments.

2.4 Discussion

The previous assessments, outlined in the literature review, estimate a technical installed capacity in UK waters of between c. 20GW and c. 40GW which may be compared to the results presented by The Crown Estate assessment (26GW) in the Summary Report.

Due to all the varying factors, as mentioned previously, two resource assessments are rarely directly comparable so it is important to recognise the main differences which are discussed here.

The Carbon Trust 2012 study, which used the same methodology and model as The Crown Estate study, calculates a technical installed capacity of 37GW, compared to 26GW for The Crown Estate. The main difference is the assumed constraint for installation of further rows of WECs, i.e. the point after which no further energy will be extracted. This is likely to be an environmental/consenting or an economic decision. The Carbon Trust report discusses an economic constraint, and their analysis considers the potential technical resource at varying cost thresholds. The 37GW quoted is the maximum technical resource, assuming very high cost thresholds. Decreasing the assumed cost thresholds would reduce the result from 37GW.

The ETSU 1985 report, which is the most common reference for UK wave energy estimates, provides an ‘achievable resource’ of 50TWh/y, and this would translate to a practical installed capacity of c. 20GW.

We believe that the MacKay, 2009, study which provides an estimation of c. 33GW for the practical resource is, as per the Carbon Trust 2012 report, an optimistic estimate of the potential wave energy development, but in this case it is due to a combination of factors. There is an assumed 50% reduction in the frontage despite the fact that this frontage can be placed at almost any distance offshore and thus avoid any major constraints, as discussed earlier. Removing this constraint would mean that the Mackay, 2009, methodology would estimate c. 66GW of installed capacity. The primary reason for the difference between the MacKay study and The Crown Estate/Carbon Trust study is that MacKay used 50% conversion of wave energy to electricity from the frontage, which is high after accounting for directionality issues, frequency-dependent capture width, conversion efficiency over multiple rows, and the need to impose economic (or kW/m) constraints on the installation and/or for any residual wave resource propagating to shore.

3 CONSIDERATION OF ALL MARINE ENERGY SOURCES

This analysis does not consider the cumulative impacts between different marine energy sources, in particular wave, tidal current and tidal range energy extraction. Each of these potential resources is considered independently and, where there is potential overlap, the extraction of one or more particular resources in the same area should be hydrodynamically modelled to optimise energy extraction.

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Appendix B – Tidal Stream Literature Review and Resource Assessment

Appendix B - UK Tidal Stream Resource in The Crown Estate's Key Resource Areas

May 2012

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CONTENTS

Contents

1 INTRODUCTION 4

2 BACKGROUND 4
2.1 MaRS GIS 5
2.2 Literature Review 5

3 METHODOLOGY 11
3.1 Site selection criteria 11
3.2 Farm methodology 12
3.3 Technical Annual Energy Production (AEP) 12
3.4 Other assumptions used in the model 12

4 REFERENCES 13

FIGURES

Figure 1 Carbon Trust Technical Results 6

1 INTRODUCTION

The Crown Estate is currently identifying Key Resource Areas for wave and tidal current energy development as part of a larger scope of work to better understand their assets. Black & Veatch (B&V) is providing technical support to The Crown Estate in three aspects:

- The provision of 'engineering criteria', along with their associated scoring and weighting, for application into The Crown Estate's GIS system (MaRS) - which is being used for constraint mapping and as a means of identifying the potential Key Resource Areas.
- A methodology for assessing the potential future installed capacity of wave and tidal current developments within the potential Key Resource Areas, including a literature review, and the results from the application of this methodology.
- Analysis of the Pentland Firth and Orkney Waters Strategic Area to generate an estimated technical installed capacity using the data output from a Hydrodynamic Model developed by ABPmer under a separate contract with The Crown Estate.

The 'engineering criteria' are defined in the UK Wave and Tidal Key Resource Areas Project – Technical Report which summarises the output of this work.

This report summarises the literature review and the associated methodology and results of analysis for the potential future installed capacity within Key Resource Areas. We believe the methodology applied is the most up-to-date and appropriate methodology to assess the resource based on existing data sets, as required for this work, and that this method has not been superseded (Section 2.2).

The analysis of the Pentland Firth and Orkney Waters Strategic Area in terms of installed capacity is provided in this report.

2 BACKGROUND

The Crown Estate identified Key Resource Areas, where wave and tidal current energy technologies could potentially be deployed in the future.

The Crown Estate required the analysis to consider the total potential future installed capacity within the Key Resource Areas. This includes the potential installed capacity using envisaged technology options and restrictions, without undue impact on the underlying hydrodynamic environment. This resource has been termed the 'Technical Resource' for the purposes of this report, and does not include any practical constraints.

2.1 MaRS GIS

The Crown Estate's GIS tool, known as the Marine Resource System (MaRS), was utilised to overlay resource and constraint data, which was restricted, weighted and scored using recommendations from B&V on envisaged technology options, in combination with strategic decisions by The Crown Estate (informed by industry engagement).

The Key Resource Areas are established by requiring a tidal current Velocity mean spring peak > 1.5m/s which is equivalent to a Power Density of >0.5kW/m^2 (based on data from the Marine Energy Atlas except for the Pentland Firth and Orkney waters Strategic Area which utilises hydrodynamic modelling data from ABPMer commissioned by The Crown Estate) along with a minimum water depth of 5m (LAT).

2.2 Literature Review

The basis for the methodology used in this study is described in the Carbon Trust 2011 report and its associated appendices (as outlined below). This is because the methodology used within the Carbon Trust 2011 report represents the approach to characterising a national-scale tidal current resource (using simple analytical expressions that can be applied to existing data sets without the need for a national-scale hydrodynamic model) which has now been widely adopted by other researchers and the industry (e.g. within the European Marine Energy Centre's 2009 'Assessment of Tidal Energy Resource' Guideline (19) and the present 2011 Committee Draft of the IEC's Tidal Energy Resource Assessment and Characterisation Technical Specification (20)). It is noted that the Energy Technology Institute is developing a UK wide hydrodynamic model (in a project led by Black & Veatch) that could be used to update the results in this study when it becomes available for use (expected to be in late 2012).

The literature review is therefore focussed on literature dealing with UK tidal current resource estimates, or regional aspects of that resource, in order to allow comparison to the figures presented in this report.

