Programme Area: Marine

Project: Tidal Modelling

Title: Extraction Scheme Modelling Scenarios Technical Report

Abstract:

This deliverable is number 3 of 10 in the Tidal Modelling project and describes the scenarios to be used within the project to investigate the potential interactions between energy extraction sites. This report will be updated later in the project once the models have been constructed. The framework for constructing the various scenarios is to consider likely industry development for tidal range and current technologies on varying time horizons from the 2010 comparator base case scenario (where no significant tidal energy generation exists in UK waters), through to 2050 scenarios where it may be realistic to consider full utilisation of the economically viable UK tidal energy resource. Scenarios considering different combinations of future timeframe and development constraints (optimistic, medium, and pessimistic) for tidal current and range technology adoption are investigated. The Executive summary of the report describes the methodology and the outcomes. Section 5 of the report summarises the principal features and constraints of the models.

Context:

Launched in October 2011 this project involved Black & Veatch, in collaboration with HR Wallingford and the University of Edinburgh to develop a model of the UK Continental Shelf and North European Waters, 100 times more accurate than existing marine data. This has been used to assess the tidal energy potential around the UK (tidal range and tidal streams), to inform the design of energy harnessing schemes, to assess their interactions, and to evaluate their impact on European coasts. It can also be used to renew and inform flood defences, coastal erosion and aggregate extraction. Now completed, the project has been launched to market under the brand of SMARTtide. This is available to the marine industry under licence from HR Wallingford.

Energy Technologies Institute

MA1009

Tidal Modelling

(Modelling Tidal Resource Interactions around the UK)

PM01.03
Extraction Scheme Modelling Scenarios Technical Report

13th January 2012

Version 3.0

Participant Lead – University of Edinburgh
Other Participants – Black & Veatch and HR Wallingford

Document issue details:

B&V project no. Client's reference no.

Version no.	Issue date	Issue status	Distribution
1.0	11.11.11	1st Issue to ETI	ETI
2.0	09.12.11	2nd Issue to ETI	ETI
3.0	13.01.12	3rd Issue to ETI	ETI

Notice:

This report was prepared by Black & Veatch Limited (BVL) solely for use by Energy Technologies Institute. This report is not addressed to and may not be relied upon by any person or entity other than Energy Technologies Institute for any purpose without the prior written permission of BVL. BVL, its directors, employees and affiliated companies accept no responsibility or liability for reliance upon or use of this report (whether or not permitted) other than by Energy Technologies Institute for the purposes for which it was originally commissioned and prepared.

In producing this report, BVL has relied upon information provided by others. The completeness or accuracy of this information is not guaranteed by BVL.

CONTENTS

1 EXECUTIVE SUMMARY

The Energy Technologies Institute (ETI) has proposed the development of a *Continental Shelf Model* (CSM) of UK waters to assess the tidal energy potential around the UK, to inform the design of energy harnessing schemes and to evaluate their impact on European coasts. This report is part of the Tidal Resource Modelling (TRM) scope of work intended to deliver the CSM for the ETI. The TRM is delivered by Black & Veatch (B&V) as Prime Contractor with HR Wallingford (HRW) and the University of Edinburgh (UoE) as Subcontractors.

The aim of the TRM scope of work is to answer the following fundamental questions:

1. How will the interactions between tidal range and tidal current systems positioned around the UK's waters combine to form an overall effect?
2. Will the extraction of tidal energy resource in one area impact the tidal energy resource at distant sites around the UK and Europe?
3. What constraints might these interactions place on the design, development and location of future systems?

This will be achieved through a series of work packages and, ultimately, 10 deliverables of which this report forms Deliverable 03 (D03 – Extraction Scheme Modelling Scenarios).

The objective of the TRM study is to improve understanding of the possible interactions between tidal energy extraction schemes as they are deployed between now and 2050. The project will develop models that can be used to investigate how energy extraction at one site may affect the energy available elsewhere. It is intended that a wide range of possible future tidal range and tidal current sites and combinations, with differing technology possibilities will be represented in the models. The project will identify how the interactions between different sites around the UK combine to form an overall effect, and what constraints these interactions will place on the design, development and location of future systems.

Deliverable D03 provides a definition of and rationale for the tidal energy development scenarios to be implemented in the CSM being developed by the project team to meet the larger project objectives outlined above. The deliverable output will also define the technology sensitivity analyses to be conducted as part of the scenario implementation in the CSM.

Framework for scenario definition

The framework for constructing the various scenarios is to consider likely industry development for tidal range and current technologies on varying time horizons from the 2010 comparator *base case* scenario (where no significant tidal energy generation exists in UK waters), through to 2050 scenarios where it may be realistic to consider full utilisation of the economically viable UK tidal energy resource. Scenarios considering different combinations of future timeframe and development constraints (*optimistic*, *medium*, and *pessimistic*) for tidal current and range technology adoption are investigated. The core set of scenarios developed using this framework present a cumulative build up of installed capacities of both technologies by defining a preferred project build order. Additional *special* scenario cases are prescribed to investigate the most radical development scenarios that have been proposed in the literature or propose alternative development timescales. An *extreme* scenario is proposed that pushes the boundaries of the most optimistic view of potential tidal energy technology deployment To allow for input from the ETI, it has been assumed that across the project lifetime, 40 scenarios rather than the 30 currently being presented may be required. The ETI therefore has flexibility to contribute to and comment further on scenario definition in order to define these additional 10 scenario cases based upon the output and learning from the project deliverables. Existing industry targets and assessments have been used to inform the proposed scenario developments in conjunction with incorporation of the outputs of deliverables D01 and D02.

Selection of extraction schemes within each scenario

For each tidal range and tidal current site identified for inclusion in a specific scenario, it is necessary to match appropriate technology characteristics with site characteristics in order to specify the extraction scheme best suited to that location. Therefore extraction scheme selection and design and choice of design must be conducted simultaneously.

Many of the factors impacting on extraction scheme selection within each scenario are common to both tidal range and tidal current systems. However, the level and quality of input data required to inform these decisions differs significantly between the two systems.

The comparative maturity of the tidal range approach, history of project development and investigation of potential deployment site issues provides a strong platform upon which to base the selection and design of extraction schemes. In contrast, there is only a very limited history to support the development of tidal current schemes as the issues involved at a project design scale remain the subject of intense debate – the difficulty experienced when conducting national scale assessment is magnified.

Therefore, once the basic decisions have been made as defined in the scenario framework, the tidal range and tidal current systems are progressed separately while attempting to best meet the specific criteria that fit that particular point on the development timeline.

Tidal range scheme selection and design

A theoretical two-dimensional matrix is being used to prescribe the varying timeframe being considered (in ten year increments from 2010 to 2050), and the degree of alignment of external support to facilitate industry development in those years (optimistic, medium and pessimistic). Deliverable D01 supplied a comprehensive review and update of the energy generation potential of the identified tidal range schemes including assessments of the viability of multiple technology and operational mode combinations. A set of constraints has then been established that is used to inform decision-making regarding the appropriate order of development of tidal range projects (see section 4). These constraints are then applied in section 5 of the document to establish the preferred build order for tidal range systems in the UK. The build order is informed by economic, environmental and practical considerations as discussed in detail in section 5 for each scheme option. Thirty distinct scenarios are prescribed.

An overview of the scenario decision outcomes in terms of build order, project combinations and preferred operational mode is summarised in the following table

Summary of the build order adopted for tidal range technologies in the scenario analysis

				Suggested installed capacity		
Year	Optimism	Location	Operational mode (turbine type)	No. of turbines	Total installed capacity (MW)	Indicative energy output (TWh/y)
2020	Medium	Bridgewater Bay	Dual (conventional)	120	3600	6.9
2020	Optimistic	Kirkcudbright Bay	Dual (Rolls-Royce)	12	110	0.3
2030	Medium	Cardiff-Weston	Ebb (conventional)	216	8640	18.7
2030	Optimistic	Mersey	Dual (Rolls-Royce)	40	570	1.4
2030	Special	Severn (Outer)	Dual (conventional)	875	15750	45.0

	(case 22)					
2030	Special (case 23)	Cardiff-Weston	Dual (Rolls-Royce)	1065	5130	17.0
2040	Medium	Morecambe Bay	Dual (Rolls-Royce)	320	3670	10.5
2040	Medium	Wash	Dual (conventional)	350	4900	8.5
2040	Optimistic	Dee	Dual (conventional)	60	1080	2.2
2050	Medium	Solway Firth	Dual (conventional)	1100	19800	31.0
2050	Medium	Rye Bay	Dual (conventional)	110	1980	3.2
2050	Medium	West Aberthaw	Dual (conventional)	45	1215	2.3
2050	Medium	Rhoose	Dual (conventional)	40	1080	2.0
2050	Optimistic	Wigtown Bay	Dual (conventional)	160	2240	3.8
2050	Optimistic	Dymchurch	Dual (conventional)	110	1980	3.2
2050	Optimistic	Oxwich Bay	Dual (conventional)	16	352	0.6
2050	Extreme	Humber	Dual (Rolls-Royce)	200	1340	3.7
2050	Extreme	Thames	Dual (Rolls-Royce)	110	530	1.8
2050	Extreme	Cumbria	Dual (conventional)	70	1260	2.2
2050	Extreme	Morte Bay	Dual (conventional)	14	252	0.4
Never		Dee/Wirral	See text	0	0	0
Never		Duddon	See text	0	0	0

The energy generation potential of the various tidal range technology scenario configurations is summarised in the table below. The steady increase in energy generation through the first half of the table as the scenarios build combine together to provide a wide range of scenario test cases for implementation in the CSM ranging from low levels of generation to very significant energy generation contributions in the UK context (for reference, total UK electricity generation from all sources in 2010 was 381 TWh). Further information relating to the development of the scenario definitions in terms of final scheme selection and build order is presented in section 5.

Indicative tidal range energy output (TWh/y) of various scenario development combinations

Year	Case numbers	Optimism	Ebb (conventional)	Dual (conventional)	Dual (Rolls-Royce)	Total (TWh/y)
2020	2, 4, 21	Medium	0	6.9	0	**6.9**
2020	3	Optimistic	0	6.9	0.3	**7.2**
2030	5, 7	Medium	18.7	6.9	0.3	**25.9**
2030	6	Optimistic	18.7	6.9	1.7	**27.3**
2030	22	Special	0	45.0	1.7	**46.7**
2030	23	Special	0	23.9	1.7	**25.6**
2040	8, 9	Medium	18.7	15.4	12.2	**46.3**
2040	10	Optimistic	18.7	17.6	12.2	**48.5**
2050	11, 14, 15	Medium	18.7	56.1	12.2	**87.0**
2050	12	Optimistic	18.7	63.7	12.2	**94.6**
2050	16, 18	Extreme	18.7	66.3	17.7	**102.7**
2050	24, 25	Special	0	0	0	**0**
2050	19	Special	18.7	51.4	12.2	**82.3**
2050	20	Special	0	14.9	5.5	**20.4**
2050	26	Sensitivity	48.1	24.6	0.3	**73**
2050	27	Sensitivity	18.7	67.6	16.0	**102.3**
2050	28	Sensitivity	0	0	83.3	**83.3**
Multiple	9, 13, 29, 30	Pessimistic	0	0	0	**0**

Tidal current scheme selection and design

Existing scenario development proposals have been reviewed to provide guidance and boundaries on potential industry development (section 6.1). This review identified that although there are a wide variety of predictions of the future potential of tidal current energy in the UK, there is generally no significant consideration of how these projections can practically be achieved. More significantly, the spatial variability of the tidal current resource requires high resolution data to ensure that a project design will coincide with the intended resource. The project team therefore agreed that it was necessary to formalise an alternative methodology for selection of tidal farms for this project. Otherwise there would be potential for significant mismatch between the resource identified by the CSM and the extraction schemes developed using the existing knowledge base. Further discussion of the reasoning behind the need for an updated approach to the specification of tidal current development scenarios beyond the original intent of the RfP is presented in section 6.2.

The new approach has developed a top down decision support tool to inform scenario definition. As detailed design of large scale TEC development projects has yet to be undertaken given the relative immaturity of the sector, it has been necessary to foresee the key drivers that will define project selection. In simple terms the scenario specification framework has been driven by the availability of appropriate tidal energy resource for exploitation, so a hierarchy of factors has been identified:

1. The strength of the resource (the mean kinetic power density has been identified as being the most appropriate measure of the resource from a technology perspective in terms of identifying energy yield potential).
2. The suitability of the resource location for technology application. Depth is therefore a leading constraint (although this is expected to relax over time as technology suited to deployment in deeper water reaches commercialisation). Distance to shore also has economic implications.
3. Environmental impact constraints potentially limiting the extent and density of farm deployments.
4. Additional factors that would have a negative impact on project cost through increased design requirements (e.g. the local wave climate).

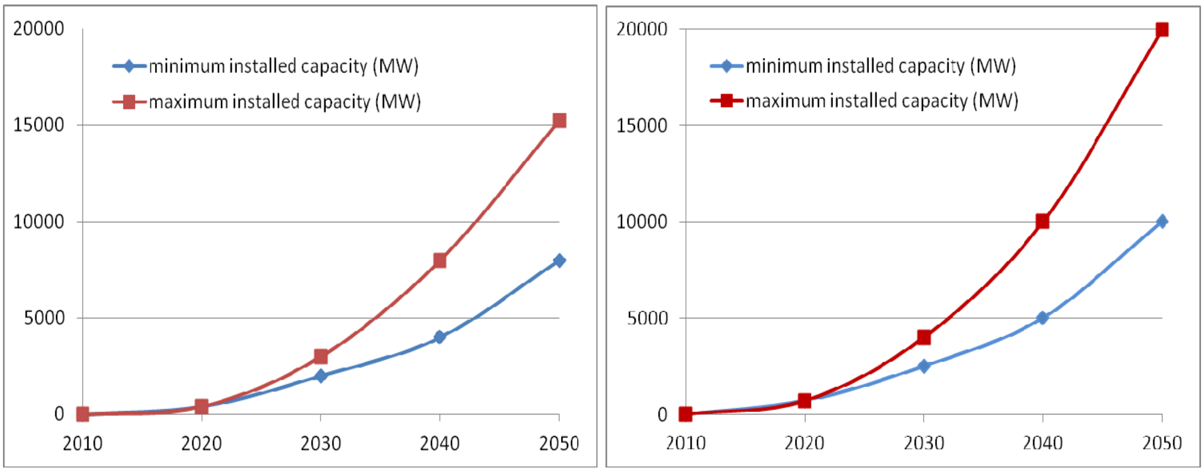
Overarching constraints underpinning development are also imposed to ensure that the proposed scenarios maintain credibility:

1. Supply chain and industry confidence: a band of minimum and maximum installed capacities is imposed in each scenario timeline to provide acceptable bounds within which the industry and supply chain can grow. This is in part reflective of economic constraints (e.g. appetite of public and private investors), and additionally engineering constraints (e.g. the ability to respond to required build rates given the inherent difficulties of weather windows, operational equipment availability, mass manufacture of device, and not least the project development timescales in terms of leasing and consent).
   This approach also has benefits from an ETI-TRM perspective as it ensures that a wide range of deployment levels will be examined across the suite of scenarios.
2. Technology capability also limits development in terms of accessing and exploiting resource. As the technology matures, a wider resource becomes potentially economic to develop in terms of opening up access to deeper water, and cost reduction through learning and development experience altering the economics of more marginal resource sites.

The final consideration in scenario specification has been considering the goals of the EI-TRM project itself. The project is intended to examine a wide range of TEC deployment levels and push the envelope in terms of the upper limits in order to better inform discussion of the potential future prospects of the technology. A summary of the identified constraints that the CSM simulations will use to identify suitable development locations is presented in the table and figures below.

Summary of overarching tidal current energy scenario constraints

			Installed capacity (MW)		Mean kinetic power density (kW/m^2)	
Year	Case numbers	Optimism	Minimum	Maximum	Target value	Absolute value
2010	1, 17	n/a	0	0	n/a	n/a
2020	2, 3	Medium	400	400	n/a	n/a
2020	4	Optimistic	700	700	n/a	n/a
2020	21	Special	1000	1000	n/a	n/a
2030	5, 6, 22, 23	Medium	2000	3000	3.0	2.25
2030	7	Optimistic	3000	4000	2.25	2.0
2040	8, 9, 10	Medium	4000	8000	2.0	1.80
2050	11, 12, 13	Medium	8000	15250	1.65	1.50
2050	14	Optimistic	1000	20000	1.50	1.50
2050	16, 18	Extreme	15250	40000	1.50	2.50
2050	24	Special	85000	85000	n/a	n/a
2050	25	Special	Unlimited	Unlimited	n/a	n/a
2050	29	Sensitivity	30000	Unlimited	1.4	1.2
2050	30	Sensitivity	Unlimited	Unlimited	1.0	1.0
Multiple	15, 19, 20, 26, 27, 28	Pessimistic	0	0	n/a	n/a



**Imposed installed capacity limits, 'medium' case (left), 'optimistic' case (right).
The 'extreme' case is not shown but builds upon the 2050 optimistic specification.**

Although a different methodology has been required to develop the tidal range and tidal current development scenarios, the approach taken in both cases is remarkably similar. The differences relate to the existing level of experience. Hence the tidal range scenarios are largely based upon existing project proposals and knowledge. The tidal current scenarios are required to envision their own future project proposals to inform scenario design and selection.

2 INTRODUCTION

The ETI has proposed to develop a *Continental Shelf Model* (CSM) of the UK waters to assess the tidal energy potential around the UK, to inform the design of energy harnessing schemes and to evaluate their impact on European coasts. *Black & Veatch* (B&V), in collaboration with *HR Wallingford* (HRW) and the *University of Edinburgh* (UoE), is providing support with regard to the development of this model and subsequent use by the tidal power industry. This report has been led by HRW and is part of the *Tidal Resource Modelling* (TRM) scope of work delivered by B&V as prime contractor.

B&V has been consulting on tidal energy since 1975 (B&V was previously Binnie & Partners in the UK until 1995). We have a very broad and in depth experience of both tidal range and current projects including resource assessment and project development, technology development, due diligence, cost of energy and policy development. Through working on these projects, we have gained a deep technical and commercial understanding of tidal energy projects in addition to simply resource assessment.

HRW has vast experience of numerical modelling of free surface waters using TELEMAC and has been instrumental in its continued development. The TELEMAC system is a state-of-the-art free surface flow suite of solvers developed by a kernel of European organisations including HR Wallingford and other partners such as Electricité de France and the Federal Waterways Engineering and Research Institute of Germany. HRW's expertise is acknowledged within the UK tidal modelling community as the only entity with an in depth experience of TELEMAC and its modification.

The University of Edinburgh (UoE) is one of the largest and most successful universities in the UK with an international reputation as a centre of academic and research excellence. The Institute for Energy Systems (IES) is one of five multi-disciplinary research groupings within the School of Engineering at the University. In the most recent UK wide Research Assessment Exercise (RAE2008), the School was ranked third in the UK for combined research quality and quantity.

The aim of the TRM scope of work is to answer the following fundamental questions:

1. How will the interactions between tidal range and tidal current systems positioned around the UK's waters combine to form an overall effect?
2. Will the extraction of tidal energy resource in one area impact the tidal energy resource at distant sites around the UK and Europe?
3. What constraints might these interactions place on the design, development and location of future systems?

This will be achieved through a series of work packages and, ultimately, 10 deliverables of which this report forms Deliverable 03 (D03) - which UoE and B&V have contributed to. The deliverables are outlined below.

D01 – Tidal resource characterisation
D02 – Continental Shelf Model (CSM) definition and requirements document
D03 – Scenarios modelling (Extraction Scheme Modelling Scenarios)
D04 – Cost of Energy Model and supporting documentation
D05 – Interface specification for detailed tidal current modelling (via PerAWaT project) with CSM
D06 – CSM (coarse and detailed versions) with supporting documentation
D07 – Interactions (analysis and conclusions report)
D08 – Interface specification for detailed tidal range model and the CSM
D09 – Tidal Range model and supporting documentation
D10 – Project dissemination

This report describes and defines the extraction scheme scenarios to be applied in the CSM (in later work-packages), addressing the requirements of deliverable D03 of this study. The report provides an explanation and justification of the:

- Framework used for selecting scenarios.
- Selection of extraction schemes within each scenario.
- Design and choice of the scenarios (including description of the technology sensitivity analysis scenarios to be implemented).

Scenario selection and definition has been informed by, and incorporates outputs from, deliverables D01 and D02 of this study. The framework for scenario development has been informed by assessment of previous work presented in the literature. In total, 30 scenarios have been detailed for implementation in the CSM. The scenarios span from operation of no tidal range and tidal current energy technology (referred to as the 2010 'base case' scenario), through to the operation of total installed capacities of 60 GW of tidal range and up to 20 GW of tidal current energy (in the 2050 'extreme' scenario). The 2050 extreme scenario has the potential to meet in the region of 45% of UK electricity demand under the assumption that the interaction between the projects is minimal. One of the main purposes of the CSM will be to demonstrate how realistic such assumptions are. Up to 10 additional scenarios can be proposed by the ETI based upon the information provided in deliverables D01, D02 and D03. Detailed prescription of these additional scenarios may also be informed by outputs arising from deliverables D6 and D7.

3 GENERAL PROJECT DESIGN/METHOD

3.1 Rationale

Developing a suite of energy extraction scenarios to investigate the impact of tidal power development requires an over-arching framework to be put in place - within which the various scenarios can be related, evolved and compared. The objective of the study is to consider a wide range of combinations of development sites and technology options, enabling analysis of varying levels of overall energy extraction. The varying levels of overall energy extraction to be modelled allow consideration of limits potentially imposed on the future extent of the tidal power industry by external constraints.

However, developing scenarios envisaging the future for immature technologies and industries is to a large extent a speculative undertaking. Given the intent of the project is to consider a range of development scenarios for tidal energy between today's existing lack of significant installed capacity in UK waters, to the potential for full exploitation of the UK resource by 2050, a positive outlook on industry development is generally assumed when developing scenarios. Such development would require a host of factors to appropriately align (e.g. government policy, private sector investment, and technology evolution and innovation timelines).

As the objective is to investigate how energy extraction at one site may affect the energy available elsewhere, this study focuses on interpreting far-field effects of tidal power generation as opposed to inter-array effects. In order to limit the scope and acknowledging the more localised impact of smaller scale developments, only energy extraction schemes with peak power output greater than 100 MW were originally considered (as required by the client). This constraint has subsequently been relaxed to peak power greater than 60 MW for tidal current projects as recommended in deliverable D01.

Figures 1 and 2 provide a general overview of the locations identified in deliverable D01 to be included in the scenario development assessment (specifically, Figure 2 is a representation of areas around the UK where the depth is greater than 20 metres and the average power density is above 1.5 kW/m^2 using the data layers provided by [ABPMER (2008)]). A summary of the outputs of deliverable D01 and D02 that feed into D03 is provided in the appropriate sections of this document as they become relevant.

The scenario prescription framework presented is representative of possible future development for the purpose of understanding potential interactions between sites considering varying levels of development of the UK tidal energy resource - as opposed to being intended as an exact prediction of the future of industry development. It is important to highlight that without pre-knowledge of the outcome of the ETI-TRM project, it is impossible to accurately estimate the combined action of large scale deployment of tidal range and tidal current technologies. Hence, there is potential that some of the proposed scenarios will operate sub-optimally (potentially severely) due to the level of interaction between projects that may be observed. The purpose of the project is to inform this debate, therefore it is to be expected (and desirable) that some of the proposed scenarios simulations go beyond what is deemed credible or acceptable levels of impact on the underlying tidal system to inform establishment of these boundaries.

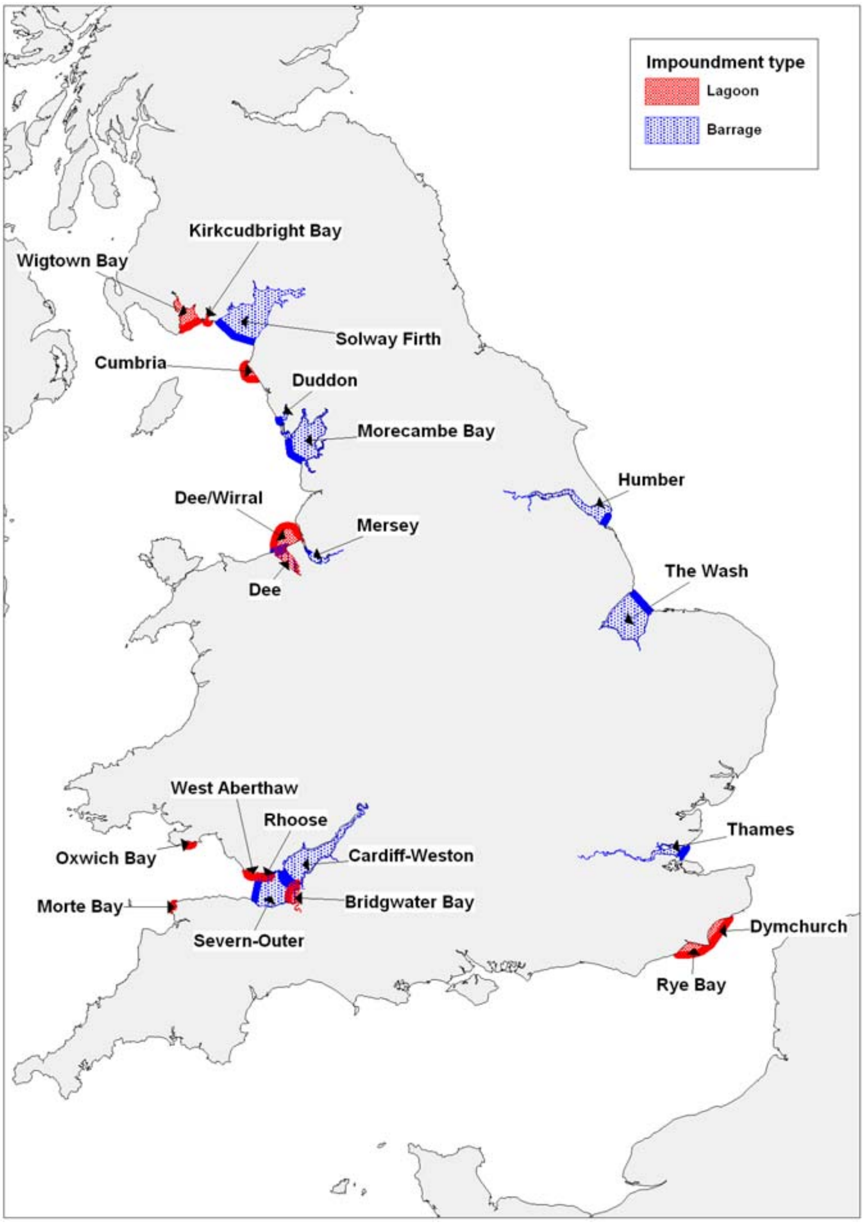


Fig. 1: Barrage and lagoon schemes identified for inclusion in scenario development by deliverable D01.

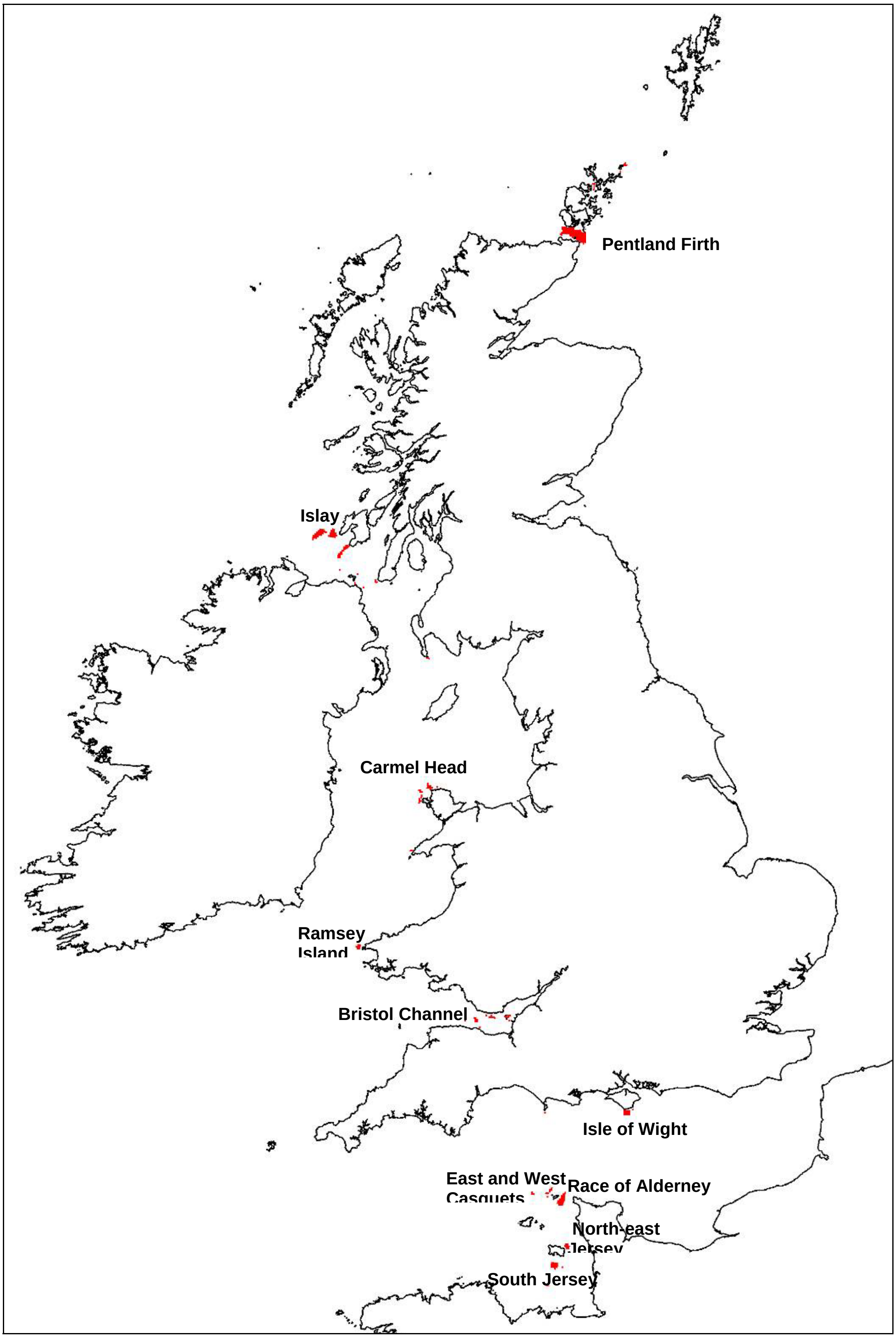


Figure 2: Tidal current locations meeting development constraints prescribed by deliverable D01.

3.2 Methodology

A two-dimensional matrix is used to prescribe the varying timeframe being considered (in ten year increments from 2010 to 2050), and the degree of alignment of external support to facilitate industry development in those years (optimistic, medium and pessimistic (see box 1 for definitions)).

Box 1 - Prescribing the external support axis of the scenario specification framework:

Within this study, the level of *external support* is considered as a measure of the overall view of society towards the development of the relevant tidal energy technology option (e.g. political will, (public and private) investment, project bankability, social acceptability (including local support/opposition)). Three broad support categories are assumed:

- Optimistic: Universal strong support for the technology option magnified by external drivers such as rapidly increasing conventional energy prices and heightened security of supply concerns. These circumstances are envisaged as producing the conditions necessary for an accelerated pro-tidal energy development environment.
- Medium: Strong support for the technology option combined with a mix of enabling energy policy drivers at an EU, UK or devolved administration level. These circumstances are envisaged as producing the conditions necessary for a generally pro-tidal energy development environment.
- Pessimistic: Under a pessimistic external support structure, no development will take place for the technology option in question[1].

[1] This is an artificial construct used within the scenario development framework to enable set-up of future scenarios where only one or other of the technologies is included. This is considered of fundamental importance within the overall project as it enables scenarios to be proposed where the impact of just that technology option can be assessed as opposed to the complex non-linear interaction expected when both technology options are simultaneously impacting on the underlying tidal dynamics.

Within these scenarios, the development of installed capacity is related to decisions made in the (proposed) preceding years (e.g. all decisions made in the 2020 'medium' case carry forward into the 2030 'medium' case). An *extreme* scenario is used to consider a highly optimistic deployment scenario in the 2050 timeframe. Additional *special* scenarios that ignore the incremental build-order development approach are also considered to enable assessment of projects that may have otherwise been 'blocked' by earlier development choices. These additional cases are also used to examine the impact of various proposed artificial external constraints (e.g. full development of tidal range technology is achieved but restricted geographically to only the east or west coast). A number of the 'special' scenarios relate to the most radical proposals that exist in the literature. These cases are considered to ensure that all views are represented across the suite of scenario test-cases. Finally, scenarios enabling direct consideration of the sensitivity of the response of the system to the extraction technology are developed. Within the limitation of 30 scenarios, it is acknowledged that not every possible combination of the development projects identified in deliverables D01 and D02 can be considered. However, all of the scenarios are prescribed with the objective of enabling direct comparison between as many different cases as possible. Table 1 presents a simple high level overview of the 30 prescribed scenarios. Each scenario is developed later in this report where detailed descriptions of the decision making approaches adopted and subsequent scenario decisions and designs are presented.

Table 1: Matrix summarising the proposed scenarios (detail descriptions provided in following sections).

		Tidal Range			Tidal Current		
Case	Year	Optimistic	Medium	Pessimistic	Optimistic	Medium	Pessimistic
1 -	2010		**X**			**X**	
2 -	2020		**X**			**X**	
3 -	2020	**X**				**X**	
4 -	2020		**X**		**X**		
5	2030		**X**			**X**	
6	2030	**X**				**X**	
7	2030		**X**		**X**		
8	2040		**X**			**X**	
9	2040			**X**		**X**	
10	2040	**X**				**X**	
11	2050		**X**			**X**	
12	2050	**X**				**X**	
13	2050			**X**		**X**	
14	2050		**X**		**X**		
15 -	2050		**X**				**X**
16	2050	Special: 'Extreme case' – Maximum TR[1] and TC[2] development.					
17	2010	Special: Run case 1 with explicit representation of vertical water column (layers).					
18	2050	Special: Run case 16 with explicit representation of vertical water column (layers).					
19	2050	Special: 'West coast TR' – As case 16, but only TR on the west coast, no TC.					
20	2050	Special: 'East coast TR' – As case 16, but only TR on the east coast, no TC.					
21 -	2020	Special: Run case 4 with PFOW[3] projects prescribed as leased by Crown Estate.					
22	2030	Special: Run case 6 with Severn Outer replacing conflicting internal options.					
23	2030	Special: Run case 6 replacing ebb TR with best alternative 80% solution.					
24 -	2050	Special: Apply Salter (2009) PF[4] development scenario (no other development).					
25 -	2050	Special: Apply Mackay (2009) UK wide development scenario (no TR)					
26 -	2050	Special: TR 'extreme' development run operating in ebb mode where possible, no TC					
27 -	2050	Special: TR 'extreme' development run operating in dual mode where possible, no TC					
28 -	2050	Special: TR 'extreme' development run operating in RR[5] mode where possible, no TC					
29	2050			**X**	(3rd gen 1)		
30	2050			**X**	(3rd gen 2)		

Table notes: [1] Tidal Range, [2] Tidal Current, [3] Pentland Firth and Orkney Waters, [4] Pentland Firth, [5] Rolls-Royce.

3.3 Rationale for prescribing individual scenario development sites

Selecting appropriate sites for tidal range and tidal current development within each scenario will be conducted separately, as the various factors influencing site selection differ between the two technology approaches. Once the basic scenario decisions have been made as encapsulated in Table 1, each case can then be progressed by defining which development sites meet the specific criteria that fit that particular point on the matrix. The details of how this is achieved are discussed in detail in sections 4 and 5 (tidal range), and 6 and 7 (tidal current) of this document.

3.3.1 Dealing with competition for sites between the two technology approaches

Other than in the Bristol Channel/Severn Estuary, none of the potential development locations identified in deliverable D01 is considered as a major source of competition between the two tidal technology approaches. The areas identified as appropriate for tidal current development in Bristol Channel/Severn Estuary region are relatively small (in terms of electricity generation potential) in comparison with the competing tidal range development solutions. Hence the Severn Estuary region will be zoned for the purposes of this study as restricted to tidal range development to avoid a minor tidal current project 'blocking' a major tidal range project. The locations identified as potentially suitable for tidal current development nearer the mouth of the Bristol Channel will also not be considered as it is highly likely that the tidal current regime in the region will be significantly altered by the presence of large tidal range project developments in the estuary[1]. Zonation of offshore renewables is already established in UK coastal regions due to the existence of various leasing agreements put in place by the Crown Estate (e.g. see Figure 3). Tidal power developments cannot be planned in isolation. Existing designations and users of a region's resources can also limit new developments. The existence of competing offshore development opportunities also has to be considered, especially in light of the ongoing rapid expansion of a variety of competing offshore renewable energy technologies and projects.