2.2.1 Carbon Trust, UK Tidal Current Resource and Economics assessment (CTC799), July 2011

In summary, the methodology used the following steps:

- **Site selection** is based on power density of > 1.5kW/m^2 and depth >15m.
- **The flux method** is first used to set the extraction limit for each of the areas, as described below. Using the power density, depth, area and other parameters identified in the site selection process, the power density and velocity limit is determined at each site. This step is used to ensure that energy extraction is limited to a certain level for each site.
- **The farm method** is then utilised to derive a theoretical tidal current array using the depth, area and other parameters identified in the site selection process combined with generic tidal technology parameters. This method is described in more detail below.
- **Economic** constraints are then applied, using iterations of the above to limit energy extraction at each site.
- **The Technical Annual Energy Production (AEP) (and installed capacity)** is then estimated by taking the lower value obtained from both the flux and the farm calculations at each site selected.
- **Practical constraints** are then considered to provide a practical resource.

The flux method

Three hydrodynamic mechanisms that result in tidal current conditions necessary for large-scale tidal current arrays are considered. These are:

- Tidal streaming: Tidal streaming is the physical response of the tidal system to maintenance of the continuity equation; when a current is forced through a constriction, the flow must accelerate.
- Hydraulic current: If two adjoining bodies of water are out of phase, or have different tidal ranges, a hydraulic current is set up in response to the pressure gradient created by the difference in water level between the two bodies.
- Resonant system: Resonant systems occur as a consequence of a standing wave being established. A standing wave arises when the incoming tidal wave and a reflected tidal wave constructively interfere.

The report concludes that the response of the different mechanisms to energy harvesting is not consistent, as previously predicted. Table 1 summarises the technical resource limit for each mechanism. The report's caveats and assumptions are important and include:

- Many sites may be impacted by more than one mechanisms, although one may dominate;
- Tidal streaming cannot be fully representative of all possible site characteristics;
- Blockage effects and alternative flow paths cannot be represented generically;
- The methodology is deemed appropriate to determine national-scale tidal current energy resources, but should not be used in isolation for the resource at any particular location.

Table 1 Technical Resource limits (Carbon Trust, 2011)

	Expression of technical limit of tidal current energy harvesting.	Hydrodynamic response limiting energy harvesting.
Hydraulic current	$P_{Technical} = 0.086 \rho g Q_{\max} a_o$	Velocity reduction
Resonant basin	$P_{Technical} = 0.033 \rho g Q_{\max} a_o$	Downstream tidal range
Tidal streaming	$P_{Technical} = 0.020 \rho g Q_{\max} a_o$	Downstream tidal range

The modelling and investigation associated with the report, and its comprehensive literature review, conclusively demonstrated that using solely the 'farm' resource assessment methodology is inappropriate, as initially indicated in the 2004/5 Carbon Trust reports (21).

Figure 1 summarises the total Technical Resource outputs, including the Annual Energy Production (TWh), Installed Capacity (GW) and area (km^2). The results presented here exclude the outputs for the Channel Islands because they are outside of The Crown Estate ownership.

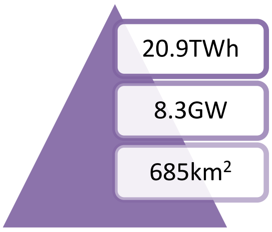

Figure 1 Carbon Trust Technical Results

We believe that this is the most up-to-date and appropriate methodology to assess the UK tidal technical resource based on existing data sets, as required for this work, and that this method has not been superseded.

2.2.2 Appraising the Extractable Tidal Energy Resource of the UK's Western Coastal Waters, Yates et al, 2011

This study covers both the tidal range and tidal current resource off the West coast. The ADCIRC model used is a 2-D depth-integrated shallow water model with an unstructured grid. Tidal current turbines were modelled (in terms of energy extraction impacts) as enhanced quadratic bed stress.

The study demonstrates that the conjunctive effect of a number of barrage schemes at different estuaries in the Irish Sea is significantly different from the linear sum of the individual scheme effects.

A tidal current study was carried out around the Isle of Man, assuming 6GW installed capacity in an area of 350km^2 between the Isle of Man and the Scottish coast based on devices spaced at 18 devices per km^2. The total annual output was found to be 14.5TWh taking no account of practical considerations and constraints. This annual output is shown to be more than a Solway barrage with a similar impact on the tidal dynamics in this region.

2.2.3 Marine Renewable Energy Strategic Framework, Approach to Sustainable Development. Report produced for the Welsh Assembly Government, 2011

The resource assessment for the above study was based on the Marine Energy Atlas (MEA), supplemented with local data sets where available. Tidal resource areas were identified as areas of > 2m/s Mean Peak Spring Current. 30MW was assumed to represent a commercial array size. The 'device spacing' was assumed to be 6MW/km^2, and only the farm method was applied. A 60% reduction in capacity was applied to represent the 'developable resource', allowing for other constraints such as environmental mitigation and other sea users. A detailed constraints analysis was then carried out; concluding that the target of 4GW of installed capacity for wave and tidal stream energy set by the Welsh Assembly Government can be achieved. The split in this target between wave and tidal energy is difficult to identify, but it appears that tidal represents about 6% of the target capacity.

2.2.4 Offshore Renewables Resource Assessment and Development (Technical report), South West Regional Development Agency, 2010

The aim of this study was to estimate the potential capacity for the South West region to develop wind, wave and tidal technologies. The process was to map the 'realisable resource' from 2010 to 2030, apply hard constraints and other constraints such as navigation, and then assess the potential capacity that could be installed in the areas with low constraints.

The tidal current resource was split into shallow water resource (5-30m water depth at LAT) and deep water. Tidal currents over 2m/s (Vmsp) were considered economically viable until 2020, 1.75m/s was considered as economically viable from 2020-30, and 1.5m/s was considered economically viable from 2030 onwards. Distances from shore ranging from 10km for shallow resource in 2010 to 50km for deep resource in 2030 were considered. Acceptable onshore distances to grid connections were considered depending on the size of the array. This identified the 'realisable resource'. Hard constraints such as MoD areas, aggregate extraction areas etc. were then applied. Soft constraints such as shipping densities were then later applied.

Generic arrays with defined dimensions were then put in the remaining areas to assess the potential capacity, using only the farm method. The results show a potential capacity of 780MW of shallow tidal current development and 300MW of deep tidal current development.

2.2.5 The Offshore Valuation, Boston Consulting Group, 2010

The Offshore Valuation utilises only the farm method on all resource areas with Vmsp>1m/s with no constraint on depth. An overall constraints reduction factor of 60% is then applied to account for practical constraints. This approach results in a 'practical resource' of 116TWh/y, equivalent (based on 30% capacity factor) to an installed capacity of c. 44GW.

2.2.6 Strategic Environmental Assessment (SEA) of Offshore Wind and Marine Renewable Energy in Northern Ireland, DETI, 2009

This study determined the 'resource areas' for offshore wind wave and tidal energy in Northern Ireland. Initially, the report estimates the theoretical resource based on a hydrodynamic model. Technical constraints of water depth (20-80m) and peak current flow (>1m/s) were then applied.

The study assumes that a commercial tidal array will be 50MW and occupy 1km^2, using the farm method. The 'resource areas' were allocated a number of arrays and then these arrays were assessed for environmental impacts and impacts on other sea users. Six arrays were found to have acceptable environmental and other sea user impacts, resulting in a predicted potential installed capacity of 300MW.

2.2.7 Mackay, "Under-estimation of the UK tidal resource", 2007 and "Sustainable Energy — without the hot air, 2009.

Mackay (13, 14) starts by evaluating the instantaneous power available from the Atlantic in UK's territorial waters. An overall average figure of 450GW (13) is initially proposed without consideration to the means of energy extraction. An arbitrary percentage is initially presumed to be extractable (13). In (14), assessment of the UK territorial extractable resource is apparently based upon a return to the 'farm' approach to resource characterisation. This approach takes in very large areas of low energy resource which is likely to be of low economic value for near term development (e.g. V_{msp} values of c. 1.65 m/s) and results in an installed capacity of c. 25GW in the UK.

2.2.8 Correcting the Under-estimate of the Tidal-Stream Resource of the Pentland Firth, Salter, 2009

Salter, most recently in (9), suggests that the tidal current energy resource available in the Pentland Firth should be at least an order of magnitude greater than identified in the Carbon Trust Marine Energy Challenge 2004/2005 analysis (17). The critical difference is the value ascribed to seabed friction. The tidal hydrodynamic modelling of the UK's continental shelf (underway by the Energy Technology Institute as discussed earlier) could assist in improving the current estimates of seabed friction across the UK and specifically for the Pentland Firth resource.

2.2.9 Quantification of Exploitable Tidal Energy Resources in UK Waters, ABPMer commissioned by npower Juice Fund, 2007

The ABPmer Juice-funded study [3] only utilises the farm method for resource estimation (15). However, this study does include shallow sites from 4m depth in a similar approach to this present study. The resource estimate was 19-36GW which accounts for area removed for exclusion constraints.

2.2.10 Atlas of the Tidal Energy Resource on the South East Coast of England. Prepared for the South East England Development Agency (SEEDA), May 2007

The SEEDA, 2007, report covers the South East of England region through Hampshire, Sussex, and Kent to Dover and North towards North Foreland. Admiralty Chart data and the BERR Marine Energy Atlas are used as data sources.

The report does not provide an overall total resource estimate. It does provide a "Potential annual mean power generation for areas of significant tidal stream resource". This assumes a 16m diameter rotor, allows for the Betz limit, a mechanical and an electrical efficiency, and provides a value for potential generation by that single device. It highlights the variability in performance of a single technology given variability in resource.

This report suggests there is more power density near to the Isle of Wight than the surrounding area, but does not give an indication of the generation capacity of arrays within these areas. In terms of tidal velocity and range, the sites with highest velocity and range are identified as per the Marine Energy Atlas data.

2.2.11 The Scottish Government – Strategic Environmental Assessment (2007) Full Environmental Report – Section B Marine Renewables Resource and Technology

The Scottish SEA refers to both the 2004/5 Carbon Trust work (17) on the UK tidal current resource and the 2004 Marine Energy Group summary on 'Harnessing Scotland's Marine Energy Potential' which was an update to the Garrad Hassan 2001 report. This incorporated a spatial farm assessment of the potential resource with a total expected capacity of 2.3GW installed capacity.

2.2.12 Scotland's Renewable Energy Resource, Garrad Hassan, 2001

The aim of the study was to develop resource maps, resource estimates and generation costs (2010 and 2025) for Scotland for a range of technologies including tidal current and wave. Only resource predicted by models to be available at less than 7p/kWh was considered to be technically and financially viable within 10 years (i.e. by 2010).

Tidal current resource estimates were based on data from Admiralty charts. In generating the power estimates for selected sites, the following assumptions were made:

2010	2025
30 m depth	60m depth
20m diameter average rotor size, twin rotor systems	40m diameter average rotor size, twin rotor systems
Lateral spacing: 60m or 16 units per km	Lateral spacing: 100m or 10 units per km
Axial spacing: 250m for narrow lines or 1000m for larger fields	Axial spacing: 1000m
Systems per km^2: 64 for narrow lines or 16 for larger fields	Systems per km^2: 10
Due to topographic problems only 66.6% actual packing density	Due to topographic problems only 66.6% actual packing density

Marine Current Turbines Ltd.'s parametric turbine model was used as the basis for calculating the potential of each area identified. Base case constraints were not applied because these were considered in the selection of the sites. Navigational constraints were applied as a sensitivity analysis using data from the COAST route database to get shipping densities for 10km by 10km squares which were then used along with other navigational constraints to allocate a level of navigational risk.

The results showed a capacity of 2 GW in 2010 with an annual energy yield of 8TWh for a number of small projects in relatively sheltered locations. The capacity reduces to 1.6GW when navigational sensitivity is applied. In 2025, the results show a capacity of 5.5GW with an annual energy yield of 25TWh for a large site in the Pentland Firth assuming no limitations on deployment. The capacity reduces to 1.3GW when navigational sensitivity is applied.

3 METHODOLOGY

As discussed above, we believe that the most appropriate underlying methodology to use for this assessment for The Crown Estate is that used by the Carbon Trust 2011 report.

The Carbon Trust results were strongly focussed on energy intensive sites that were likely to be economically feasible in the relatively near-term, although some of the less energy intensive sites considered were shown to be relatively uneconomic. The Crown Estate's interest is longer-term, and therefore the various assumptions in the Carbon Trust 2011 report need to be re-assessed, as discussed below, and it should be noted that the economic and practical constraints considered in the Carbon Trust 2011 study have not been considered in this assessment.