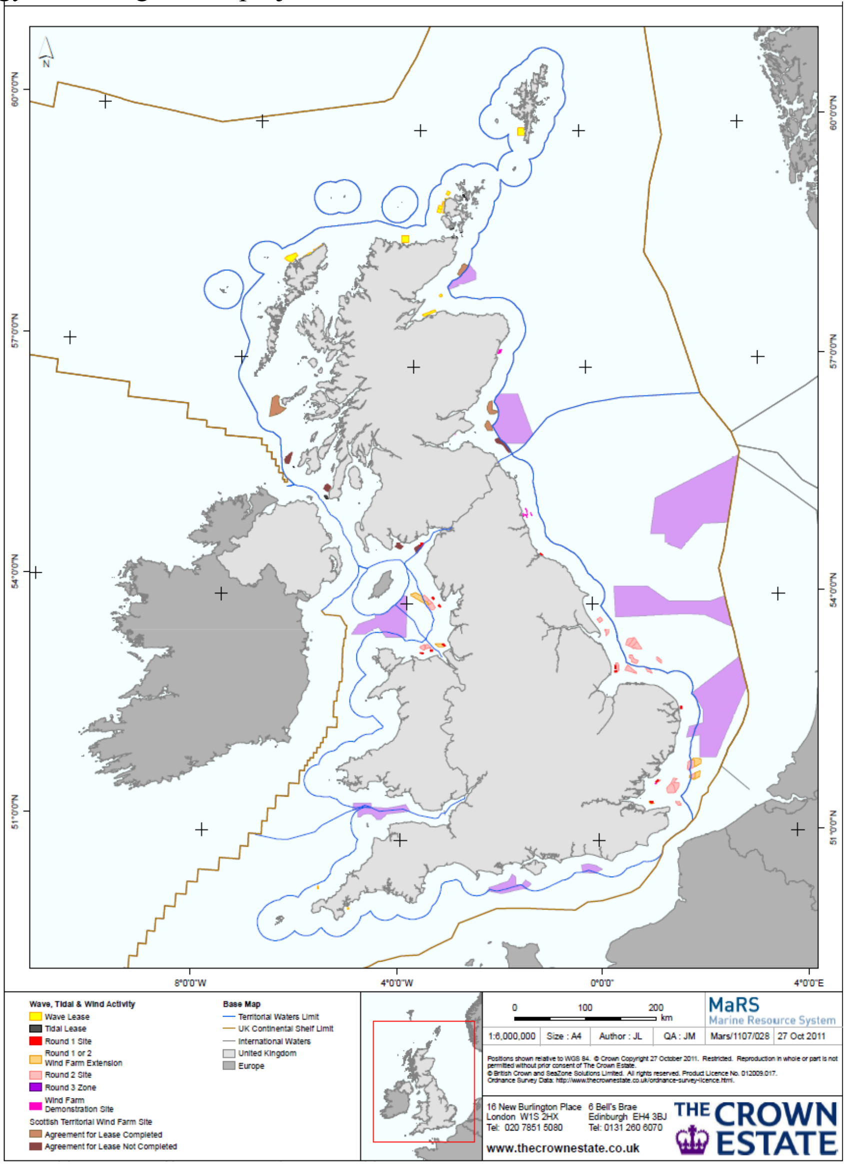


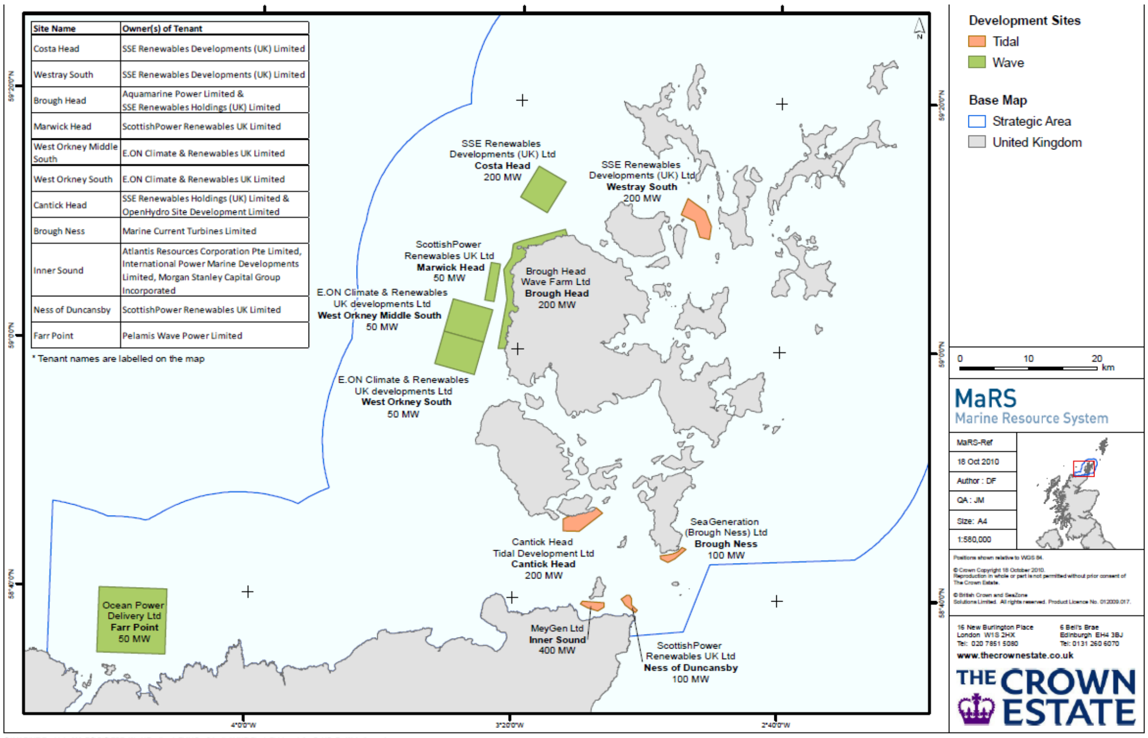
Figure 3: Offshore projects leased or usage agreed by the Crown Estate (source: The Crown Estate)

---

[1] It is suggested that investigation of such interactions would be appropriate for designation as one or more of the additional 10 cases available to the ETI to request after the designated 30 cases have been considered – this would enable appropriate identification of which existing scenario simulation is most appropriate to designate as the appropriate updated 'base case' for such analysis. This would enable design of the tidal current farm (e.g. technology selection) to be informed by inputs from the 'new' base case identified therefore already accounting for the alteration to the local tidal dynamics by significant tidal range technology development.

3.4 Rationale for prescribing the extraction scheme characteristics in each scenario

For each tidal range and tidal current site identified for inclusion in a specific scenario, it is necessary to match appropriate technology characteristics with site characteristics in order to specify a development strategy best suited to that location. Conventional turbines for tidal barrages and lagoons are represented using turbine characteristics derived from a bulb turbine design which was developed by B&V for the recent re-appraisal of the Severn schemes for DECC. Next generation very low head turbines for tidal barrage and lagoon developments are also represented in this study using public domain data and further details provided by Rolls-Royce (one of the companies developing this technology approach) to derive appropriate turbine characteristics. Details of the turbine characteristics for tidal range technology application are presented in deliverable D01 and D02. Relevant outputs from deliverable D01 and D02 are combined with the various scenario development constraints identified in section 4 to present the finalised tidal range technology scenario outputs in section 5. Appropriate matching of technology characteristics with site characteristics for tidal current turbines is mainly dependent upon accurate prescription of the bathymetric data at the site and the variability of the local flow velocity (both spatially and temporally). The rapid spatial variability of tidal currents provides an issue in this context as the resolution of existing data-sets is sub-optimal (one of the points being addressed by building the CSM in this study). Therefore the preferred approach for specifying technology characteristics is to prescribe a set of conditions and constraints that will be applied when improved tidal current data is provided by the CSM 'base case' simulation (scenario 1). The concept developed enables the majority of the process to be automated in conjunction with the post-processing analysis of the 'base case' scenario. To back this approach up, the process can be applied manually in a step-wise manner using the best available input tidal current data. Example cases of the manual application of the approach are therefore also presented. The final approach adopted to match technology with site characteristics is to use existing medium-large tidal current array project proposals that have matured enough to have gained a sea-bed lease from the Crown Estate (e.g. see Figure 4). Within the scenario timeframes, it is also necessary to consider the



Site Name	Owner(s) of Tenant
Costa Head	SSE Renewables Developments (UK) Limited
Westray South	SSE Renewables Developments (UK) Limited
Brough Head	Aquamarine Power Limited & SSE Renewables Holdings (UK) Limited
Marwick Head	ScottishPower Renewables UK Limited
West Orkney Middle South	E.ON Climate & Renewables UK Limited
West Orkney South	E.ON Climate & Renewables UK Limited
Cantick Head	SSE Renewables Holdings (UK) Limited & OpenHydro Site Development Limited
Brough Ness	Marine Current Turbines Limited
Inner Sound	Atlantis Resources Corporation Pte Limited, International Power Marine Developments Limited, Morgan Stanley Capital Group Incorporated
Ness of Duncansby	ScottishPower Renewables UK Limited
Farr Point	Pelamis Wave Power Limited

* Tenant names are labelled on the map

Figure 4: Pentland Firth and Orkney Waters round 1 development sites (source: The Crown Estate).

development timeline for delivery of second and third generation technology solutions for widening the exploitable tidal current energy resource. Further details regarding the prescription of tidal current extraction scheme scenarios are provided in section 6 with appropriate inputs from deliverable document D01. Relevant outputs from deliverables D01 and D02 are combined with the various scenario development constraints identified in section 6 to present the finalised tidal current technology scenario outputs in section 7.

4 TIDAL RANGE SCENARIO SELECTION

Deliverables D01 and D02 have extensively investigated potential locations and configurations for tidal barrages and lagoons (tidal range technologies) in UK coastal waters with peak power output greater than 100MW. A brief summary of the relevant outputs from both deliverables D01 and D02 that inform the tidal range scenario selection framework is now presented.

For barrages, site selection was based on a review of existing literature. Potentially feasible locations for tidal lagoons were identified from mapping of tidal range and water depth. Twenty-one barrage and lagoon sites were deemed to meet the requirements of the ETI-TRM study and are therefore taken forward for further consideration. For each of these sites, a preferred barrage/lagoon location was identified from the available alternatives and options identified. The finalised location and orientation of the 21 tidal range projects is presented in Figure 1. Each site provides an opportunity for the development of multiple scheme options using a range of operational mode and technology combinations, with some locations being deemed suitable for one, two or all three approaches advocated in deliverable D01 (ebb and dual mode generation using conventional turbines and dual mode generation using very low head turbines designed by Rolls-Royce). The finalised set of identified sites and summary data relating to the configuration of each barrage/lagoon (e.g. impounded area, barrage length, number of turbines, rated power) as presented in deliverable D01 is reproduced in Appendix A. At this stage, no scheme is identified for the Duddon estuary, as for each of the operating modes considered there is no deep water to install turbines and it is therefore removed from further consideration within the scenario definition exercise.

Additional commentary is presented in the deliverable D01 report for each of the preferred sites and configurations identified relating to factors that may influence the development potential at each particular site (e.g. cost/energy generation benefit analysis, environmental designations impacting consenting, competing use of resource). These factors are a major determinant used to inform scenario selection for tidal range technology, and are therefore referred to in more detail throughout section 4 of this document.

Deliverable D02 provides details of the parameterisation of tidal range technology for implementation in the CSM simulations. Each of the preferred site and operational mode combinations identified in deliverable D01 is parameterised in detail using various functions to describe (i) optimal configuration of the tidal range technology to match that location and (ii) optimised control strategies for the operation of the turbine to maximise electricity generation. Both of the dual mode generation optimisations are designed with the intent of maintaining 80% tidal range within the impounded area (as specifically requested by ETI) to provide technology options that attempt to limit environmental impact.

4.1 Existing scenario development proposals

A wide variety of literature exists relating to tidal barrage/lagoon developments in the UK, as has been highlighted in deliverable D01. There is, however, limited discussion of potential build order and associated timelines projecting the growth of the tidal range technology industry. As tidal barrage/lagoon is already a mature technology approach, there has not been a significant need for road-mapping activities to assist technology development. Additionally, given the vast capital cost of each project and the potential for individual projects to wrap up the supply chain for a number of years due to the scale of the projects, there appears to have been limited attempts by the various interested stakeholders to be considered as an ‘industry’. Instead, each tidal range project is generally considered as a separate individual entity. The predominance of Severn Estuary proposals in defining various UK governments’ appetite towards tidal range technology also tends to create a disjointed approach. The timescale for construction of the major tidal range schemes proposed in the UK is perhaps also relevant in this context (e.g. even if initiated on the date of the submission of this document, the Cardiff-Weston barrage would not be fully operational in time to contribute towards 2020 renewable energy provision targets). Reflecting the outcomes of the recent re-appraisal of the Severn schemes by DECC, the most recent UK government view on tidal range technology development is that no deployment is expected by 2020, with up to 1GW (excluding Severn) possible by 2030 [DECC (2011(a))]. This is in contrast to the more optimistic prevailing view towards tidal range technology adoption in vogue as recently as 2007, when the potential development of large scale Severn Estuary tidal barrage proposals was proposed as a cornerstone of meeting 2020 renewable energy and Greenhouse Gas emission reduction targets [SDC (2007)]. For the purposes of this study, an optimistic view-point towards the initiation of development of tidal range technologies (somewhere between that endorsed in the previous two citations) will be adopted, with inclusion of meaningful tidal range technology development occurring in 2020 scenarios. This best meets the overall intent of the ETI-TRM project in terms of examining the various interactions between tidal power project developments and the tidal resource at various stages of potential industry development.

4.2 Constraints impacting tidal range scenario selection

A theoretical two-dimensional matrix is being used to prescribe the varying timeframe being considered (in ten year increments from 2010 to 2050), and the degree of alignment of external support to facilitate industry development in those years (optimistic, medium and pessimistic). It is therefore necessary to establish a set of constraints that can be used to inform decision-making regarding the appropriate order of development of the identified tidal range project developments within the context of this study. A number of these constraints have also been discussed in deliverable D01, both in informing site selection and the high level project design undertaken. A summary of the relevant constraints and associated metrics used in deliverable D01 is presented in Table 2. For a detailed explanation of the identified constraints, derivation and sources in Table 2, the reader is referred to deliverable D01. A high value of the indicative measure of energy/cost rating is desirable.

The overarching reasoning underpinning development of a tidal range project is the product that is produced – energy in the form of electricity. Therefore the relative return on investment in terms of electricity generated and hence revenue generated across the life-time of a project is a major determinant of the projects' viability. An indicative measure of the relative energy/cost of each proposed tidal range development project is provided in Table 2. This presents a simple means of comparing between projects. For this study, a more sophisticated means of differentiating between the project options is required that also takes a high-level account of potential constraints associated with each project. This can then inform decision-making in populating the two-dimensional timeframe/external support matrix. The additional factors taken into consideration are summarised in the following sub-sections.

Table 2: Input data used to inform tidal range technology scenario selection

Location	Indicative measure of energy/cost			Environmental designations - area within basin (km2)			Ports		Annual mean significant wave height	No. of EU designated bathing water locations within basin
	Ebb	Dual	Dual, Rolls-Royce	Special Areas of Conservation (SACs)	Special Protection Areas (SPAs)	Ramsar sites[1]	Total freight traffic (2001-2010) in million tonnes	% of total UK freight		
Solway Firth	9.1	10.3	8.4	381	381	381	4	0%	Low	7
Duddon				32	32	32	0	-	Low	3
Morecambe Bay	10.5		9.9	455	319	319	55	1%	Low	7
Mersey	9.0	6.5	8.2	0	39	39	76	1%	Low	-
Dee	8.9	9.7	8.1	103	103	103	4	0%	Low	1
Severn Outer	18.7	18.3	8.9	708	209	209	172	3%	Low	12
Severn Cardiff-Weston	18.7		10.0	504	157	157	167	3%	Low	4
Thames	3.7		3.8	0	41	41	511	8%	Low	7
The Wash	9.0	7.9	6.9	599	591	591	23	0%	Low	3
Humber	5.6		5.1	283	283	284	841	14%	Low	1
Wigtown Bay		4.8	4.1	0	0	0	0	-	Low	2
Kirkcudbright Bay		2.4	1.9	0	0	0	0	-	Low	1
Cumbria		2.6	1.9	0	0	0	0	-	Low	1
Dee-Wirral		8.6	7.0	138	268	120	4	0%	Low	4
Oxwich Bay		3.0	2.5	0	0	0	0	-	Moderate	1
West Aberthaw		3.7	2.6	0	0	0	0	-	Low	-
Rhoose		3.7	2.4	0	0	0	0	-	Low	1
Bridgwater Bay		11.6	7.0	90	51	51	1	0%	Low	3
Morte Bay		2.3	2.0	0	0	0	0	-	High	3
Rye Bay		3.7	3.0	2	1	0	1	0%	Moderate	2
Dymchurch		3.1	2.5	4	0	0	0	-	Moderate	5

Table notes: The Convention on Wetlands (Ramsar, Iran, 1971) - hence "Ramsar Convention" - is an intergovernmental treaty that embodies the commitments of its member countries to maintain the ecological character of their Wetlands of International Importance and to plan for the "wise use", or sustainable use, of all of the wetlands in their territories.

4.2.1 Overall electricity generation potential

The purpose of all the tidal barrage/lagoons identified is fundamentally to generate electricity. Within the identified potential development projects, some site and technology combinations maximise the total amount of electricity generation more than others. This is simply highlighted in the Tables in Appendix A where an indicative assessment of the Annual Energy Production (AEP) is provided for each proposed scheme. Although the simple energy/cost analysis metrics already discussed are derived based upon the electricity generation potential of each project, the overall AEP itself is also of general interest in terms of defining the contribution that each project can make towards meeting future demand.

4.2.2 Potential environmental impact

It is well understood that one of the major constraints that has restricted tidal range technology implementation in the UK to date is the potential environmental impact arising from the project construction and operation. Physical alterations of the tidal range and currents inside and outside the barrage are the most obvious impacts of the introduction of a tidal barrage/lagoon. The implications of changes in tidal dynamics create a vast array of linked physical, biological and chemical environmental responses. Excessive environmental impact will ensure that a project will not gain the appropriate licenses and consents required to proceed. These issues are particularly contentious and potentially restrictive in regions which are already designated as being of particular environmental interest (e.g. Special Protection Areas or Ramsar sites). This thought process underpins the ETI-TRM project. Hence the project team has been tasked (where possible) with examining cases which limit tidal range reduction within the barrage/lagoon to a maximum of 20% (maintaining 80% of the existing tidal range).

Dealing with these complex issues in detail is beyond the scope of the project. The intention of the construction and operation of the CSM within the ETI-TRM project is to investigate the physical changes to the tidal dynamics only. Further detailed interpretation of the consequence of these alterations will be facilitated by the CSM outputs, but is not within the ETI-TRM project remit. Before the CSM is in place, output from the simple models used to optimise the various barrage/lagoon configurations has been used as a measure of the potential environmental impact by considering the overall reduction in tidal range associated with each project (these values are summarised in the Tables in Appendix A). This information is used in combination with the extent of existing environmental designation in place (see Table 2) to consider project viability in the context of scenario selection.

4.2.3 Impact on shipping

If the barrage/lagoon impounds an existing major port this has significant implications for the operation of the port. It is possible to overcome some of these issues by including appropriate transport mechanisms (e.g. navigation locks) in the embankment at a cost to the project. However, there is an operational cost in terms of time associated with the need to use such measures during ship transit that can impact on the viability of port operations. More significantly, alterations to tidal range can impact severely on port operation, and hence these issues have to be dealt with in minute detail during project design and in terms of balancing the needs of maintaining tidal conditions to facilitate port operation with the preferred operational cycle of tidal range technology. The degree of importance of this issue for each proposed barrage/lagoon design is summarised by relevant statistics in Table 2.

4.2.4 Impact of local wave climate

The severity of the local wave climate has a significant bearing on the capital cost of a barrage/lagoon design. A region subjected to more intensive wave action requires the construction of a higher embankment and increased embankment protection. Figure 6 details the variability of annual mean significant wave height in UK coastal waters. This is used as a simple metric to differentiate whether a tidal range site is located in a potentially low, medium or high wave climate area.

4.2.5 Loss or alteration of recreational beaches

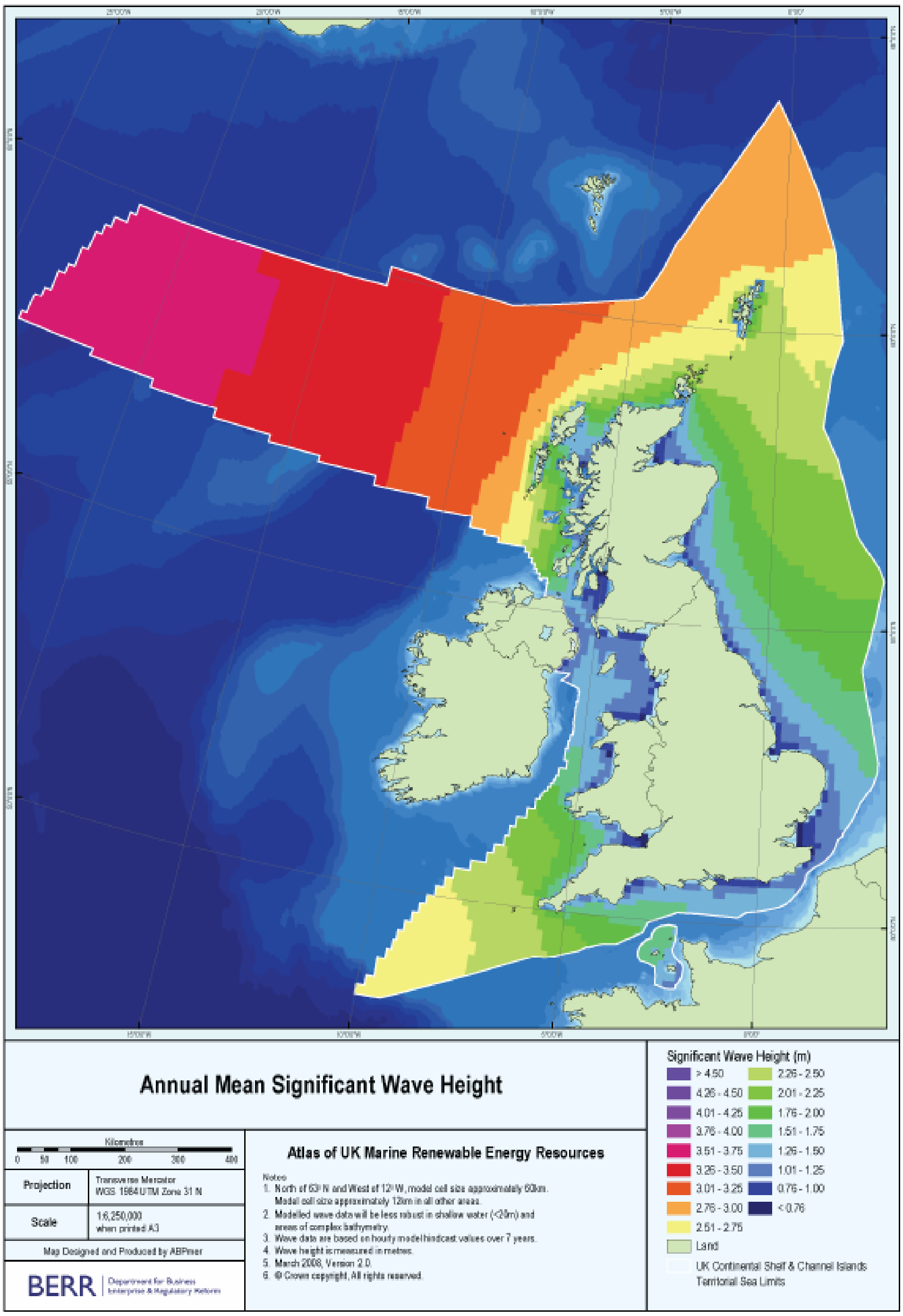
Impounding recreational beaches can lead to a reduction in usability of the facility. There are also safety implications to beach users associated with the rapid flooding that may be experienced in certain impoundments due to the operation of the barrage/lagoon. This impact would generally be most severe in dual generation mode (although to a lesser extent when using very low head turbine designs rather than the conventional approach).