The following steps from the Carbon Trust methodology discussed in Section 2.2.1 were used.

- **Site selection;**
- **Flux method;**
- **Farm method;**
- **The Technical Annual Energy Production (AEP) (and installed capacity)** is then estimated by taking the lower value obtained from both the flux and the farm calculations at each site selected.

The 2008 version of the Marine Energy Atlas (MEA) was used as primary source of data for both the Carbon Trust report and this resource assessment for all areas outside the Pentland Firth and Orkney Waters Strategic Area. The Crown Estate commissioned hydrodynamic modelling of the Pentland Firth and Orkney Waters Strategic Area, by ABPMer, and this data was used for analysis of the Pentland Firth and Orkney Waters Strategic Area.

3.1 Site selection criteria

Sites retained from the source data in the present analysis feature:

- **Power density threshold**: > c. 0.5kW/m^2 (1.5m/s Vmsp).
- **Depths: >** 5m. However, only sites where there is an average depth > 10m are used.

The consequence of expanding the site selection criteria (from the 1.5kW/m^2 and >15m depth used in the Carbon Trust 2011 report) is that much of the resource identified is unlikely to be economic, and therefore developed, in the near-term.

3.2 Flux methodology

Given there has not yet been any further assessment of the arbitrarily prescribed limits to potential impacts (used by the Carbon Trust 2011 study) in the literature, the same limits are used in this present study, except that no economic constraints are applied. It should be noted that these limits have no legislative or regulatory basis; they are simply hypotheses. The impacts of large-scale tidal array deployments will likely be examined in detail on a case-by-case basis, but this study does not allow for this as it is a national-scale resource assessment and there is no data available.

For each of the sites identified, flux lines were generated and the primary hydraulic mechanism selected following the process used in the Carbon Trust 2011 work. As noted in the Carbon Trust 2011 report, many of the high velocity sites will be the result of a combination of 2 or more of the hydraulic mechanisms, and there remain uncertainties over the application of the methodology as described in Section 2.2.

3.3 Farm methodology

The B&V model to estimate the power output using the farm method relies on various underlying assumptions, as detailed below:

- **Clearance:** A maximum rotor diameter of 30m has been considered. B&V's recommendation for sites with a minimum depth of 15m was extended by The Crown Estate to a minimum of 5m. However, for sites in shallower waters**,** we have set a minimum rotor diameter equivalent of 10m to represent shallow technologies which could expand horizontally rather than vertically. For sites that are deeper than 20m, a top clearance of 5m has been considered (from LAT), as recommended in the EMEC standard. A bottom clearance of 25% of the depth has been applied to all applicable sites.
- **Spacing of turbines:** A spacing of 2.5d by 10d (or 1.25d by 20d) is used for first generation technologies. We believe that the spacing we have used is reasonable given the aim of this report is to assess the potential technical resource rather than the size of development sites.
- **Other generic parameters:** the following have been used to represent a generic tidal current technology:
  - Ratio of Vrated/Vmsp: 72%
  - Cp at Prated: 47%
  - Conversion Efficiency (mechanical to electrical): 90%
  - Availability: 90%

3.4 Technical Annual Energy Production (AEP)

The technical AEP is then obtained by taking the minimum of the fa**r**m and the flux AEP estimates to ensure that the energy extraction limit and the turbine packing density are not exceeded.

3.5 Other assumptions used in the model

To prescribe how much of the energy removal from the tidal hydrodynamic system can actually be ascribed to useful energy generation, one also needs to consider the following losses, which are described in more detail in the Carbon Trust 2011 report:

- **Drag losses on structure:** B&V assumed the percentage of energy wasted through the presence of the TEC device itself is around 15% of the total amount of energy extracted from the system.

Wake losses: B&V assumed the percentage of energy not captured by the turbines due to wake turbulence propagation between rows of turbine is around 10% of the total amount of energy extracted from the system.

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Appendix C - Tidal Range Literature Review and Resource Assessment

Appendix C - UK Tidal Range Resource in The Crown Estate's Key Resource Areas

With support from the Energy Technologies Institute

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CONTENTS

1 INTRODUCTION 4

2 LITERATURE REVIEW 4

3 POTENTIAL LOCATIONS FOR BARRAGE AND LAGOONS SCHEMES 4

3.1 Known barrage and lagoon locations 5

3.2 Other potential locations for lagoons....6

4 SUMMARY OF ASSUMPTIONS 11

4.2 Optimisation of the Tidal Current or Tidal Range resource 12

5 REFERENCES 13

TABLE OF FIGURES

Figure 1 Mean tidal range....8

Figure 2 Depth below mean sea level....9

Figure 3 Possible tidal lagoon locations 10

TABLE OF TABLES

Table 1 Summary of UK tidal barrage schemes from literature review 5

1 INTRODUCTION

The Crown Estate (TCE) requested that Black & Veatch (B&V), as an additional part of the scope of works for the Key Resource Areas technical input, provide guidance on the parameters for Key Resource Area identification for tidal range (tidal barrage and tidal lagoons).

B&V has experience of tidal barrage and site identification and therefore initially provided an introduction and initial overview of the likely parameters for selection of Key Resource Areas for Tidal Range technologies in the UK.

During later discussions, it was identified that the detailed work completed by B&V for the Energy Technologies Institute (ETI) on identification of Tidal Range sites (for their Tidal Modelling project) would be beneficial to this project for the purposes of identifying the most likely economic developments. The ETI was approached for the provision of this information and a licence for use of their information was provided. Therefore, the information on Tidal Range provided within this report, including the literature review on potential UK Barrage options and the model results for the Tidal Lagoon solutions were developed by the Energy Technologies Institute during the development of the UK Continental Shelf Models.

It should be noted that the literature review only covers tidal barrage as there is limited information published on lagoons other than the Severn Estuary lagoons from the Severn Tidal Power studies commissioned by DECC. The information from the ETI identifies new potential tidal lagoon sites.

The sites identified in this report incorporate, in some locations, alternative barrage and/or lagoon options. It is noted that these are therefore not cumulative in the amount of energy production at each location and only in certain circumstances (following detailed optimisation and modelling) could 2 lagoons, or a small barrage and a lagoon be installed at a single location.

2 LITERATURE REVIEW

There have been several previous tidal power studies for estuaries around the UK. The following studies of tidal power at locations in the UK have been reviewed:

- *Duddon Estuary Tidal Energy* (Parsons Brinckerhoff, 2010)
- *Mersey Tidal Power Feasibility Study* (Peel Energy, 2011a)
- *Preliminary Survey of Small Scale Tidal Energy* (Binnie & Partners [now B&V], 1984)
- *Preliminary Survey of Tidal Energy of UK Estuaries* (Binnie & Partners [now B&V], 1980)
- *Severn Tidal Power Feasibility Study* (DECC, 2010b)
- *Solway Energy Gateway Feasibility Study* (Halcrow et al, 2009)
- *Tapping the Tidal Power of the Eastern Irish Sea* (Joule Centre, 2009)
- *The Severn Barrage Project; General Report, Energy Paper No. 57* (Department of Energy, 1989)
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- *Tidal Power* (Baker, 1991)
- *Tidal Power from the Severn Estuary, Energy Paper No. 46* (Severn Barrage Committee, 1981)
- *Turning the Tide: Tidal Power in the UK* (Sustainable Development Commission, 2007)

The *Atlas of UK Marine Renewable Energy Resources* (BERR, 2008) has been reviewed and used to identify potential sites for tidal lagoons.

3 POTENTIAL LOCATIONS FOR BARRAGE AND LAGOONS SCHEMES

The potential estuary locations for large (greater than 100MW) schemes are well known and can be summarised from the previous studies listed in section 2. In the past, there has been less focus on tidal lagoons due to the additional length (and therefore cost) of their embankments relative to the energy output. The potential locations of tidal lagoons are less well documented, except in the Severn.

A coastal lagoon might, however, be chosen in preference to one of the previously identified barrage sites for other reasons. For example, so that the impounded basin is not within an area of particular environmental importance or so the embankment does not obstruct a major shipping route.

3.1 Known barrage and lagoon locations

A summary of the locations identified in the studies listed in Section 2 are given in Table 1, taken primarily from Baker (1991). The schemes are listed in descending order of installed capacity. This gives nine estuaries (shown in bold text) that have both installed capacity greater than 100MW and mean tidal range greater than 4m (commonly taken as a lower limit for economic viability and therefore used within this study). Strangford Lough has an installed capacity greater than 100MW but the mean tidal range is only 3.1m so has not been selected.

The preferred installed capacities and energy outputs from the recent Severn, Solway Firth, Mersey and Joule studies are different from those listed by Baker and given in Table 1 but this does not affect the selection of locations. In each of the cases listed in Table 1, the barrages use ebb-only operation.

Table 1 Summary of UK tidal barrage schemes from literature review

Location	Mean tidal range (m)	Basin area (km^2)	Installed capacity (MW)	Annual energy output (GWh)	Source
Severn Outer Severn Cardiff-Weston	7.2 7.8	1000 450	12,000 7,200	19,700 12,900	Baker (1991) Baker (1991)
Solway Firth	5.6	860	5,580	10,050	Baker (1991)
Morecambe Bay	6.3	350	3,040	5,400	Baker (1991)
Wash	4.7	590	2,760	4,690	Baker (1991)
Humber	4.1	270	1,200	2,010	Baker (1991)
Thames	4.2	190	1,120	1,370	Baker (1991)
Dee	6.0	90	800	1,250	Baker (1991)
Mersey	6.5	70	620	1,320	Baker (1991)
Duddon	5.8	38	220	336	PB (2010)
Stangford Lough	3.1	144	210	528	Baker (1991)
Milford Haven	4.5	20	96	180	Baker (1991)
Ribble	6.1	11	72	76	Joule Centre (2009)
Wyre	6.6		64	133	SDC (2007)
Cromarty Firth	2.8	36	47	100	Baker (1991)
Conwy	5.2		33	60	SDC (2007)
Loch Broom	3.2	7	29	42	Baker (1991)
Padstow	4.8	6	28	55	Baker (1991)
Loch Etive	2.0	29	28	55	Baker (1991)
Langstone Harbour	3.1	19	24	53	Baker (1991)

Location	Mean tidal range (m)	Basin area (km^2)	Installed capacity (MW)	Annual energy output (GWh)	Source
Hamford Water	3.0	11	20	38	Baker (1991)
Dovey	2.9	13	20	45	Baker (1991)
Loughor	3.9	41	5	15	SDC (2007)

3.2 Other potential locations for lagoons

The Atlas of UK Marine Renewable Energy Resources (Ref 13) has been used to identify potential sites for tidal lagoons. Areas were identified with both:

- Mean tidal range greater than 4m (assessed by taking the average of mean spring and mean neap tidal range). Contours of mean tidal range above 3.5m are shown in Figure 1.
- Water depth below mean sea level of 25m or less. Contours of depths below 30m are shown in Figure 2. A depth of 25m was chosen as this is approximately the submergence depth below mean sea level required for conventional turbines. There is some advantage in choosing a site with depths of 25m as turbines could be installed with minimal dredging. Building a barrage/lagoon embankment in deeper water than this would be very expensive, except for very short distances. Embankment costs are roughly proportional to the square of their depth, so lagoons become much less economically feasible as depth increases.

Note that the resolution of the grid in the Marine Atlas is relatively coarse. As a result, narrow deeper channels into estuaries are not picked up. In addition, the tidal range in the Thames estuary had to be manually adjusted based on Admiralty tide tables to reflect the increasing tidal range in the outer Thames estuary.

The areas where both criteria are met are shown in Figure 3. An additional constraint for a tidal barrage or lagoon design is the minimum depth of water at the turbines themselves. For example, the base level of a 9m diameter bulb turbine needs to be submerged to about 20m below spring low tide level to avoid cavitation problems. The required submergence can be achieved by dredging (cost and bed materials permitting). It should be noted that the submergence requirement is technology dependent and the DECC Severn Embryonic Technology Support (SETS) report (Ref 14) identifies a number of the upcoming tidal range technologies.

A second constraint on turbine siting is the depth of water into which the turbines will discharge. If the turbines discharge into shallow water there will be a large energy penalty due to additional head losses downstream of the turbines. This is because of the high velocities that will be forced to occur in these shallow waters as water flows away from the turbines. For illustration, the area where the depth is greater than 15m below mean sea level is shaded blue in Figure 3, with the shallower area shaded red.