4.2.6 Competing use with other offshore renewable technologies

The footprint of tidal range projects are generally considered to be able to be developed in harmony with co-located offshore wind developments (in reality such an arrangement might benefit wind development by reducing functional loadings if located within the impounded area), but are incompatible with wave energy development. Fortunately the location of the identified tidal range projects does not have a significant overlap with areas that would be considered as appropriate for wave energy project development (e.g. compare regions in Figure 6 with a mean significant wave height in excess of 2 metres with the locations identified for tidal range development in Figure 1).

4.2.7 Supply chain issues

A major constraint on rapid development of tidal range technologies is the underlying build time required due to the planning and consenting process, large civil works involved and procurement challenges. The larger installations proposed in this study would practically take anywhere from 10-15 years to deliver from project initiation. The procurement challenges become heightened if multiple projects were to be brought forward simultaneously (or overlapped). Deliverable D01 highlights that



Notes
1. North of 63° N and West of 12° W, model cell size approximately 60km. Model cell size approximately 12km in all other areas.
2. Modelled wave data will be less robust in shallow water (<20m) and areas of complex bathymetry.
3. Wave data are based on hourly model hindcast values over 7 years.
4. Wave height is measured in metres.
5. March 2008, Version 2.0.
6. © Crown copyright, All rights reserved.

Figure 6: Annual mean significant wave height in UK coastal waters (Source: [ABPmer, *et al.* (2008)])

previous work on the Severn Cardiff-Weston ebb generation proposals identified that provision of turbines for the project (216 40MW turbines) was considered an upper limit for global production capacity during the project development timeframe. These aspects will also have to be balanced along the timescale axis of the scenario selection matrix.

4.2.8 Grid accessibility

Consideration of grid accessibility impacts in differentiating between scenario selection decisions is beyond the scope of this project. However, it is important to recognise that grid accessibility, provision and strengthening requirements will have a major impact on the viability of any tidal barrage/lagoon project development. The variability of the resource and hence electricity generation is also acknowledged as a major issue, particularly as penetration of the technology increases (in particular due to the relative phasing of tidal variability at a number of the major tidal range sites in the UK [Burrows *et al*.(2009)]).

4.3 Other factors taken into consideration during scenario development

Section 4.2 has established the various project constraints to be taken into consideration when establishing the relative merits of the identified tidal barrage/lagoon options to establish their position in the scenario framework matrix. Other factors that are considered include:

- <u>The relative maturity of the technology options</u>: Conventional generation turbines (ebb-only and dual mode operation) present a mature technology approach. The very low head tidal range turbine technologies are still undergoing design development, although they can be seen as iterations of existing knowledge rather than a revolutionary technology innovation, hence although relatively immature, there is less risk in the technology development than for a completely new technology. Hence for scenario development purposes, the very low head Rolls-Royce turbine is considered to be at a demonstration stage in 2020, and is then unrestricted beyond.
- <u>Industry progression</u>: Underpinning the build order decision making is also consideration of the growth of the industry. This combines supply chain issues, investor confidence and lessons learned from project experience. It is considered likely that there would be opportunity to accelerate deployment as time progresses due to these changing circumstances, and the ‘proving’ of the technology implicit in the 2020 development and operation scenarios providing more confidence for increased activity in later years.
- <u>The needs of the ETI-TRM project</u>: On occasion it is deemed to be of benefit to the interpretation of the CSM simulation scenarios if certain projects in close physical proximity are introduced sequentially rather than in tandem (hence one will be delayed or brought forward within the scenario framework). The benefit of doing so is to gain a better understanding of the various contributions that each project makes at the regional level.

Similarly, it is acknowledged that some of the decision making in the scenario developments may be viewed as overly optimistic. This is again justified to meet the ETI-TRM project needs in ensuring that each scenario test-case provides answers to interesting questions regarding the regional and national impacts of the addition of projects of various scales, and their combined cumulative impact. In this context, the scenario framework on 10 year horizons could just as easily be applied assuming 20 year time horizons (2010, 2030, 2050, 2070 and 2090). The designation of development between 2020 and 2050 makes sense in terms of being the medium and long term planning horizon that UK and EU government targets are currently set against.

A final point is that the approach adopted for the majority of the 30 scenario cases is to build one on top of the other through time such that any development taking place in 2020 remains throughout the following years, so that the cumulative impact of the sequential addition of projects can be considered. There are, however, a select number of cases where this approach is put to one side in order to investigate interesting alternative approaches in order not to be overly constrained by the scenario development framework. For instance, it will be highly informative to compare the relative response of the tidal system to various different deployment strategies of the most dominant Severn estuary technology and site choices.

<u>Sensitivity studies</u>: There are 45 possible site/technology combinations proposed in deliverable D01 across the 20 identified sites (9 ebb-only conventional turbine schemes, 16 dual-mode conventional turbine schemes and 20 dual mode very low head (Rolls-Royce) turbine schemes). Each potential

site/technology option identified is included in at least one of the three specific technology sensitivity tests. In order to include all the available technology options in only 3 test cases, it is necessary to examine technology sensitivity within a full deployment scenario. It is beyond the scope of this project to test each of the individual site/technology options in all possible build order combinations. However some of the intermediate cases do provide the opportunity for additional consideration of technology sensitivity.

5 TIDAL RANGE RESULTS

The following sections provide the outcomes of the scenario definition for tidal range technologies along with supporting commentary and summary tables detailing the combined characteristics and parameters used to describe each scheme as it is introduced. Section 4 of this document (Table 2 in particular) and the summary site/technology characteristics tables in Appendix A provide a means of differentiating between the projects and defining build order. Decisions are presented in 'build order' (the medium case first, then optimistic case for each timeframe, as the optimistic case would incorporate the outcomes of the medium case).

5.1 Identifying preferred build order (2020 medium case)

In the 2020 medium case, due consideration must be given to the project achievability in the timescale between now and 2020 to ensure credibility. This limited the selection of the largest options (even assuming the project was ready to begin immediately). Given the environmental concerns surrounding barrage/lagoon operations, it has additionally been envisaged that only technology options that limit tidal range reduction to 80% of the natural tidal range are viable. This limits the selection to dual mode operation. Selection of a medium size development of Rolls-Royce turbines is considered premature as the technology would remain relatively unproven in 2020. Of the medium size dual mode operation options, Bridgewater Bay has the highest energy/cost rating (Table 2) and is therefore selected despite the environmental designations in the region – the 80% tidal range maintenance is seen as being important in this selection being robust. The Bridgewater Bay lagoon results are presented in Table 3.

Table 3: Bridgewater Bay lagoon

		Location:		Bridgewater Bay lagoon			
Mean tidal range:		8.2 m		Impounded basin area:		90 km^2	
Embankment length:		15.9 km		Operational mode		Dual (Conventional)	
Total installed capacity:		3600 MW		Minimum tidal range inside basin:			81%
AEP:	6.9 TWh/y	# turbines:	120	Diameter:	9.0 m	$A_{0\text{turbine}}$:	228.2 m^2
TCW:	20.5 m	β_{ebb}:	1.62	β_{flood}:	1.62	H_{rated}:	5.25 m
P_{max}:	30 MW	H_{min}:	1.17 m	H_{int}:	3.62 m	T_{start}:	5
B_1:	44.4212	B_2:	320.1676	B_3:	-65.2245	B_4:	6.3856
C_1:	537.6780	C_2:	50.6237	C_3:	-6.0566	C_4:	0.1939
E_1:	1963.1389	E_2:	-390.4417	E_3:	31.5880	E_4:	-0.89147
F_1:	-1.3175	F_2:	0.6439	F_3:	1.8774	F_4:	-0.1651

L_1:	-8.25	L_2:	-6.60	L_3:	-4.95	L_4:	-4.13	L_5:	-3.30	L_6:	-1.65
L_7:	1.65	L_8:	3.30	L_9:	4.13	L_{10}:	4.95	L_{11}:	6.60	L_{12}:	8.25
H_1:	7.50	H_2:	7.75	H_3:	7.25	H_4:	7.00	H_5:	7.00	H_6:	7.00
H_7:	7.00	H_8:	7.00	H_9:	7.00	H_{10}:	7.25	H_{11}:	7.75	H_{12}:	7.50

As the Bridgewater Bay deployment would represent the first significant tidal range technology in operation in UK coastal waters it is considered that it would be viewed as a test case by the regulatory authorities before further consents and leases would be granted for similar scale projects. Hence no other tidal range development is considered in this scenario.

5.2 Identifying preferred build order (2020 optimistic case)

Having just identified that the initial deployment is likely to be limited in order to use the first case as a test case to observe the environmental response, options for the 2020 optimistic case are limited. Therefore it is proposed that the additional tidal range development to take place in the 2020 optimistic case relates to a pilot scale 'proof of concept' test of very low head technology (dual mode Rolls-Royce). Of the smallest options available within the study, Kirkcudbright Bay is the furthest removed geographically from Bridgewater Bay, has the smallest number of turbines, no existing special environmental designations and is a low wave environment, therefore presenting a credible option for a proof-of-concept test deployment. The Kirkcudbright Bay lagoon results are presented in Table 4. The test case will enable assessment of the geographic extent of the operation of a comparatively large (Bridgewater Bay) and small (Kirkcudbright Bay) tidal range power plant.

Table 4: Kirkcudbright Bay lagoon

<table>
<tr><td colspan="6"></td><td colspan="6">Location:</td><td colspan="6">Kirkcudbright Bay lagoon</td><td colspan="6"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">5.1 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">16 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">4 km</td><td colspan="6">Operational mode</td><td colspan="6">Dual (Rolls-Royce)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">110 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">80 %</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">0.3 TWh/y</td><td colspan="3">$N_{9m\ turbines}$:</td><td colspan="3">0</td><td colspan="3">N_{14m} turbines:</td><td colspan="3">12</td><td colspan="3">$A_{9m\ t}$:</td><td colspan="3">52.1 m^2</td></tr>
<tr><td colspan="3">$A_{14m\ t}$:</td><td colspan="3">126.1 m^2</td><td colspan="3">k</td><td colspan="3">0.86</td><td colspan="3">$H_{\min}$:</td><td colspan="3">1</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">R_1:</td><td colspan="3">57.5906</td><td colspan="3">R_2:</td><td colspan="3">39.1934</td><td colspan="3">R_3:</td><td colspan="3">-2.6943</td><td colspan="3">R_4:</td><td colspan="3">-0.0004</td></tr>
<tr><td colspan="3">U_1:</td><td colspan="3">139.3550</td><td colspan="3">U_2:</td><td colspan="3">94.8382</td><td colspan="3">U_3:</td><td colspan="3">-6.5195</td><td colspan="3">U_4:</td><td colspan="3">-0.0009</td></tr>
<tr><td colspan="3">S_1:</td><td colspan="3">-0.2629</td><td colspan="3">S_2:</td><td colspan="3">0.6490</td><td colspan="3">S_3:</td><td colspan="3">0.2085</td><td colspan="3">S_4:</td><td colspan="3">-0.0002</td></tr>
<tr><td colspan="3">V_1:</td><td colspan="3">-0.6362</td><td colspan="3">V_2:</td><td colspan="3">1.5705</td><td colspan="3">V_3:</td><td colspan="3">0.5044</td><td colspan="3">V_4:</td><td colspan="3">-0.0006</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-5.10</td><td colspan="2">L_2:</td><td colspan="2">-4.08</td><td colspan="2">L_3:</td><td colspan="2">-3.06</td><td colspan="2">L_4:</td><td colspan="2">-2.55</td><td colspan="2">L_5:</td><td colspan="2">-2.04</td><td colspan="2">L_6:</td><td colspan="2">-1.02</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">1.02</td><td colspan="2">L_8:</td><td colspan="2">2.04</td><td colspan="2">L_9:</td><td colspan="2">2.55</td><td colspan="2">L_{10}:</td><td colspan="2">3.06</td><td colspan="2">L_{11}:</td><td colspan="2">4.08</td><td colspan="2">L_{12}:</td><td colspan="2">5.10</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">2.00</td><td colspan="2">H_2:</td><td colspan="2">2.00</td><td colspan="2">H_3:</td><td colspan="2">2.25</td><td colspan="2">H_4:</td><td colspan="2">2.50</td><td colspan="2">H_5:</td><td colspan="2">2.50</td><td colspan="2">H_6:</td><td colspan="2">2.50</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">2.50</td><td colspan="2">H_8:</td><td colspan="2">2.50</td><td colspan="2">H_9:</td><td colspan="2">2.50</td><td colspan="2">H_{10}:</td><td colspan="2">2.25</td><td colspan="2">H_{11}:</td><td colspan="2">2.00</td><td colspan="2">H_{12}:</td><td colspan="2">2.00</td></tr>
</table>

5.3 Identifying preferred build order (2030 medium case)

Perhaps the most interesting intra-project test case is the impact of the operation of the Bridgewater Bay lagoon in conjunction with the Cardiff-Weston barrage given the extremely close proximity of the sites and large electricity generation potential. The Cardiff-Weston barrage is the most highly studied tidal range technology project option in UK coastal waters. Ebb-generation mode designs for the Cardiff-Weston barrage have been close to being given the green light on a number of occasions over the last 35 years. The difficulties in minimising and mitigating environmental impact are acknowledged, as are the impacts on impounded port operation (although there has been significant planning in the various stages of the existing project designs to mitigate or at least reduce these impacts). Despite all of these caveats, the project team believe that a pro-tidal range environment (as defined by a 'medium' case) could enable the Cardiff-Weston barrage to proceed relatively early in the build order, and it is important to model this project development as it is the most studied and well developed of all proposed projects in the UK. Cardiff-Weston offers the highest energy/cost rating of all the identified schemes other than the Severn Outer case which would be precluded from the evolving scenario as it would enclose the Bridgewater Bay development (a specific Severn Outer case is presented in scenario 22). The Cardiff-Weston barrage results are presented in Table 5.

One deviation from the standard approach that will only be applied in this case is to conduct a high level assessment after the introduction of the Cardiff-Weston barrage (scenario number 6), and running scenario 23 (it is recommended that in terms of simulation order, scenario 23 is conducted alongside scenario 6 before proceeding to other scenarios later in the timeline). This would enable assessment examining the relative performance of the Cardiff-Weston barrage and Bridewater Bay lagoon in different combinations. If there is a dramatic reduction in the combined electricity generation by the two schemes in either configuration (scenario 6 or 23) (defined as overall generation

Table 5: Cardiff-Weston barrage

<table>
<tr><td colspan="6"></td><td colspan="3">Location:</td><td colspan="3">Cardiff-Weston</td><td colspan="12"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">7.9 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">504 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">16 km</td><td colspan="6">Operational mode</td><td colspan="6">Ebb (conventional)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">8640 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">49 %</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">18.7 TWh/y</td><td colspan="3">$N_{turbines}$:</td><td colspan="3">216</td><td colspan="3">Diameter:</td><td colspan="3">9 m</td><td colspan="3">$A_{0\text{turbine}}$:</td><td colspan="3">228.2 m^2</td></tr>
<tr><td colspan="3">TCW:</td><td colspan="3">20.5 m</td><td colspan="3">β_{ebb}:</td><td colspan="3">1.62</td><td colspan="3">β_{flood}:</td><td colspan="3">1.62</td><td colspan="3">H_{rated}:</td><td colspan="3">6.33 m</td></tr>
<tr><td colspan="3">P_{max}:</td><td colspan="3">40 MW</td><td colspan="3">H_{min}:</td><td colspan="3">1.18 m</td><td colspan="3">H_{int}:</td><td colspan="3">3.62 m</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">B_1:</td><td colspan="3">50.7255</td><td colspan="3">B_2:</td><td colspan="3">331.8523</td><td colspan="3">B_3:</td><td colspan="3">-66.5287</td><td colspan="3">B_4:</td><td colspan="3">6.4423</td></tr>
<tr><td colspan="3">C_1:</td><td colspan="3">505.3604</td><td colspan="3">C_2:</td><td colspan="3">93.0577</td><td colspan="3">C_3:</td><td colspan="3">-14.9324</td><td colspan="3">C_4:</td><td colspan="3">0.8079</td></tr>
<tr><td colspan="3">E_1:</td><td colspan="3">2587.5340</td><td colspan="3">E_2:</td><td colspan="3">-519.2081</td><td colspan="3">E_3:</td><td colspan="3">42.8784</td><td colspan="3">E_4:</td><td colspan="3">-1.2580</td></tr>
<tr><td colspan="3">F_1:</td><td colspan="3">-1.5402</td><td colspan="3">F_2:</td><td colspan="3">0.9600</td><td colspan="3">F_3:</td><td colspan="3">1.7887</td><td colspan="3">F_4:</td><td colspan="3">-0.1437</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-7.90</td><td colspan="2">L_2:</td><td colspan="2">-6.32</td><td colspan="2">L_3:</td><td colspan="2">-4.74</td><td colspan="2">L_4:</td><td colspan="2">-3.95</td><td colspan="2">L_5:</td><td colspan="2">-3.16</td><td colspan="2">L_6:</td><td colspan="2">-1.58</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">1.58</td><td colspan="2">L_8:</td><td colspan="2">3.16</td><td colspan="2">L_9:</td><td colspan="2">3.95</td><td colspan="2">L_{10}:</td><td colspan="2">4.74</td><td colspan="2">L_{11}:</td><td colspan="2">6.32</td><td colspan="2">L_{12}:</td><td colspan="2">7.90</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">4.00</td><td colspan="2">H_2:</td><td colspan="2">5.50</td><td colspan="2">H_3:</td><td colspan="2">5.50</td><td colspan="2">H_4:</td><td colspan="2">5.75</td><td colspan="2">H_5:</td><td colspan="2">5.25</td><td colspan="2">H_6:</td><td colspan="2">3.75</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">3.75</td><td colspan="2">H_8:</td><td colspan="2">5.25</td><td colspan="2">H_9:</td><td colspan="2">5.75</td><td colspan="2">H_{10}:</td><td colspan="2">5.50</td><td colspan="2">H_{11}:</td><td colspan="2">5.50</td><td colspan="2">H_{12}:</td><td colspan="2">4.00</td></tr>
<tr><td colspan="3">$N_{sluices}$:</td><td colspan="3">166</td><td colspan="3">$A_{1sluice}$:</td><td colspan="3">144</td><td colspan="3">$A_{0sluice}$:</td><td colspan="3">263</td><td colspan="3">SCW:</td><td colspan="3">20</td></tr>
<tr><td colspan="3">α_{ebb}:</td><td colspan="3">1.6</td><td colspan="3">α_{flood}:</td><td colspan="3">1.6</td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td></tr>
</table>

of less than 73% of the design case, e.g. the theoretical capacity of the Cardiff-Weston barrage operating in isolation), the project team will make a collective decision with the benefit of the outputs from the combination of scenarios presented whether to remove either the Cardiff-Weston or Bridgewater Bay scheme from the relevant test cases that follow (7-16, 18), or to change prescription of the Cardiff-Weston scheme to an alternative technology option as investigated in scenarios 22 and 23 (in particular scenario 23 may reduce interaction effects as it maintains 80% tidal range in the Cardiff-Weston alignment through dual operation as opposed to the ebb generation mode operation in scenario 6) . It is therefore recommended that scenarios 22 and 23 are run in conjunction with scenario 6 before proceeding further with scenario testing to enable this decision to be carried forward into the other scenarios. This is recommended to ensure that the credibility of the prescribed multiple Bristol Channel/Severn Estuary proposals is robust, and therefore does not detract from the wider value of the other CSM scenario simulations that follow whose outputs will also incorporate this configuration.

5.4 Identifying preferred build order (2030 optimistic case)

Under the assumption that the 2020 optimistic scenario would have demonstrated the viability of the very low head tidal range approach, the 2030 optimistic case envisages a further development using the same technology. However, the timescale between proof of concept in the early years of the decade and construction for operation by 2030 limits the opportunity for development of a very large barrage/lagoon. Of the medium scale developments, the Mersey would likely have the shortest build time due to the short barrage length. In the dual-mode Rolls-Royce configuration it also offers a high energy/cost rating (in part because of the short barrage length) and the modelling in deliverable D01 indicates that this approach offers the highest generation potential out of the three technology/operation mode options (the Thames is the only other location where this is the case). Additional benefits include the very protected site in terms of wave climate, small enclosed basin area limiting geographic footprint and longer generation cycle reducing the variability or ‘spiking’ of electricity delivery. The Mersey barrage results are presented in Table 6.

Table 6: Mersey barrage

<table>
<tr><td colspan="6"></td><td colspan="5">Location:</td><td colspan="7">Mersey</td><td colspan="6"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">6.5 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">56 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">2 km</td><td colspan="6">Operational mode</td><td colspan="6">Dual (Rolls-Royce)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">570 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">80%</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">1.4 TWh/y</td><td colspan="3">$N_{9m\ turbines}$:</td><td colspan="3">0</td><td colspan="3">$N_{14m\ \mathrm{turbines}}$:</td><td colspan="3">40</td><td colspan="3">$A_{9m\ \mathrm{t}}$:</td><td colspan="3">52.1 m^2</td></tr>
<tr><td colspan="3">$A_{14m\ \mathrm{t}}$:</td><td colspan="3">126.1 m^2</td><td colspan="3">k</td><td colspan="3">0.86</td><td colspan="3">H_{min}:</td><td colspan="3">1</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">R_1:</td><td colspan="3">57.5906</td><td colspan="3">R_2:</td><td colspan="3">39.1934</td><td colspan="3">R_3:</td><td colspan="3">-2.6943</td><td colspan="3">R_4:</td><td colspan="3">-0.0004</td></tr>
<tr><td colspan="3">U_1:</td><td colspan="3">139.3550</td><td colspan="3">U_2:</td><td colspan="3">94.8382</td><td colspan="3">U_3:</td><td colspan="3">-6.5195</td><td colspan="3">U_4:</td><td colspan="3">-0.0009</td></tr>
<tr><td colspan="3">S_1:</td><td colspan="3">-0.2629</td><td colspan="3">S_2:</td><td colspan="3">0.6490</td><td colspan="3">S_3:</td><td colspan="3">0.2085</td><td colspan="3">S_4:</td><td colspan="3">-0.0002</td></tr>
<tr><td colspan="3">V_1:</td><td colspan="3">-0.6362</td><td colspan="3">V_2:</td><td colspan="3">1.5705</td><td colspan="3">V_3:</td><td colspan="3">0.5044</td><td colspan="3">V_4:</td><td colspan="3">-0.0006</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-6.46</td><td colspan="2">L_2:</td><td colspan="2">-5.17</td><td colspan="2">L_3:</td><td colspan="2">-3.88</td><td colspan="2">L_4:</td><td colspan="2">-3.23</td><td colspan="2">L_5:</td><td colspan="2">-2.58</td><td colspan="2">L_6:</td><td colspan="2">-1.29</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">1.29</td><td colspan="2">L_8:</td><td colspan="2">2.58</td><td colspan="2">L_9:</td><td colspan="2">3.23</td><td colspan="2">L_{10}:</td><td colspan="2">3.88</td><td colspan="2">L_{11}:</td><td colspan="2">5.17</td><td colspan="2">L_{12}:</td><td colspan="2">6.46</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">1.00</td><td colspan="2">H_2:</td><td colspan="2">1.75</td><td colspan="2">H_3:</td><td colspan="2">2.00</td><td colspan="2">H_4:</td><td colspan="2">3.00</td><td colspan="2">H_5:</td><td colspan="2">3.00</td><td colspan="2">H_6:</td><td colspan="2">3.00</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">3.00</td><td colspan="2">H_8:</td><td colspan="2">3.00</td><td colspan="2">H_9:</td><td colspan="2">3.00</td><td colspan="2">H_{10}:</td><td colspan="2">2.00</td><td colspan="2">H_{11}:</td><td colspan="2">1.75</td><td colspan="2">H_{12}:</td><td colspan="2">1.00</td></tr>
</table>

5.5 Identifying preferred build order (2040 medium case)

Deployment at Morecambe Bay (Rolls-Royce dual mode generation) and the Wash (conventional dual mode generation) is proposed for the 2040 medium case. Both sites provide substantial energy generation potential at a high indicative energy/cost rating. However, both sites face possible difficulties relating to gaining regulatory consent due to the extensive impoundment of areas subject to environmental designation. Therefore imposing the 80% tidal range maintenance criteria on technology selection is considered a means of constraining the development to reflect environmental sensitivities. Neither impounds a significant port, an advantage over comparable competing sites still to be introduced to the scenario build order, and are subject to low annual mean significant wave heights.

The Morecambe Bay barrage results are presented in Table 7. Morecambe Bay is not suited to conventional dual mode operation as there is not a large enough extent of deep water to house the 220 turbines required to achieve optimal generation conditions while maintaining 80% of the natural tidal range as identified in deliverable D01. Hence the very low head Roll Royce technology approach is the only technology approach that meets the imposed criteria.

Table 7: Morecambe Bay barrage

<table>
<tr><td colspan="6"></td><td colspan="5">Location:</td><td colspan="7">Morecambe Bay</td><td colspan="6"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">6.2 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">455 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">18 km</td><td colspan="6">Operational mode</td><td colspan="6">Dual (Rolls-Royce)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">3670 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">80%</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">10.5 TWh/y</td><td colspan="3">$N_{9m\ turbines}$:</td><td colspan="3">0</td><td colspan="3">$N_{14m\ \mathrm{turbines}}$:</td><td colspan="3">320</td><td colspan="3">$A_{9m\ \mathrm{t}}$:</td><td colspan="3">52.1 m^2</td></tr>
<tr><td colspan="3">$A_{14m\ \mathrm{t}}$:</td><td colspan="3">126.1 m^2</td><td colspan="3">k</td><td colspan="3">0.86</td><td colspan="3">H_{min}:</td><td colspan="3">1</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">R_1:</td><td colspan="3">57.5906</td><td colspan="3">R_2:</td><td colspan="3">39.1934</td><td colspan="3">R_3:</td><td colspan="3">-2.6943</td><td colspan="3">R_4:</td><td colspan="3">-0.0004</td></tr>
<tr><td colspan="3">U_1:</td><td colspan="3">139.3550</td><td colspan="3">U_2:</td><td colspan="3">94.8382</td><td colspan="3">U_3:</td><td colspan="3">-6.5195</td><td colspan="3">U_4:</td><td colspan="3">-0.0009</td></tr>
<tr><td colspan="3">S_1:</td><td colspan="3">-0.2629</td><td colspan="3">S_2:</td><td colspan="3">0.6490</td><td colspan="3">S_3:</td><td colspan="3">0.2085</td><td colspan="3">S_4:</td><td colspan="3">-0.0002</td></tr>
<tr><td colspan="3">V_1:</td><td colspan="3">-0.6362</td><td colspan="3">V_2:</td><td colspan="3">1.5705</td><td colspan="3">V_3:</td><td colspan="3">0.5044</td><td colspan="3">V_4:</td><td colspan="3">-0.0006</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-6.14</td><td colspan="2">L_2:</td><td colspan="2">-4.91</td><td colspan="2">L_3:</td><td colspan="2">-3.68</td><td colspan="2">L_4:</td><td colspan="2">-3.07</td><td colspan="2">L_5:</td><td colspan="2">-2.46</td><td colspan="2">L_6:</td><td colspan="2">-1.23</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">1.23</td><td colspan="2">L_8:</td><td colspan="2">2.46</td><td colspan="2">L_9:</td><td colspan="2">3.07</td><td colspan="2">L_{10}:</td><td colspan="2">3.68</td><td colspan="2">L_{11}:</td><td colspan="2">4.91</td><td colspan="2">L_{12}:</td><td colspan="2">6.14</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">1.00</td><td colspan="2">H_2:</td><td colspan="2">1.25</td><td colspan="2">H_3:</td><td colspan="2">2.25</td><td colspan="2">H_4:</td><td colspan="2">3.00</td><td colspan="2">H_5:</td><td colspan="2">3.00</td><td colspan="2">H_6:</td><td colspan="2">3.00</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">3.00</td><td colspan="2">H_8:</td><td colspan="2">3.00</td><td colspan="2">H_9:</td><td colspan="2">3.00</td><td colspan="2">H_{10}:</td><td colspan="2">2.25</td><td colspan="2">H_{11}:</td><td colspan="2">1.25</td><td colspan="2">H_{12}:</td><td colspan="2">1.00</td></tr>
</table>

Both technology approaches operating in dual mode would be appropriate for implementation in the Wash barrage development. Although there is little difference between the overall assessment of the technologies in this particular case, the conventional turbine scheme is selected as the turbine supply chain requirements for Morecambe Bay and the Wash could well be too great for one supplier (Rolls-Royce in this case). The Wash barrage results are presented in Table 8.

Table 8: Wash barrage

<table>
<tr><td colspan="6"></td><td colspan="6">Location:</td><td colspan="6">Wash</td><td colspan="6"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">4.8 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">650 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">19 km</td><td colspan="6">Operational mode</td><td colspan="6">Dual (conventional)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">4900 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">80%</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">8.5 TWh/y</td><td colspan="3"># turbines:</td><td colspan="3">350</td><td colspan="3">Diameter:</td><td colspan="3">9.0 m</td><td colspan="3">$A_{0\text{turbine}}$:</td><td colspan="3">228.2 m^2</td></tr>
<tr><td colspan="3">TCW:</td><td colspan="3">20.5 m</td><td colspan="3">β_{ebb}:</td><td colspan="3">1.62</td><td colspan="3">β_{flood}:</td><td colspan="3">1.62</td><td colspan="3">H_{rated}:</td><td colspan="3">3.13 m</td></tr>
<tr><td colspan="3">P_{max}:</td><td colspan="3">14 MW</td><td colspan="3">H_{min}:</td><td colspan="3">1.17 m</td><td colspan="3">H_{int}:</td><td colspan="3">3.62 m</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">B_1:</td><td colspan="3">32.6340</td><td colspan="3">B_2:</td><td colspan="3">339.5230</td><td colspan="3">B_3:</td><td colspan="3">-75.2708</td><td colspan="3">B_4:</td><td colspan="3">8.0371</td></tr>
<tr><td colspan="3">C_1:</td><td colspan="3">32.6340</td><td colspan="3">C_2:</td><td colspan="3">339.5230</td><td colspan="3">C_3:</td><td colspan="3">-75.2708</td><td colspan="3">C_4:</td><td colspan="3">8.0371</td></tr>
<tr><td colspan="3">E_1:</td><td colspan="3">2272.6748</td><td colspan="3">E_2:</td><td colspan="3">-891.7772</td><td colspan="3">E_3:</td><td colspan="3">133.2140</td><td colspan="3">E_4:</td><td colspan="3">-6.7645</td></tr>
<tr><td colspan="3">F_1:</td><td colspan="3">-0.2209</td><td colspan="3">F_2:</td><td colspan="3">-1.1078</td><td colspan="3">F_3:</td><td colspan="3">2.7564</td><td colspan="3">F_4:</td><td colspan="3">-0.3040</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-4.46</td><td colspan="2">L_2:</td><td colspan="2">-3.57</td><td colspan="2">L_3:</td><td colspan="2">-2.68</td><td colspan="2">L_4:</td><td colspan="2">-2.23</td><td colspan="2">L_5:</td><td colspan="2">-1.78</td><td colspan="2">L_6:</td><td colspan="2">-0.89</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">0.89</td><td colspan="2">L_8:</td><td colspan="2">1.78</td><td colspan="2">L_9:</td><td colspan="2">2.23</td><td colspan="2">L_{10}:</td><td colspan="2">2.68</td><td colspan="2">L_{11}:</td><td colspan="2">3.57</td><td colspan="2">L_{12}:</td><td colspan="2">4.46</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">3.25</td><td colspan="2">H_2:</td><td colspan="2">3.50</td><td colspan="2">H_3:</td><td colspan="2">3.25</td><td colspan="2">H_4:</td><td colspan="2">3.25</td><td colspan="2">H_5:</td><td colspan="2">2.75</td><td colspan="2">H_6:</td><td colspan="2">2.75</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">2.75</td><td colspan="2">H_8:</td><td colspan="2">2.75</td><td colspan="2">H_9:</td><td colspan="2">3.25</td><td colspan="2">H_{10}:</td><td colspan="2">3.25</td><td colspan="2">H_{11}:</td><td colspan="2">3.50</td><td colspan="2">H_{12}:</td><td colspan="2">3.25</td></tr>
</table>

5.6 Identifying preferred build order (2040 optimistic case)

The Dee barrage is introduced in the 2040 optimistic scenario. In terms of build order it is slightly out of order, but has been introduced later in the timeline than the identified 2040 ‘medium’ scenario that its characteristics best fit (in terms of the favourability of the energy/cost rating that the project offers). This is to enable the regional impact of this particular scheme to be separated out from coincident deployment of the relatively nearby Morcambe Bay development prescribed in the 2040 ‘medium’ case. Both of these barrages are located in the north-eastern extent of the Irish Sea bounded by North Wales and the north-west of England. The project team is expecting that as maximum deployment is approached in this region of the UK, extreme responses may be experienced in the tidal system. Hence there is significant interest in separating out the contribution made by each scheme by adding them incrementally. In terms of technology selection, the dual mode conventional turbine approach is preferred. The environmental designations in the Dee estuary suggest that maintaining 80% of the natural tidal range offers a much more realistic opportunity of this deployment gaining consent on this timescale. Dual mode conventional turbine technology is also the most productive of the three identified options for the Dee in terms of overall indicative energy output achieved. The Dee barrage results are presented in Table 9

Table 9: Dee barrage

<table>
<tr><td colspan="2"></td><td colspan="2">Location:</td><td colspan="2">Dee</td><td colspan="2"></td></tr>
<tr><td colspan="2">Mean tidal range:</td><td colspan="2">5.9 m</td><td colspan="2">Impounded basin area:</td><td colspan="2">103 km^2</td></tr>
<tr><td colspan="2">Embankment length:</td><td colspan="2">8 km</td><td colspan="2">Operational mode</td><td colspan="2">Dual (conventional)</td></tr>
<tr><td colspan="2">Total installed capacity:</td><td colspan="2">1080 MW</td><td colspan="3">Minimum tidal range inside basin:</td><td>80%</td></tr>
<tr><td>AEP:</td><td>2.2 TWh/y</td><td># turbines:</td><td>60</td><td>Diameter:</td><td>9.0 m</td><td>$A_{0\text{turbine}}$:</td><td>228.2 m^2</td></tr>
<tr><td>TCW:</td><td>20.5 m</td><td>β_{ebb}:</td><td>1.62</td><td>β_{flood}:</td><td>1.62</td><td>H_{rated}:</td><td>3.65 m</td></tr>
<tr><td>P_{max}:</td><td>18 MW</td><td>H_{min}:</td><td>1.17 m</td><td>H_{int}:</td><td>3.62 m</td><td>T_{start}:</td><td>5</td></tr>
</table>

B_1:	50.3361	B_2:	310.7393	B_3:	-60.5084	B_4:	-5.6435
C_1:	50.3361	C_2:	310.7393	C_3:	-60.5084	C_4:	-5.6435
E_1:	3728.5906	E_2:	-1584.5345	E_3:	250.8029	E_4:	-13.5105
F_1:	-0.8723	F_2:	-0.0514	F_3:	2.2162	F_4:	-0.2167

L_1:	-5.95	L_2:	-4.76	L_3:	-3.57	L_4:	-2.98	L_5:	-2.38	L_6:	-1.19
L_7:	1.19	L_8:	2.38	L_9:	2.98	L_{10}:	3.57	L_{11}:	4.76	L_{12}:	5.95
H_1:	1.17	H_2:	4.50	H_3:	4.50	H_4:	4.75	H_5:	4.50	H_6:	1.17
H_7:	1.17	H_8:	4.50	H_9:	4.74	H_{10}:	4.50	H_{11}:	4.50	H_{12}:	1.17

5.7 Identifying preferred build order (2050 medium case)

By 2050 in the scenario development, the majority of the prime tidal range projects in terms of (i) indicative energy output, and (ii) energy/cost rating comparisons have been deployed. The remaining projects that are competitive regarding the previous two metrics that have not yet been developed are because of specific project constraints such as impounding a major port. The Solway Firth is a special case, as will now be discussed.

The Solway Firth barrage offers a good energy/cost benefit assessment in all three operating modes. Dual mode offers the highest return, and also by default maintains 80% natural tidal range. Most significantly, the indicative energy output of the Solway Firth operating in dual mode with conventional turbines is 31 TWh/y, a major contribution towards UK energy demand (over 8% from this one project alone). The reader may be surprised that this project is therefore only being introduced in 2050 in the timeline when the metrics above suggest that development could be supported earlier. The major limiting factor that is identified is the sheer scale of the project – the installed capacity is 19800 MW requiring 1100 turbines. In the first instance, although the basin level is appropriately maintained to meet the first order constraint imposed in terms of internal tidal range, this scale of project is likely to have a measurable impact over a significant extent of the UK continental shelf. The second reason for delaying introducing this project in the timeline is that manufacture of this many turbines in an earlier stage in the build order is not deemed realistic by the project team. The supply chain able to respond to this need is not envisaged to be in place until tidal range technology development is a very mature industry. Even in each of the preceding cases presented, it is a very optimistic view to assume that the supply chain will be able to cope with the required demand. Only the development of these previous projects and similar project development in other countries around the globe would create the circumstances where the technology providers would have the capability to respond to the need for this many turbines. Nonetheless, including this scheme later on in the timeline enables the development of the correct conditions for this project to be brought forward to develop. The Solway Firth barrage results are presented in Table 10.