Figure 3 indicates where lagoons operating at 80% tidal range, that we perceive as most likely to be economic, are potentially feasible:

- Along the eastern Irish Sea coast from Luce Bay in south-west Scotland as far as the east coast of Anglesey in north Wales. This includes the Solway Firth, Duddon, Morecambe Bay, Mersey and Dee estuaries identified previously. Lagoons are also possible on the eastern coast of the Isle of Man. Shallow water depths prevent effective turbine operation within the Solway Firth and close to the Liverpool Bay / north Wales coast.
- On the south Wales coast, the Severn estuary and along the north Devon and Cornwall coast. Large or small lagoons are possible in the Severn or south Wales coast but only

relatively small areas are possible in Devon or Cornwall (except at Bideford Bay) due to deep water off the coast.

- On the south-east England coast, between Brighton and Deal.
- In the Thames estuary, upstream of Southend and the Isle of Sheppey.
- Along the north of Norfolk and the Lincolnshire coast from east of The Wash to north of the Humber.
- Around the Channel Islands (the Channel Islands are excluded from this work by TCE).

There are an infinite number of possible lagoon alignments within this area, depending on the size and shape of the lagoon. The ideal barrage/lagoon location will have a high tidal range with a shape that maximises the impounded area whilst keeping the length of embankment to a minimum. The shape of embankment/coastline that maximises the impounded area to embankment length ratio can be broadly ranked as a:

1. Straight embankment across an estuary;
2. Straight embankment across a bay;
3. Semi-circular shaped embankment extending from a concave coastline;
4. Semi-circular shaped embankment extending from a straight coastline;
5. Rectangular shaped embankment extending from a straight coastline (the optimum shape for rectangular lagoon is for it to extend into the sea half the distance of the landside boundary, assuming that bed levels are uniform).

For any lagoon, economies of scale apply. For a straight coastline, a semi-circular lagoon has an impounded area equal to D/4 times the embankment length, where D is the landward boundary length. Hence as lagoon size increases, the basin area becomes proportionally larger compared to the embankment length. So, with the same coastline shape and bed levels, larger lagoons will be more cost effective than smaller ones. The same logic applies to other lagoon shapes.

As mentioned above, the lagoon embankment needs to have sufficient deep water to fit the optimum number of turbines for energy generation. Ideally the remaining embankment will be shallow to minimise construction costs. The lagoon shape will be largely determined by the shape of the coastline and bed depths so usually departs from a theoretical semi-circular shape.

To enclose the same area with a circular offshore lagoon as for a semi-circular lagoon attached to a linear coastline requires a 40% longer impoundment length. Most of the selected coastal lagoons take advantage of bays to reduce their impoundment length, making the additional embankment required for an offshore lagoon even greater. In addition, the water depths are likely to be deeper for an offshore lagoon and construction more difficult than for a coastal land-connected lagoon. So an offshore lagoon would have considerably higher construction cost, whilst the energy output would remain the same.

3.2.1 Other considerations for detailed lagoon selection

Note that a detailed site selection of tidal lagoon locations for actual project development purposes would consider many factors. Examples of important considerations include:

- Shipping routes and ports;
- Environmental designations;
- Geology along the embankment line;
- Longshore drift; and
- Wave exposure.