Although prescribed as an indicative rating of energy/cost as opposed to an absolute value, there is significant separation between those projects that achieve a rating in double figures, or close to doing so, and a separate defined group that achieve a rating of half or even a quarter of these levels. This is reflective of the combination of either a relatively low tidal range (in energy terms, as opposed to oceanographic terms where 4-5 metres is still generally considered to be large), a relatively small impounded basin area with respect to the required embankment length, or often both conditions. By 2050, under the assumption of the industry development already mapped out in the 'future' scenarios, it is reasonable to assume that there has been cost reduction through learning and experience and the benefit of the development of an established supply chain. Therefore, it becomes more realistic that projects with a marginal cost/benefit rating become more viable. For the reasons just discussed, now that the more obvious deployments have been introduced to the scenarios, more marginal projects are deemed to be more viable

Table 10: Solway Firth barrage

	Location:	Solway Firth (Outer)									
Mean tidal range:	5.6 m	Impounded basin area:	814km^2								
Embankment length:	28 km	Operational mode	Dual (conventional)								
Total installed capacity:	19800 MW	Minimum tidal range inside basin:	83%								
AEP:	31.0 TWh/y	# turbines:	1100	Diameter:	9.0 m	$A_{0\mathrm{turbine}}$:	228.2 m^2				
TCW:	20.5 m	β_{ebb}:	1.62	β_{flood}:	1.62	H_{rated}:	3.65 m				
$P_{\max}$:	18 MW	$H_{\min}$:	1.17 m	H_{int}:	3.62 m	T_{start}:	5				
B_1:	50.3361	B_2:	310.7393	B_3:	-60.5084	B_4:	-5.6435				
C_1:	50.3361	C_2:	310.7393	C_3:	-60.5084	C_4:	-5.6435				
E_1:	3728.5906	E_2:	-1584.5345	E_3:	250.8029	E_4:	-13.5105				
F_1:	-0.8723	F_2:	-0.0514	F_3:	2.2162	F_4:	-0.2167				
L_1:	-5.48	L_2:	-4.38	L_3:	-3.29	L_4:	-2.74	L_5:	-2.19	L_6:	-1.10
L_7:	1.10	L_8:	2.19	L_9:	2.74	L_{10}:	3.29	L_{11}:	4.38	L_{12}:	5.48
H_1:	5.25	H_2:	5.50	H_3:	5.25	H_4:	5.00	H_5:	4.75	H_6:	3.50
H_7:	3.50	H_8:	4.75	H_9:	5.00	H_{10}:	5.25	H_{11}:	5.50	H_{12}:	5.25

The West Aberthaw and Rhoose dual mode generation lagoons both present a good case for development in terms of the basin area being free of existing environmental designation and having no impact on port access. There is little to differentiate these two neighbouring developments. In comparison with the other less favourable deployment options, they have the highest energy/cost rating (3.7), and combine to produce an indicated energy output of 4.3 TWh/y. Given the very extensive regional development already included in the Severn Estuary by this stage of the scenario analysis, it is considered acceptable to introduce these two smaller developments in tandem. The West Aberthaw lagoon results are presented in Table 11. The Rhoose lagoon results are presented in Table 12.

Table 11: West Aberthaw lagoon

	Location:	West Aberthlaw lagoon									
Mean tidal range:	7.2 m	Impounded basin area:	30 km^2								
Embankment length:	13 km	Operational mode	Dual (conventional)								
Total installed capacity:	1215 MW	Minimum tidal range inside basin:	82%								
AEP:	2.3 TWh/y	# turbines:	45	Diameter:	9.0 m	$A_{0\mathrm{turbine}}$:	228.2 m^2				
TCW:	20.5 m	β_{ebb}:	1.62	β_{flood}:	1.62	H_{rated}:	4.84 m				
$P_{\max}$:	27 MW	$H_{\min}$:	1.17 m	H_{int}:	3.62 m	T_{start}:	5				
B_1:	44.4212	B_2:	320.1676	B_3:	-65.2245	B_4:	6.3856				
C_1:	795.4994	C_2:	-135.6645	C_3:	38.5536	C_4:	-3.3466				
E_1:	2014.4589	E_2:	-445.5479	E_3:	39.6954	E_4:	-1.2293				
F_1:	-1.1970	F_2:	0.4794	F_3:	1.9448	F_4:	-0.1735				
L_1:	-7.45	L_2:	-5.96	L_3:	-4.47	L_4:	-3.73	L_5:	-2.98	L_6:	-1.49
L_7:	1.49	L_8:	2.98	L_9:	3.73	L_{10}:	4.47	L_{11}:	5.96	L_{12}:	7.45
H_1:	6.75	H_2:	6.75	H_3:	6.75	H_4:	6.25	H_5:	5.00	H_6:	5.00
H_7:	5.00	H_8:	5.00	H_9:	6.25	H_{10}:	6.75	H_{11}:	6.75	H_{12}:	6.75

The Rye Bay lagoon, also operating in dual mode with conventional turbines offers, a similar energy /cost rating as the preceding two cases although the associated indicative energy output is increased. This has to be balanced against the slightly less sheltered location (so small increase in wave action). The impounded basin area impinges marginally on an environmentally designated area. Rye Bay is

Table 12: Rhoose barrage

		Location:		Rhoose lagoon			
Mean tidal range:		7.5 m		Impounded basin area:		25 km^2	
Embankment length:		12 km		Operational mode		Dual (conventional)	
Total installed capacity:		1080 MW		Minimum tidal range inside basin:			82%
AEP:	2.0 TWh/y	# turbines:	40	Diameter:	9.0 m	$A_{0turbine}$:	228.2 m^2
TCW:	20.5 m	β_{ebb}:	1.62	β_{flood}:	1.62	H_{rated}:	4.84 m
P_{max}:	27 MW	H_{min}:	1.17 m	H_{int}:	3.62 m	T_{start}:	5
B_1:	44.4212	B_2:	320.1676	B_3:	-65.2245	B_4:	6.3856
C_1:	795.4994	C_2:	-135.6645	C_3:	38.5536	C_4:	-3.3466
E_1:	2014.4589	E_2:	-445.5479	E_3:	39.6954	E_4:	-1.2293
F_1:	-1.1970	F_2:	0.4794	F_3:	1.9448	F_4:	-0.1735

L_1:	-7.45	L_2:	-5.96	L_3:	-4.47	L_4:	-3.73	L_5:	-2.98	L_6:	-1.49
L_7:	1.49	L_8:	2.98	L_9:	3.73	L_{10}:	4.47	L_{11}:	5.96	L_{12}:	7.45
H_1:	6.75	H_2:	6.75	H_3:	6.75	H_4:	6.25	H_5:	5.00	H_6:	5.00
H_7:	5.00	H_8:	5.00	H_9:	6.25	H_{10}:	6.75	H_{11}:	6.75	H_{12}:	6.75

considered an appropriate site for deployment in the 2050 ‘medium’ scenario. The Rye Bay lagoon results are presented in Table 13.

Table 13: Rye Bay lagoon

		Location:		Rye bay			
Mean tidal range:		5.2 m		Impounded basin area:		103 km^2	
Embankment length:		25 km		Operational mode		Dual (conventional)	
Total installed capacity:		1980 MW		Minimum tidal range inside basin:			80%
AEP:	3.2 TWh/y	# turbines:	110	Diameter:	9.0 m	$A_{0turbine}$:	228.2 m^2
TCW:	20.5 m	β_{ebb}:	1.62	β_{flood}:	1.62	H_{rated}:	3.65 m
P_{max}:	18 MW	H_{min}:	1.17 m	H_{int}:	3.62 m	T_{start}:	5
B_1:	50.3361	B_2:	310.7393	B_3:	-60.5084	B_4:	5.6435
C_1:	50.3361	C_2:	310.7393	C_3:	-60.5084	C_4:	5.6435
E_1:	3728.5906	E_2:	-1584.5345	E_3:	250.8029	E_4:	-13.5105
F_1:	-0.8723	F_2:	-0.0514	F_3:	2.2162	F_4:	-0.2167

L_1:	-5.15	L_2:	-4.12	L_3:	-3.09	L_4:	-2.58	L_5:	-2.06	L_6:	-1.03
L_7:	1.03	L_8:	2.06	L_9:	2.58	L_{10}:	3.09	L_{11}:	4.12	L_{12}:	5.15
H_1:	5.25	H_2:	5.25	H_3:	4.50	H_4:	4.25	H_5:	3.75	H_6:	3.25
H_7:	3.25	H_8:	3.75	H_9:	4.25	H_{10}:	4.50	H_{11}:	5.25	H_{12}:	5.25

5.8 Identifying preferred build order (2050 optimistic case)

The 2050 medium case is getting close to the full potential for deployment of tidal range technologies. An ‘extreme’ case will also be presented where all compatible sites are included in the analysis, thereby ignoring all possible economic, regulatory or competing use constraints on development

However, the 2050 ‘optimistic’ case begins with an outlier in the form of Wigtown Bay lagoon. For similar reasoning presented as to why the Dee estuary was delayed with respect to Morecambe Bay, Wigtown Bay was delayed from its more realistic position in the build order of 2040 ‘optimistic’ to avoid clashing with the Dee or later Solway Firth deployments in terms of interpreting the alteration to the tidal dynamics in the north-eastern Irish Sea. A similar approach has also helped inform the roll out of the Severn options, but less manipulation was required as the build order fitted more appropriately with the needs of the project from the perspective of ascribing additional sensitivities to a particular deployment, at least within a regional area. These aspects are worth highlighting for future scenario prescription (either for the additional 10 cases the ETI has available to them, or during the fee-for-service period of CSM operation).

Only dual operation mode options are provided by deliverable D01 outputs for the Wigtown Bay site. Of these, the conventional turbine approach presents the largest energy yield potential. Wigtown Bay is not subject to any of the identified environmental designations and has no impact on port access. The Wigtown Bay lagoon results are presented in Table 14.

Table 14: Wigtown Bay lagoon

<table>
<tr><td colspan="6"></td><td colspan="6">Location:</td><td colspan="6">Wigtown Bay</td><td colspan="6"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">4.8 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">163 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">15 km</td><td colspan="6">Operational mode</td><td colspan="6">Dual (conventional)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">2240 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">80%</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">3.8TWh/y</td><td colspan="3"># turbines:</td><td colspan="3">160</td><td colspan="3">Diameter:</td><td colspan="3">9.0 m</td><td colspan="3">$A_{0\text{turbine}}$:</td><td colspan="3">228.2 m^2</td></tr>
<tr><td colspan="3">TCW:</td><td colspan="3">20.5 m</td><td colspan="3">β_{ebb}:</td><td colspan="3">1.62</td><td colspan="3">β_{flood}:</td><td colspan="3">1.62</td><td colspan="3">H_{rated}:</td><td colspan="3">3.13 m</td></tr>
<tr><td colspan="3">P_{max}:</td><td colspan="3">14 MW</td><td colspan="3">H_{min}:</td><td colspan="3">1.17 m</td><td colspan="3">H_{int}:</td><td colspan="3">3.62 m</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">B_1:</td><td colspan="3">32.6340</td><td colspan="3">B_2:</td><td colspan="3">339.5230</td><td colspan="3">B_3:</td><td colspan="3">-75.2708</td><td colspan="3">B_4:</td><td colspan="3">8.0371</td></tr>
<tr><td colspan="3">C_1:</td><td colspan="3">32.6340</td><td colspan="3">C_2:</td><td colspan="3">339.5230</td><td colspan="3">C_3:</td><td colspan="3">-75.2708</td><td colspan="3">C_4:</td><td colspan="3">8.0371</td></tr>
<tr><td colspan="3">E_1:</td><td colspan="3">2272.6748</td><td colspan="3">E_2:</td><td colspan="3">-891.7772</td><td colspan="3">E_3:</td><td colspan="3">133.2140</td><td colspan="3">E_4:</td><td colspan="3">-6.7645</td></tr>
<tr><td colspan="3">F_1:</td><td colspan="3">-0.2209</td><td colspan="3">F_2:</td><td colspan="3">-1.1078</td><td colspan="3">F_3:</td><td colspan="3">2.7564</td><td colspan="3">F_4:</td><td colspan="3">-0.3040</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-4.75</td><td colspan="2">L_2:</td><td colspan="2">-3.80</td><td colspan="2">L_3:</td><td colspan="2">-2.85</td><td colspan="2">L_4:</td><td colspan="2">-2.38</td><td colspan="2">L_5:</td><td colspan="2">-1.90</td><td colspan="2">L_6:</td><td colspan="2">-0.95</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">0.95</td><td colspan="2">L_8:</td><td colspan="2">1.90</td><td colspan="2">L_9:</td><td colspan="2">2.38</td><td colspan="2">L_{10}:</td><td colspan="2">2.85</td><td colspan="2">L_{11}:</td><td colspan="2">3.80</td><td colspan="2">L_{12}:</td><td colspan="2">4.75</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">4.25</td><td colspan="2">H_2:</td><td colspan="2">4.25</td><td colspan="2">H_3:</td><td colspan="2">4.25</td><td colspan="2">H_4:</td><td colspan="2">4.00</td><td colspan="2">H_5:</td><td colspan="2">4.00</td><td colspan="2">H_6:</td><td colspan="2">3.75</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">3.75</td><td colspan="2">H_8:</td><td colspan="2">4.00</td><td colspan="2">H_9:</td><td colspan="2">4.00</td><td colspan="2">H_{10}:</td><td colspan="2">4.25</td><td colspan="2">H_{11}:</td><td colspan="2">4.25</td><td colspan="2">H_{12}:</td><td colspan="2">4.25</td></tr>
</table>

Dymchurch lagoon can be viewed as a sister project to Rye Bay due to their relative proximity and shared technology characteristics. In fact little differentiates the two cases other than the reduced energy/cost rating attributed to the Dymchurch development. Although the basin areas and embankment lengths are very similar, and both projects utilise the same number of identical turbines, Dymchurch is less cost efficient because the embankment orientation passes through deeper water. Dymchurch also impounds a slightly increased area that is identified as environmentally designated, but at a level (absolute and percentage of enclosed basin area) that is still relatively marginal in comparison to many of the much larger tidal range deployments. Hence the separation of the two cases in the build order (again for the purposes of local and regional interpretation it is additionally beneficial that the two projects are introduced to the scenario analysis at different stages). The Dymchurch lagoon results are presented in Table 15.

Table 15: Dymchurch lagoon

<table>
<tr><td colspan="2"></td><td colspan="2">Location:</td><td colspan="2">Dymchurch lagoon</td><td colspan="2"></td></tr>
<tr><td colspan="2">Mean tidal range:</td><td colspan="2">5.2 m</td><td colspan="2">Impounded basin area:</td><td colspan="2">103 km^2</td></tr>
<tr><td colspan="2">Embankment length:</td><td colspan="2">23 km</td><td colspan="2">Operational mode</td><td colspan="2">Dual (conventional)</td></tr>
<tr><td colspan="2">Total installed capacity:</td><td colspan="2">1980 MW</td><td colspan="3">Minimum tidal range inside basin:</td><td>80%</td></tr>
<tr><td>AEP:</td><td>3.2 TWh/y</td><td># turbines:</td><td>110</td><td>Diameter:</td><td>9.0 m</td><td>$A_{0\text{turbine}}$:</td><td>228.2 m^2</td></tr>
<tr><td>TCW:</td><td>20.5 m</td><td>β_{ebb}:</td><td>1.62</td><td>β_{flood}:</td><td>1.62</td><td>H_{rated}:</td><td>3.65 m</td></tr>
<tr><td>P_{max}:</td><td>18 MW</td><td>H_{min}:</td><td>1.17 m</td><td>H_{int}:</td><td>3.62 m</td><td>T_{start}:</td><td>5</td></tr>
<tr><td>B_1:</td><td>50.3361</td><td>B_2:</td><td>310.7393</td><td>B_3:</td><td>-60.5084</td><td>B_4:</td><td>5.6435</td></tr>
<tr><td>C_1:</td><td>50.3361</td><td>C_2:</td><td>310.7393</td><td>C_3:</td><td>-60.5084</td><td>C_4:</td><td>5.6435</td></tr>
</table>

<table>
<tr><td colspan="3">E_1:</td><td colspan="3">3728.5906</td><td colspan="3">E_2:</td><td colspan="3">-1584.5345</td><td colspan="3">E_3:</td><td colspan="3">250.8029</td><td colspan="3">E_4:</td><td colspan="3">-13.5105</td></tr>
<tr><td colspan="3">F_1:</td><td colspan="3">-0.8723</td><td colspan="3">F_2:</td><td colspan="3">-0.0514</td><td colspan="3">F_3:</td><td colspan="3">2.2162</td><td colspan="3">F_4:</td><td colspan="3">-0.2167</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-5.15</td><td colspan="2">L_2:</td><td colspan="2">-4.12</td><td colspan="2">L_3:</td><td colspan="2">-3.09</td><td colspan="2">L_4:</td><td colspan="2">-2.58</td><td colspan="2">L_5:</td><td colspan="2">-2.06</td><td colspan="2">L_6:</td><td colspan="2">-1.03</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">1.03</td><td colspan="2">L_8:</td><td colspan="2">2.06</td><td colspan="2">L_9:</td><td colspan="2">2.58</td><td colspan="2">L_{10}:</td><td colspan="2">3.09</td><td colspan="2">L_{11}:</td><td colspan="2">4.12</td><td colspan="2">L_{12}:</td><td colspan="2">5.15</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">5.25</td><td colspan="2">H_2:</td><td colspan="2">5.25</td><td colspan="2">H_3:</td><td colspan="2">4.50</td><td colspan="2">H_4:</td><td colspan="2">4.25</td><td colspan="2">H_5:</td><td colspan="2">3.75</td><td colspan="2">H_6:</td><td colspan="2">3.25</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">3.25</td><td colspan="2">H_8:</td><td colspan="2">3.75</td><td colspan="2">H_9:</td><td colspan="2">4.25</td><td colspan="2">H_{10}:</td><td colspan="2">4.50</td><td colspan="2">H_{11}:</td><td colspan="2">5.25</td><td colspan="2">H_{12}:</td><td colspan="2">5.25</td></tr>
</table>

The case for the Oxwich Bay lagoon is very similar to the majority of the smaller deployments in the 2050 scenario cases. There are not many barriers to development of the project in terms of environmental constraints or port access, although the location is more open to a slightly harsher wave climate than the majority of feasible tidal range deployment sites. What holds these developments back in the build order is their relatively poor energy/cost rating reflecting the small (but still meaningful) overall contribution that these projects make in terms of energy generation in comparison with the extensive civil works and manufacturing requirements that developing these sites requires. The Oxwich Bay lagoon results are presented in Table 16.

Table 16: Oxwich Bay lagoon

<table>
<tr><td colspan="6"></td><td colspan="5">Location:</td><td colspan="7">Oxwich Bay</td><td colspan="6"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">6.1 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">14 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">6 km</td><td colspan="6">Operational mode</td><td colspan="6">Dual (conventional)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">352 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">80%</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">0.6 TWh/y</td><td colspan="3"># turbines:</td><td colspan="3">16</td><td colspan="3">Diameter:</td><td colspan="3">9.0 m</td><td colspan="3">$A_{0turbine}$:</td><td colspan="3">228.2 m^2</td></tr>
<tr><td colspan="3">TCW:</td><td colspan="3">20.5 m</td><td colspan="3">β_{ebb}:</td><td colspan="3">1.62</td><td colspan="3">β_{flood}:</td><td colspan="3">1.62</td><td colspan="3">H_{rated}:</td><td colspan="3">4.15 m</td></tr>
<tr><td colspan="3">P_{max}:</td><td colspan="3">22 MW</td><td colspan="3">H_{min}:</td><td colspan="3">1.17 m</td><td colspan="3">H_{int}:</td><td colspan="3">3.62 m</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">B_1:</td><td colspan="3">44.4212</td><td colspan="3">B_2:</td><td colspan="3">320.1676</td><td colspan="3">B_3:</td><td colspan="3">-65.2245</td><td colspan="3">B_4:</td><td colspan="3">6.3856</td></tr>
<tr><td colspan="3">C_1:</td><td colspan="3">1240.6930</td><td colspan="3">C_2:</td><td colspan="3">-482.0776</td><td colspan="3">C_3:</td><td colspan="3">128.2655</td><td colspan="3">C_4:</td><td colspan="3">-11.0787</td></tr>
<tr><td colspan="3">E_1:</td><td colspan="3">2976.3724</td><td colspan="3">E_2:</td><td colspan="3">-1008.0453</td><td colspan="3">E_3:</td><td colspan="3">132.6627</td><td colspan="3">E_4:</td><td colspan="3">-6.0453</td></tr>
<tr><td colspan="3">F_1:</td><td colspan="3">-1.6279</td><td colspan="3">F_2:</td><td colspan="3">1.1035</td><td colspan="3">F_3:</td><td colspan="3">1.6682</td><td colspan="3">F_4:</td><td colspan="3">-0.1357</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-6.10</td><td colspan="2">L_2:</td><td colspan="2">-4.88</td><td colspan="2">L_3:</td><td colspan="2">-3.66</td><td colspan="2">L_4:</td><td colspan="2">-3.05</td><td colspan="2">L_5:</td><td colspan="2">-2.44</td><td colspan="2">L_6:</td><td colspan="2">-1.22</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">1.22</td><td colspan="2">L_8:</td><td colspan="2">2.44</td><td colspan="2">L_9:</td><td colspan="2">3.05</td><td colspan="2">L_{10}:</td><td colspan="2">3.66</td><td colspan="2">L_{11}:</td><td colspan="2">4.88</td><td colspan="2">L_{12}:</td><td colspan="2">6.10</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">5.50</td><td colspan="2">H_2:</td><td colspan="2">5.50</td><td colspan="2">H_3:</td><td colspan="2">5.25</td><td colspan="2">H_4:</td><td colspan="2">5.00</td><td colspan="2">H_5:</td><td colspan="2">4.50</td><td colspan="2">H_6:</td><td colspan="2">4.25</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">4.25</td><td colspan="2">H_8:</td><td colspan="2">4.50</td><td colspan="2">H_9:</td><td colspan="2">5.00</td><td colspan="2">H_{10}:</td><td colspan="2">5.25</td><td colspan="2">H_{11}:</td><td colspan="2">5.50</td><td colspan="2">H_{12}:</td><td colspan="2">5.50</td></tr>
</table>

5.9 Introducing the ‘special’ scenario cases (scenarios 16+18, 19, 20, 22 and 23)

Various additional scenarios that do not fit strictly into the build order discussion or framework are now presented to examine specific cases of interest. These scenarios are referred to as ‘special’ to designate that they are not part of the core 15 scenarios introduced to date that have been constructed through the incremental build approach previously discussed. Ten ‘special’ cases are introduced across the scenario analysis, six of which involve or are specific to tidal range projects.

5.10 Scenario 16 & 18 (‘extreme’ deployment levels)

Scenario 16 and 18 take the build order scenario development to the extreme – representing deployment and operation of all the compatible tidal range (and extreme levels of tidal current) potential. The scenario again ignores the Severn Outer and Dee/Wirral sites in order to avoid the acknowledged difficulties of having to design the enclosed barrage/lagoons to operate in such circumstances. This means that 4 more sites are introduced for this scenario. The 4 new sites are each presented in brief to justify the technology choice for each site.

A large proportion of the basin area enclosed by the Humber barrage is identified as environmentally designated, hence a solution mainlining 80% of natural tidal range is imposed to reflect potential consenting issues. No dual mode conventional approach is presented in deliverable D01, so dual mode operation using Rolls-Royce turbines is the only available option. However, the Humber barrage was not included even in an 'optimistic' scenario because of the conflict of use in the region of the Humber as a major port. The introduction of the Humber barrage would impact on the landing of 14% of total UK shipping freight. This was viewed as unworkable in the build-order scenario development. In this 'extreme' scenario, such restrictions will be ignored. The Humber barrage results are presented in Table 17.

Table 17: Humber barrage

<table>
<tr><td colspan="6"></td><td colspan="6">Location:</td><td colspan="6">Humber</td><td colspan="6"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">4.3 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">292 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">7 km</td><td colspan="6">Operational mode</td><td colspan="6">Dual (Rolls-Royce)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">1340 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">80%</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">3.7 TWh/y</td><td colspan="3">$N_{9m\ turbines}$:</td><td colspan="3">0</td><td colspan="3">$N_{14m\ \mathrm{turbines}}$:</td><td colspan="3">200</td><td colspan="3">$A_{9m\ \mathrm{t}}$:</td><td colspan="3">52.1 m^2</td></tr>
<tr><td colspan="3">$A_{14m\ \mathrm{t}}$:</td><td colspan="3">126.1 m^2</td><td colspan="3">k</td><td colspan="3">0.86</td><td colspan="3">H_{min}:</td><td colspan="3">1</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">B_1:</td><td colspan="3">57.5906</td><td colspan="3">B_2:</td><td colspan="3">39.1934</td><td colspan="3">B_3:</td><td colspan="3">-2.6943</td><td colspan="3">B_4:</td><td colspan="3">-0.0004</td></tr>
<tr><td colspan="3">$D01$:</td><td colspan="3">139.3550</td><td colspan="3">$D02$:</td><td colspan="3">94.8382</td><td colspan="3">$D03$:</td><td colspan="3">-6.5195</td><td colspan="3">$D04$:</td><td colspan="3">-0.0009</td></tr>
<tr><td colspan="3">F_1:</td><td colspan="3">-0.2629</td><td colspan="3">F_2:</td><td colspan="3">0.6490</td><td colspan="3">F_3:</td><td colspan="3">0.2085</td><td colspan="3">F_4:</td><td colspan="3">-0.0002</td></tr>
<tr><td colspan="3">G_1:</td><td colspan="3">-0.6362</td><td colspan="3">G_2:</td><td colspan="3">1.5705</td><td colspan="3">G_3:</td><td colspan="3">0.5044</td><td colspan="3">G_4:</td><td colspan="3">-0.0006</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-4.10</td><td colspan="2">L_2:</td><td colspan="2">-3.28</td><td colspan="2">L_3:</td><td colspan="2">-2.46</td><td colspan="2">L_4:</td><td colspan="2">-2.05</td><td colspan="2">L_5:</td><td colspan="2">-1.64</td><td colspan="2">L_6:</td><td colspan="2">-0.82</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">0.82</td><td colspan="2">L_8:</td><td colspan="2">1.64</td><td colspan="2">L_9:</td><td colspan="2">2.05</td><td colspan="2">L_{10}:</td><td colspan="2">2.46</td><td colspan="2">L_{11}:</td><td colspan="2">3.28</td><td colspan="2">L_{12}:</td><td colspan="2">4.10</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">1.75</td><td colspan="2">H_2:</td><td colspan="2">1.75</td><td colspan="2">H_3:</td><td colspan="2">2.25</td><td colspan="2">H_4:</td><td colspan="2">2.25</td><td colspan="2">H_5:</td><td colspan="2">2.25</td><td colspan="2">H_6:</td><td colspan="2">2.25</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">2.25</td><td colspan="2">H_8:</td><td colspan="2">2.25</td><td colspan="2">H_9:</td><td colspan="2">2.25</td><td colspan="2">H_{10}:</td><td colspan="2">2.25</td><td colspan="2">H_{11}:</td><td colspan="2">1.75</td><td colspan="2">H_{12}:</td><td colspan="2">1.75</td></tr>
</table>

The Thames barrage is a similar story to the Humber, in that the 8% of total UK shipping freight that would be impacted by the construction and operation of the barrage was viewed as a barrier to deployment. Technology selection in this case was a straight choice between the two identified alternatives, ebb, and dual Rolls-Royce. Rolls-Royce is selected as very low head turbine operation (as embodied by the Rolls-Royce technology) is generally better suited to mean tidal ranges of the order 4 metres, the limit generally considered below which ebb generation conventional turbines are not capable of producing an economic solution. The Thames barrage results are presented in Table 18.

Table 18: Thames barrage

<table>
<tr><td colspan="6"></td><td colspan="6">Location:</td><td colspan="6">Thames</td><td colspan="6"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">4.2 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">160 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">8 km</td><td colspan="6">Operational mode</td><td colspan="6">Dual (Rolls-Royce)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">530 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">80%</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">1.8 TWh/y</td><td colspan="3">$N_{9m\ turbines}$:</td><td colspan="3">20</td><td colspan="3">$N_{14m\ \mathrm{turbines}}$:</td><td colspan="3">90</td><td colspan="3">$A_{9m\ \mathrm{t}}$:</td><td colspan="3">52.1 m^2</td></tr>
<tr><td colspan="3">$A_{14m\ \mathrm{t}}$:</td><td colspan="3">126.1 m^2</td><td colspan="3">k</td><td colspan="3">0.86</td><td colspan="3">H_{min}:</td><td colspan="3">1</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">B_1:</td><td colspan="3">57.5906</td><td colspan="3">B_2:</td><td colspan="3">39.1934</td><td colspan="3">B_3:</td><td colspan="3">-2.6943</td><td colspan="3">B_4:</td><td colspan="3">-0.0004</td></tr>
<tr><td colspan="3">$D01$:</td><td colspan="3">139.3550</td><td colspan="3">$D02$:</td><td colspan="3">94.8382</td><td colspan="3">$D03$:</td><td colspan="3">-6.5195</td><td colspan="3">$D04$:</td><td colspan="3">-0.0009</td></tr>
<tr><td colspan="3">F_1:</td><td colspan="3">-0.2629</td><td colspan="3">F_2:</td><td colspan="3">0.6490</td><td colspan="3">F_3:</td><td colspan="3">0.2085</td><td colspan="3">F_4:</td><td colspan="3">-0.0002</td></tr>
<tr><td colspan="3">G_1:</td><td colspan="3">-0.6362</td><td colspan="3">G_2:</td><td colspan="3">1.5705</td><td colspan="3">G_3:</td><td colspan="3">0.5044</td><td colspan="3">G_4:</td><td colspan="3">-0.0006</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-4.20</td><td colspan="2">L_2:</td><td colspan="2">-3.36</td><td colspan="2">L_3:</td><td colspan="2">-2.52</td><td colspan="2">L_4:</td><td colspan="2">-2.10</td><td colspan="2">L_5:</td><td colspan="2">-1.68</td><td colspan="2">L_6:</td><td colspan="2">-0.84</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">0.84</td><td colspan="2">L_8:</td><td colspan="2">1.68</td><td colspan="2">L_9:</td><td colspan="2">2.10</td><td colspan="2">L_{10}:</td><td colspan="2">2.52</td><td colspan="2">L_{11}:</td><td colspan="2">3.36</td><td colspan="2">L_{12}:</td><td colspan="2">4.20</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">1.00</td><td colspan="2">H_2:</td><td colspan="2">1.00</td><td colspan="2">H_3:</td><td colspan="2">1.00</td><td colspan="2">H_4:</td><td colspan="2">1.75</td><td colspan="2">H_5:</td><td colspan="2">2.00</td><td colspan="2">H_6:</td><td colspan="2">2.00</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">2.00</td><td colspan="2">H_8:</td><td colspan="2">2.00</td><td colspan="2">H_9:</td><td colspan="2">1.75</td><td colspan="2">H_{10}:</td><td colspan="2">1.00</td><td colspan="2">H_{11}:</td><td colspan="2">1.00</td><td colspan="2">H_{12}:</td><td colspan="2">1.00</td></tr>
</table>

The Cumbria lagoon has not been introduced thus far in the scenario analysis because it offers one of the lowest energy/cost benefit ratings. It is also very closely located geographically to other more promising, and much more productive sites around the north-eastern Irish Sea (e.g. Solway Firth and Morecambe Bay). It will therefore be interesting to examine whether the additional change in tidal dynamics due to the introduction of the Cumbria lagoon, although making a measurable contribution in its own right, actually significantly impacts the overall combined indicative energy output from the region in the CSM simulation. Technology selection is largely unaffected by environmental designation in the region (although an ebb generation option is not provided). Hence dual mode, conventional turbine operation is imposed as this scheme offers a higher indicative energy output rating. The Cumbria lagoon results are presented in Table 19.

Table 19: Cumbria lagoon

<table>
<tr><td colspan="6"></td><td colspan="5">Location:</td><td colspan="7">Cumbria lagoon</td><td colspan="6"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">5.5 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">62 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">20 km</td><td colspan="6">Operational mode</td><td colspan="6">Dual (conventional)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">1260 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">82 %</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">2.2 TWh/y</td><td colspan="3"># turbines:</td><td colspan="3">70</td><td colspan="3">Diameter:</td><td colspan="3">9.0 m</td><td colspan="3">$A_{0\text{turbine}}$:</td><td colspan="3">228.2 m^2</td></tr>
<tr><td colspan="3">TCW:</td><td colspan="3">20.5 m</td><td colspan="3">β_{ebb}:</td><td colspan="3">1.62</td><td colspan="3">β_{flood}:</td><td colspan="3">1.62</td><td colspan="3">H_{rated}:</td><td colspan="3">3.65 m</td></tr>
<tr><td colspan="3">P_{max}:</td><td colspan="3">18 MW</td><td colspan="3">H_{min}:</td><td colspan="3">1.17 m</td><td colspan="3">H_{int}:</td><td colspan="3">3.62 m</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">B_1:</td><td colspan="3">50.3361</td><td colspan="3">B_2:</td><td colspan="3">310.7393</td><td colspan="3">B_3:</td><td colspan="3">-60.5084</td><td colspan="3">B_4:</td><td colspan="3">5.6435</td></tr>
<tr><td colspan="3">*D01*:</td><td colspan="3">50.3361</td><td colspan="3">*D02*:</td><td colspan="3">310.7393</td><td colspan="3">*D03*:</td><td colspan="3">-60.5084</td><td colspan="3">*D04*:</td><td colspan="3">5.6435</td></tr>
<tr><td colspan="3">E_1:</td><td colspan="3">3728.5906</td><td colspan="3">E_2:</td><td colspan="3">-1584.5435</td><td colspan="3">E_3:</td><td colspan="3">250.8029</td><td colspan="3">E_4:</td><td colspan="3">-13.5105</td></tr>
<tr><td colspan="3">F_1:</td><td colspan="3">-0.8723</td><td colspan="3">F_2:</td><td colspan="3">-0.0514</td><td colspan="3">F_3:</td><td colspan="3">2.2162</td><td colspan="3">F_4:</td><td colspan="3">-0.2167</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-5.45</td><td colspan="2">L_2:</td><td colspan="2">-4.36</td><td colspan="2">L_3:</td><td colspan="2">-3.27</td><td colspan="2">L_4:</td><td colspan="2">-2.73</td><td colspan="2">L_5:</td><td colspan="2">-2.18</td><td colspan="2">L_6:</td><td colspan="2">-1.09</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">1.09</td><td colspan="2">L_8:</td><td colspan="2">2.18</td><td colspan="2">L_9:</td><td colspan="2">2.73</td><td colspan="2">L_{10}:</td><td colspan="2">3.27</td><td colspan="2">L_{11}:</td><td colspan="2">4.36</td><td colspan="2">L_{12}:</td><td colspan="2">5.45</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">4.50</td><td colspan="2">H_2:</td><td colspan="2">4.75</td><td colspan="2">H_3:</td><td colspan="2">4.75</td><td colspan="2">H_4:</td><td colspan="2">4.25</td><td colspan="2">H_5:</td><td colspan="2">4.25</td><td colspan="2">H_6:</td><td colspan="2">4.25</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">4.25</td><td colspan="2">H_8:</td><td colspan="2">4.25</td><td colspan="2">H_9:</td><td colspan="2">4.25</td><td colspan="2">H_{10}:</td><td colspan="2">4.75</td><td colspan="2">H_{11}:</td><td colspan="2">4.75</td><td colspan="2">H_{12}:</td><td colspan="2">4.50</td></tr>
</table>

The Morte Bay lagoon has also not been introduced thus far because of its comparatively low energy/cost ratio. Other potential issues to highlight include the sites exposure to a higher wave climate than the other tidal range deployment site options identified. The Morte Bay lagoon results are presented in Table 20.

Table 20: Morte Bay lagoon

<table>
<tr><td colspan="6"></td><td colspan="5">Location:</td><td colspan="7">Morte Bay</td><td colspan="6"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">5.5 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">12 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">5 km</td><td colspan="6">Operational mode</td><td colspan="6">Dual (conventional)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">252 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">83%</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">0.4 TWh/y</td><td colspan="3"># turbines:</td><td colspan="3">14</td><td colspan="3">Diameter:</td><td colspan="3">9.0 m</td><td colspan="3">$A_{0\text{turbine}}$:</td><td colspan="3">228.2 m^2</td></tr>
<tr><td colspan="3">TCW:</td><td colspan="3">20.5 m</td><td colspan="3">β_{ebb}:</td><td colspan="3">1.62</td><td colspan="3">β_{flood}:</td><td colspan="3">1.62</td><td colspan="3">H_{rated}:</td><td colspan="3">3.65 m</td></tr>
<tr><td colspan="3">P_{max}:</td><td colspan="3">18 MW</td><td colspan="3">H_{min}:</td><td colspan="3">1.17 m</td><td colspan="3">H_{int}:</td><td colspan="3">3.62 m</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">B_1:</td><td colspan="3">50.3361</td><td colspan="3">B_2:</td><td colspan="3">310.7393</td><td colspan="3">B_3:</td><td colspan="3">-60.5084</td><td colspan="3">B_4:</td><td colspan="3">5.6435</td></tr>
<tr><td colspan="3">*D01*:</td><td colspan="3">50.3361</td><td colspan="3">*D02*:</td><td colspan="3">310.7393</td><td colspan="3">*D03*:</td><td colspan="3">-60.5084</td><td colspan="3">*D04*:</td><td colspan="3">5.6435</td></tr>
<tr><td colspan="3">E_1:</td><td colspan="3">3728.5906</td><td colspan="3">E_2:</td><td colspan="3">-1584.5345</td><td colspan="3">E_3:</td><td colspan="3">250.8029</td><td colspan="3">E_4:</td><td colspan="3">-13.5105</td></tr>
<tr><td colspan="3">F_1:</td><td colspan="3">-0.8723</td><td colspan="3">F_2:</td><td colspan="3">-0.0514</td><td colspan="3">F_3:</td><td colspan="3">2.2162</td><td colspan="3">F_4:</td><td colspan="3">-0.2167</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-5.45</td><td colspan="2">L_2:</td><td colspan="2">-4.36</td><td colspan="2">L_3:</td><td colspan="2">-3.27</td><td colspan="2">L_4:</td><td colspan="2">-2.73</td><td colspan="2">L_5:</td><td colspan="2">-2.18</td><td colspan="2">L_6:</td><td colspan="2">-1.09</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">1.09</td><td colspan="2">L_8:</td><td colspan="2">2.18</td><td colspan="2">L_9:</td><td colspan="2">2.73</td><td colspan="2">L_{10}:</td><td colspan="2">3.27</td><td colspan="2">L_{11}:</td><td colspan="2">4.36</td><td colspan="2">L_{12}:</td><td colspan="2">5.45</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">5.00</td><td colspan="2">H_2:</td><td colspan="2">5.00</td><td colspan="2">H_3:</td><td colspan="2">4.75</td><td colspan="2">H_4:</td><td colspan="2">4.50</td><td colspan="2">H_5:</td><td colspan="2">3.75</td><td colspan="2">H_6:</td><td colspan="2">3.50</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">3.50</td><td colspan="2">H_8:</td><td colspan="2">3.75</td><td colspan="2">H_9:</td><td colspan="2">4.50</td><td colspan="2">H_{10}:</td><td colspan="2">4.75</td><td colspan="2">H_{11}:</td><td colspan="2">5.00</td><td colspan="2">H_{12}:</td><td colspan="2">5.00</td></tr>
</table>

Scenario 18 also uses the same set-up in terms of tidal range (and tidal current) development and deployment selections as scenario 16. As the most extreme overall deployment strategy in terms of installed capacity and indicative energy output, it will be of great interest to compare the response of the tidal system in the scenario 16 case with scenario 1 output where no deployments are imposed. Scenario 18 provides the opportunity for a similar comparison with scenario 17, the difference being that scenarios 17 and 18 are simulated to include representation of variability in the water column by using TELEMAC's layered approach to provide a 3D representation of tidal flow variability. Hence comparison between scenarios 1 and 17 and 16 and 18 will also be of note to compare and contrast the simulation outputs when operating in 2D and 3D.