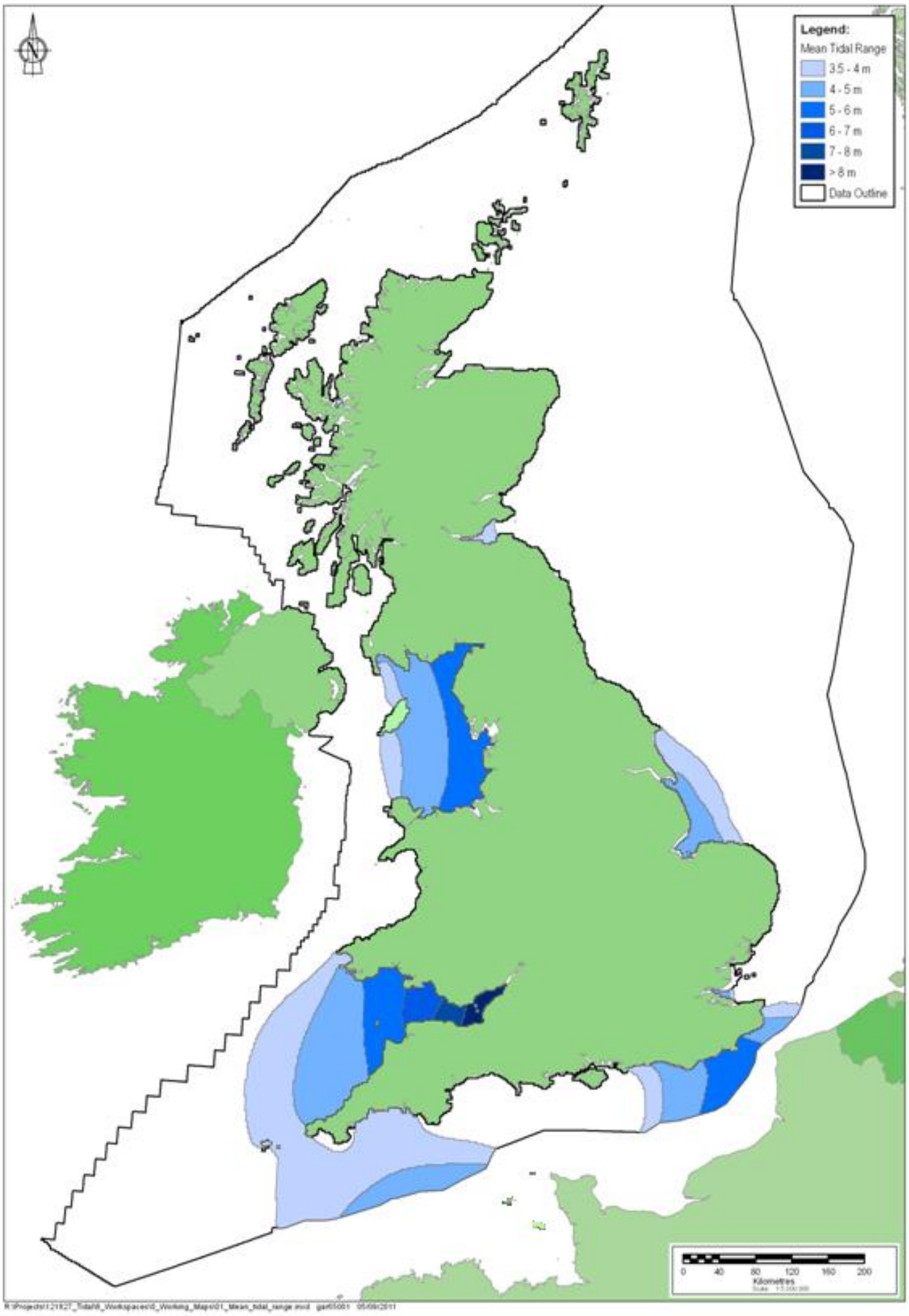

Figure 1 Mean tidal range

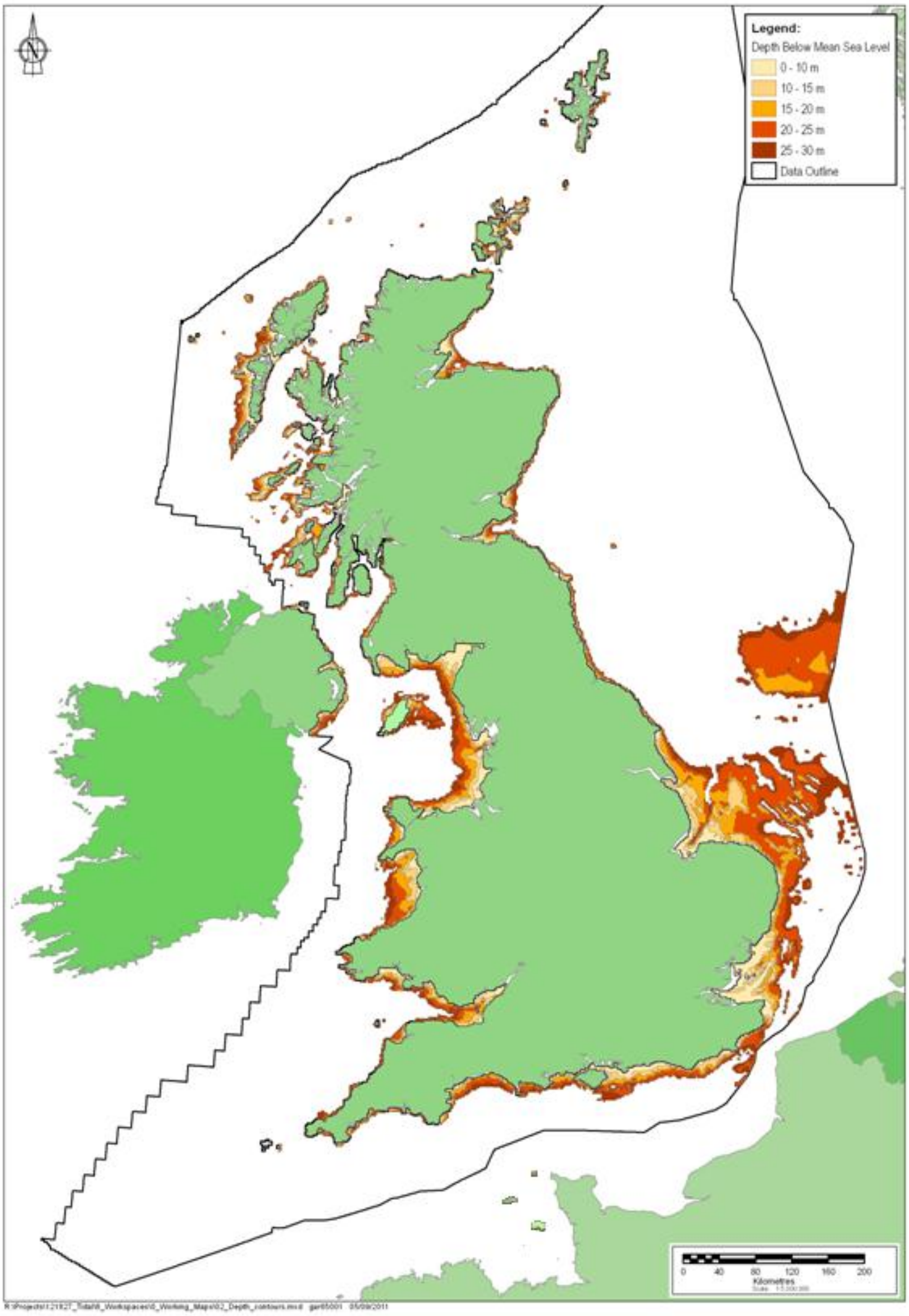

Figure 2 Depth below mean sea level

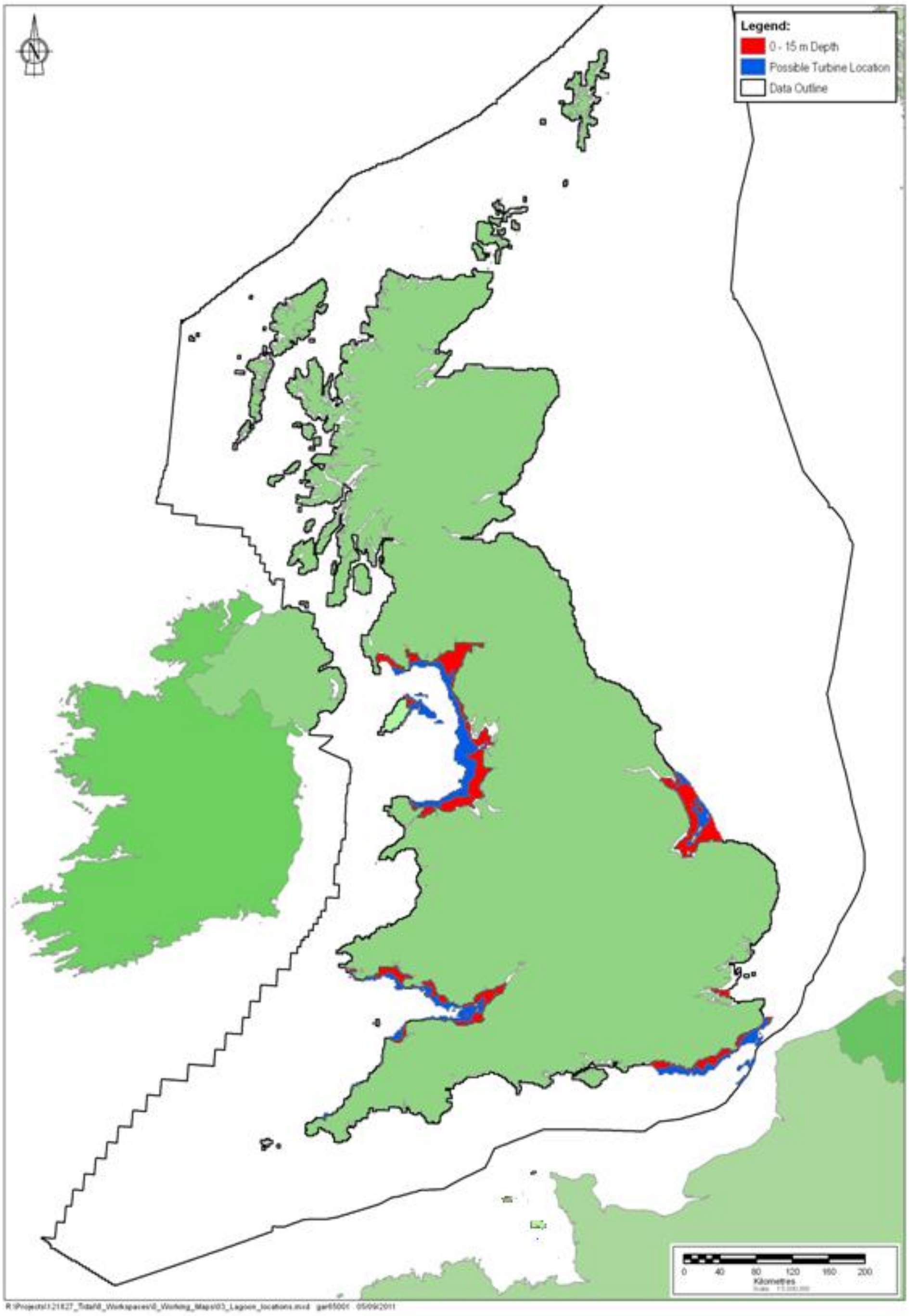

Figure 3 Possible tidal lagoon locations

4 SUMMARY OF ASSUMPTIONS

In the analysis, conventional turbines were reviewed. The turbine selection is based on a number of assumptions and a summary of the assumptions are listed below:

- Conventional turbines:
  - For ebb-only operation, the selection of diameter, speed and capacity have been taken from those used in previous studies.
  - For dual mode, the selection is as follows:
    - In all cases a runner diameter of 9m has been used;
    - A turbine speed of 50rpm has been adopted;
    - The turbine submergence requirement has been calculated using the method described by Baker (1991). This indicates that the base of the turbines should be approximately 20m below low tide level to prevent cavitation.
    - The rated head, and hence generator capacity, has been set at approximately 65% of the mean tidal range at the site;

The selection of installed capacity is based on the following assumptions:

- For ebb-only operation by conventional turbines, the installed turbine and sluice capacity from the most recent previous study of the estuary has been adopted;
- The installed capacity for dual mode schemes has been determined by comparing options using a flat estuary 0-d model. This model uses:
  - A tidal profile for three identical spring-neap cycles based on the M_2 and S_2 tidal constituents;
  - A scaling factor (equivalent to 8.295) to calculate the annual energy output (for 365 days) from that simulated over three spring-neap cycles (44 days);
  - An elevation-area table for the impounded area, where possible taken from previous studies;
  - Impoundment length and typical bed level;
  - Number and type of turbines;
  - Operating logic for starting power generation using head difference across the turbines and time since high or low water outside the impoundment.

4.1.1 Site specific considerations

Unfortunately the locations with large environmentally designated areas are those with the greatest energy. In these areas it will be important to maximise the tidal range within the basin to minimise the amount of compensatory habitat that would be required. This need is particularly likely to affect development of ebb-only operation as this causes larger reductions in tidal range.

The effect of a Cardiff-Weston barrage on shipping was found to be a major impact in the Severn Tidal Power study (DECC, 2010b). The volume of shipping is much greater in the Thames (three times as much as the Severn) and Humber (five times as much as the Severn).

Significant wave heights are considered at each location as this could impact design and ultimately costs.

Consideration of beaches designated as bathing waters, with the number of beaches roughly proportional to the impounded basin, should also be considered. A dual mode scheme with conventional turbines can lead to sudden, fast rises and falls in tide levels within the impounded basin. This could potentially affect the public's utility of the beaches within the basin.

4.2 Optimisation of the Tidal Current or Tidal Range resource

This analysis does not consider the cumulative impacts between different projects or different marine energy sources, in particular wave, tidal current and tidal range energy extraction. Each of these potential resources is considered independently and, where there is potential overlap, the extraction of one or more particular resource should be hydrodynamically modelled to optimise energy extraction.

Tidal current and tidal range sites have been identified as part of this work, and have the greatest potential overlap. The potential for overlap in relation to the Bristol Channel/Severn Estuary area, which has both a significant tidal range and tidal current potential, is discussed briefly below.

The Analysis of options for tidal power development in the Severn estuary - Interim options analysis report, Department of Energy and Climate Change studies (Ref 15) for the Severn Estuary did not consider tidal current generation (unless in combination with range) because the Severn Estuary was considered to have the most significant tidal range resource in the UK whilst the tidal current resource was not considered nationally significant (only 4% of the potential of UK waters).

The SDC report (Ref 12) provides a summary of the compatibility of tidal current, barrage and lagoon options in the Severn. The report estimates that a barrage would reduce the tidal velocity upstream by approx. 50% and downstream by approx. 10% and this effect would reduce at distances downstream. The effect of large scale tidal current deployment on a tidal barrage would need to be considered.

In conclusion, it would seem to be unlikely that tidal current technology would be deployed upstream of proposed or potential barrage alignments unless the possibility of developing a barrage was completely ruled out. Downstream of the proposed barrage alignments, it would be possible to deploy tidal current devices, although the interactions with potential barrage generation schemes would need to be modelled. It would also be necessary to consider conflicts with potential tidal lagoon sites. It is likely that similar conclusions would apply in other estuary locations; however, the respective energy outputs, economics and other site specific details would need to be considered on a case by case basis.

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