5.11 Scenarios 19 and 20

Scenarios 19 and 20 utilise a sub-set of the tidal range development scenarios presented in scenario 16 to examine the impact of regional clustering. No tidal current developments are included in these cases. Scenario 19 uses only those barrage and lagoon options from scenario 16 that are located on the west coast of the UK. Scenario 20 uses only those barrage and lagoon options from scenario 16 that are located on the east coast of the country.

5.12 Scenario 22

Scenario 22 will repeat the scenario 6 simulation, but with the Cardiff-Weston barrage and Bridgewater Bay lagoon replaced by the Severn Outer barrage utilising conventional turbines in dual mode operation (as this is the single scheme with the largest overall energy generation potential). Scenario 6 is selected as the basis for this assessment. The reasoning for choosing the combination of the less developed 2030 'medium' scenario in conjunction with the largest single project (in energy generation terms) as the basis of this analysis is that:

- It enables direct comparison of the relative impacts of these schemes in a like-for-like comparison.
- The Severn Outer project would appear highly unlikely to gain consent and attract the vast capital investment required for development of the project by 2030, therefore the smaller (but still major) alternative incremental options in the region of adopting the Bridewater Bay and then Cardiff-Weston deployment, although also on a timeline that is difficult to achieve does not stretch credibility quite as far. However, if it can be identified that there are even more positive reasons for the Seven Outer alignment, and that the two smaller projects combine non-linearly to create (for instance) a more complex and environmentally sensitive response, then these circumstances would potentially alter build order priorities. For instance, a government led decision could be that: in order to later allow the benefits of the Severn Outer project it would be beneficial to leave other Severn/Bristol Channel tidal range options undeveloped to allow the Severn Outer to be introduced when the correct circumstances presented themselves.
- It is also likely that the impact of the other relatively small (in comparison) tidal range and tidal current developments prescribed in the 2030 'medium' development case will not be of sufficient scale to be having a UK wide impact. Hence, at least the regional impact of the most significant (in energy terms) identified tidal range project will also be essentially directly comparable with the scenario 1 'base case'.

The Severn Outer barrage results are presented in Table 21.

Table 21: Severn Outer barrage

<table>
<tr><td colspan="6"></td><td colspan="4">Location:</td><td colspan="8">Severn Estuary (Outer)</td><td colspan="6"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">7.0 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">1060 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">20 km</td><td colspan="6">Operational mode</td><td colspan="6">Dual (conventional)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">15750 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">80%</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">45.0 TWh/y</td><td colspan="3"># turbines:</td><td colspan="3">875</td><td colspan="3">Diameter:</td><td colspan="3">9.0 m</td><td colspan="3">$A_{0\mathrm{turbine}}$:</td><td colspan="3">228.2 m^2</td></tr>
<tr><td colspan="3">TCW:</td><td colspan="3">20.5 m</td><td colspan="3">β_{ebb}:</td><td colspan="3">1.62</td><td colspan="3">β_{flood}:</td><td colspan="3">1.62</td><td colspan="3">H_{rated}:</td><td colspan="3">3.65 m</td></tr>
<tr><td colspan="3">P_{max}:</td><td colspan="3">18 MW</td><td colspan="3">H_{min}:</td><td colspan="3">1.17 m</td><td colspan="3">H_{int}:</td><td colspan="3">3.65 m</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">B_1:</td><td colspan="3">50.3361</td><td colspan="3">B_2:</td><td colspan="3">310.7393</td><td colspan="3">B_3:</td><td colspan="3">-60.5084</td><td colspan="3">B_4:</td><td colspan="3">5.6435</td></tr>
<tr><td colspan="3">C_1:</td><td colspan="3">50.3361</td><td colspan="3">C_2:</td><td colspan="3">310.7393</td><td colspan="3">C_3:</td><td colspan="3">-60.5084</td><td colspan="3">C_4:</td><td colspan="3">5.6435</td></tr>
<tr><td colspan="3">E_1:</td><td colspan="3">3728.5906</td><td colspan="3">E_2:</td><td colspan="3">-1584.5435</td><td colspan="3">E_3:</td><td colspan="3">250.8029</td><td colspan="3">E_4:</td><td colspan="3">-13.5105</td></tr>
<tr><td colspan="3">F_1:</td><td colspan="3">-0.8723</td><td colspan="3">F_2:</td><td colspan="3">-0.0514</td><td colspan="3">F_3:</td><td colspan="3">2.2162</td><td colspan="3">F_4:</td><td colspan="3">-0.2167</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-6.95</td><td colspan="2">L_2:</td><td colspan="2">-5.56</td><td colspan="2">L_3:</td><td colspan="2">-4.17</td><td colspan="2">L_4:</td><td colspan="2">-3.48</td><td colspan="2">L_5:</td><td colspan="2">-2.78</td><td colspan="2">L_6:</td><td colspan="2">-1.39</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">1.39</td><td colspan="2">L_8:</td><td colspan="2">2.78</td><td colspan="2">L_9:</td><td colspan="2">3.48</td><td colspan="2">L_{10}:</td><td colspan="2">4.17</td><td colspan="2">L_{11}:</td><td colspan="2">5.56</td><td colspan="2">L_{12}:</td><td colspan="2">6.95</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">1.17</td><td colspan="2">H_2:</td><td colspan="2">2.75</td><td colspan="2">H_3:</td><td colspan="2">3.25</td><td colspan="2">H_4:</td><td colspan="2">3.50</td><td colspan="2">H_5:</td><td colspan="2">3.50</td><td colspan="2">H_6:</td><td colspan="2">3.00</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">3.00</td><td colspan="2">H_8:</td><td colspan="2">3.50</td><td colspan="2">H_9:</td><td colspan="2">3.50</td><td colspan="2">H_{10}:</td><td colspan="2">3.25</td><td colspan="2">H_{11}:</td><td colspan="2">2.75</td><td colspan="2">H_{12}:</td><td colspan="2">1.17</td></tr>
</table>

5.13 Scenario 23

Scenario 23 examines the impact of a consenting regime where only projects designed to maintain a minimum tidal range of 80% were permitted. Hence the Cardiff-Weston conventional ebb operation barrage introduced in the 2030 'medium' scenario is replaced by a Rolls-Royce dual mode operation scheme (the only alternative presented by deliverable D01 as maintaining 80% tidal range). No other ebb generation technologies were introduced during the build order/constraints approach to development of the tidal range resource. This scenario again considers the 2030 stage of development to try and isolate the impacts of simulation such that direct comparison can be made between this scenario simulation and scenarios 1, 6 and 22. The Cardiff-Weston barrage results are presented in Table 22.

Table 22: Cardiff-Weston barrage

<table>
<tr><td colspan="6"></td><td colspan="4">Location:</td><td colspan="8">Cardiff-Weston</td><td colspan="6"></td></tr>
<tr><td colspan="6">Mean tidal range:</td><td colspan="6">7.9 m</td><td colspan="6">Impounded basin area:</td><td colspan="6">504 km^2</td></tr>
<tr><td colspan="6">Embankment length:</td><td colspan="6">19 km</td><td colspan="6">Operational mode</td><td colspan="6">Dual (Rolls-Royce)</td></tr>
<tr><td colspan="6">Total installed capacity:</td><td colspan="6">5130 MW</td><td colspan="9">Minimum tidal range inside basin:</td><td colspan="3">80%</td></tr>
<tr><td colspan="3">AEP:</td><td colspan="3">17.0 TWh/y</td><td colspan="3">$N_{9m\ turbines}$:</td><td colspan="3">900</td><td colspan="3">$N_{14m\ \mathrm{turbines}}$:</td><td colspan="3">165</td><td colspan="3">$A_{9m\ \mathrm{t}}$:</td><td colspan="3">52.1 m^2</td></tr>
<tr><td colspan="3">$A_{14m\ \mathrm{t}}$:</td><td colspan="3">126.1 m^2</td><td colspan="3">k</td><td colspan="3">0.86</td><td colspan="3">H_{min}:</td><td colspan="3">1</td><td colspan="3">T_{start}:</td><td colspan="3">5</td></tr>
<tr><td colspan="3">R_1:</td><td colspan="3">57.5906</td><td colspan="3">R_2:</td><td colspan="3">39.1934</td><td colspan="3">R_3:</td><td colspan="3">-2.6943</td><td colspan="3">R_4:</td><td colspan="3">-0.0004</td></tr>
<tr><td colspan="3">U_1:</td><td colspan="3">139.3550</td><td colspan="3">U_2:</td><td colspan="3">94.8382</td><td colspan="3">U_3:</td><td colspan="3">-6.5195</td><td colspan="3">U_4:</td><td colspan="3">-0.0009</td></tr>
<tr><td colspan="3">S_1:</td><td colspan="3">-0.2629</td><td colspan="3">S_2:</td><td colspan="3">0.6490</td><td colspan="3">S_3:</td><td colspan="3">0.2085</td><td colspan="3">S_4:</td><td colspan="3">-0.0002</td></tr>
<tr><td colspan="3">V_1:</td><td colspan="3">-0.6362</td><td colspan="3">V_2:</td><td colspan="3">1.5705</td><td colspan="3">V_3:</td><td colspan="3">0.5044</td><td colspan="3">V_4:</td><td colspan="3">-0.0006</td></tr>
<tr><td colspan="2">L_1:</td><td colspan="2">-6.20</td><td colspan="2">L_2:</td><td colspan="2">-4.96</td><td colspan="2">L_3:</td><td colspan="2">-3.72</td><td colspan="2">L_4:</td><td colspan="2">-3.10</td><td colspan="2">L_5:</td><td colspan="2">-2.48</td><td colspan="2">L_6:</td><td colspan="2">-1.24</td></tr>
<tr><td colspan="2">L_7:</td><td colspan="2">1.24</td><td colspan="2">L_8:</td><td colspan="2">2.48</td><td colspan="2">L_9:</td><td colspan="2">3.10</td><td colspan="2">L_{10}:</td><td colspan="2">3.72</td><td colspan="2">L_{11}:</td><td colspan="2">4.96</td><td colspan="2">L_{12}:</td><td colspan="2">6.20</td></tr>
<tr><td colspan="2">H_1:</td><td colspan="2">1.00</td><td colspan="2">H_2:</td><td colspan="2">1.25</td><td colspan="2">H_3:</td><td colspan="2">1.50</td><td colspan="2">H_4:</td><td colspan="2">2.50</td><td colspan="2">H_5:</td><td colspan="2">3.00</td><td colspan="2">H_6:</td><td colspan="2">3.00</td></tr>
<tr><td colspan="2">H_7:</td><td colspan="2">3.00</td><td colspan="2">H_8:</td><td colspan="2">3.00</td><td colspan="2">H_9:</td><td colspan="2">2.50</td><td colspan="2">H_{10}:</td><td colspan="2">1.50</td><td colspan="2">H_{11}:</td><td colspan="2">1.25</td><td colspan="2">H_{12}:</td><td colspan="2">1.00</td></tr>
</table>

5.14 Introducing the tidal range sensitivity analysis cases (scenarios 26-28)

The final set of tidal range scenarios to be introduced are the technology sensitivity cases. Some of the 'special' scenarios have already included aspects of technology sensitivity testing. However, the 'sensitivity' scenarios consider the impact of wider technology selection throughout the UK. Of the five sensitivity scenarios, three are used to examine tidal range technology sensitivity. Each of the three cases that follow adopt the development scenario previously examined in scenario 16 (2050 ‘extreme’) with the exception of all the recommended tidal current development schemes, which are removed. This is the basis of the tidal range sensitivity analysis. It provides a baseline of 19 tidal range sites where the performance, interaction and impacts of the selection of operational mode and technology can now be examined.

Examining the table in Appendix A, we can see that there is an uneven distribution of site/technology options available for tidal range development. The concept therefore is that scenario 16 (minus Tidal Current) presents the upper limit of potential development without creating competition between options by complete enclosure (hence the Severn Outer and Dee/Wirral barrage are the sites ignored). This represents 18 tidal range deployments (Duddon is also not considered due to the shallow depths in terms of turbine housing/design/operation as has already been highlighted). Rather than simply adopt the technology sensitivity analysis indicated by accepting the contents of Tables A1, A2 and A3 as definitions, the project team propose that there is more value to conducting a like-for-like comparison. Hence using scenario 16 (no Tidal Current) as a basis means that within each scenario test, all 18 tidal range deployments will be maintained. However, where deliverable D01 provided multiple technology options for a particular site, the technology that is available to do so will be appropriately substituted in each of the sensitivity test cases (as will be explained in Tables 23-25). This enables a direct comparison between the three technology sensitivity tests of the consequences of adopting a particular technology versus the other alternatives. This will become more clear with each scenario description, and by examining the project specific results. If this approach was not taken it would not be possible to directly compare between the technology approaches other than for a few (4) barrage sites where all technologies are identified as being suitable.

5.14.1 Ebb mode conventional turbine sensitivity testing (scenario 26)

Of the 9 sites identified in deliverable D01 as suitable for ebb mode conventional turbine generation (as summarised in Table A1), only one (Cardiff-Weston) was included in the build order approach scenario tests. In the 2050 extreme scenario (16), this was therefore the only site already operating in ebb mode generation. Of the 8 remaining site locations that can be effectively operated in ebb mode as identified in deliverable D01, only the Severn Outer is not included in scenario 16. Hence for this technology sensitivity test, Table 23 describes the technology alterations imposed. This means that the other sites continue to operate under the conditions prescribed in scenario 16.

Table 23: Technology alterations from scenario 16 case used in ebb generation mode sensitivity testing

Site	Scenario 26 operational mode and technology	Scenario 16 operational mode and technology
Solway Firth (Outer)	Ebb mode, conventional turbines	Dual mode, conventional turbines
Morecambe Bay	Ebb mode, conventional turbines	Dual mode Rolls-Royce turbines
Mersey	Ebb mode, conventional turbines	Dual mode Rolls-Royce turbines
Dee	Ebb mode, conventional turbines	Dual mode, conventional turbines
Thames	Ebb mode, conventional turbines	Dual mode Rolls-Royce turbines
Wash	Ebb mode, conventional turbines	Dual mode, conventional turbines
Humber	Ebb mode, conventional turbines	Dual mode Rolls-Royce turbines

5.14.2 Dual mode conventional turbine sensitivity testing (scenario 27)

The majority of locations in the build order scenarios utilise the dual mode, conventional turbine approach, hence there are not many changes required to establish the set-up of scenario 27. As a dual mode, conventional turbine configuration is not generated for the Cardiff-Weston barrage from the output of deliverable D01, this scheme maintains ebb operational characteristics. Similarly, dual mode

Rolls-Royce set-up is maintained for the Thames and Morecambe Bay, as again, a dual mode conventional turbine scheme is not identified in deliverable D01. All the other sites are therefore utilising dual mode conventional turbine operation. This requires the changes indicated in Table 24 to finalise scenario 27.

Table 24: Technology alterations from scenario 16 case used in dual generation mode sensitivity testing

Site	Scenario 27 operational mode and technology	Scenario 16 operational mode and technology
Mersey	Dual mode, conventional turbines	Dual mode Rolls-Royce turbines
Humber	Dual mode, conventional turbines	Dual mode Rolls-Royce turbines
Kirkcudbright Bay	Dual mode, conventional turbines	Dual mode Rolls-Royce turbines

5.14.3 Dual mode very low head (Rolls-Royce) turbine sensitivity testing (scenario 28)

Dual mode very low head (Rolls-Royce) turbines schemes were identified for all of the proposed site locations identified in deliverable D01 included in scenario 16. Therefore all of the sites are switched to operating using this approach. This requires a significant number of alterations to be made from the original set-up of scenario 16 as summarised in Table 25.

Table 25: Technology alterations from scenario 16 case used in dual mode (Rolls-Royce) sensitivity testing

Site	Scenario 28 operational mode and technology	Scenario 16 operational mode and technology
Solway Firth (Outer)	Dual mode Rolls-Royce turbines	Dual mode conventional turbines
Dee	Dual mode Rolls-Royce turbines	Dual mode conventional turbines
Cardiff-Weston	Dual mode Rolls-Royce turbines	Ebb mode, conventional turbines
Wash	Dual mode Rolls-Royce turbines	Dual mode conventional turbines
Wigtown Bay	Dual mode Rolls-Royce turbines	Dual mode conventional turbines
Cumbria	Dual mode Rolls-Royce turbines	Dual mode conventional turbines
Oxwich	Dual mode Rolls-Royce turbines	Dual mode conventional turbines
West Aberthaw	Dual mode Rolls-Royce turbines	Dual mode conventional turbines
Rhoose	Dual mode Rolls-Royce turbines	Dual mode conventional turbines
Bridgewater Bay	Dual mode Rolls-Royce turbines	Dual mode conventional turbines
Morte Bay	Dual mode Rolls-Royce turbines	Dual mode conventional turbines
Rye Bay	Dual mode Rolls-Royce turbines	Dual mode conventional turbines
Dymchurch	Dual mode Rolls-Royce turbines	Dual mode conventional turbines

Direct comparison between the 3 sensitivity tests is now possible given the updated scenario specification presented in section 5.13.

5.15 Summarising the outcomes of the build order/constraints scenario development approach

An overview of the scenario decision outcomes in terms of build order, project combinations and preferred operational mode is summarised in Table 26 for ease of reference. The reasoning for not prescribing the Duddon estuary in terms of lack of suitable depths for turbine operation has already been highlighted. The Dee/Wirral lagoon has not been considered as both the Mersey and Dee would be enclosed by installation of the Dee/Wirral lagoon. These locations have already been included in the scenario development so effectively ‘block’ the Dee/Wirral development. Deliverable D01 highlighted that there is potential for barrage/lagoons to be enclosed by larger embankments and still operate effectively, but that providing a robust design of such a scheme is beyond the scope of the project (as the internal deployments would require a complete re-design to ensure optimal operation).

Table 26: Summary of the build order adopted for tidal range technologies in the scenario analysis

				Suggested installed capacity		
Year	Optimism	Location	Operational mode (turbine type)	No. of turbines	Total installed capacity (MW)	Indicative energy output (TWh/y)
2020	Medium	Bridgewater Bay	Dual (conventional)	120	3600	6.9
2020	Optimistic	Kirkcudbright Bay	Dual (Rolls-Royce)	12	110	0.3
2030	Medium	Cardiff-Weston	Ebb (conventional)	216	8640	18.7
2030	Optimistic	Mersey	Dual (Rolls-Royce)	40	570	1.4
2030	Special (case 22)	Severn (Outer)	Dual (conventional)	875	15750	45.0
2030	Special (case 23)	Cardiff-Weston	Dual (Rolls-Royce)	1065	5130	17.0
2040	Medium	Morecambe Bay	Dual (Rolls-Royce)	320	3670	10.5
2040	Medium	Wash	Dual (conventional)	350	4900	8.5
2040	Optimistic	Dee	Dual (conventional)	60	1080	2.2
2050	Medium	Solway Firth	Dual (conventional)	1100	19800	31.0
2050	Medium	Rye Bay	Dual (conventional)	110	1980	3.2
2050	Medium	West Aberthaw	Dual (conventional)	45	1215	2.3
2050	Medium	Rhoose	Dual (conventional)	40	1080	2.0
2050	Optimistic	Wigtown Bay	Dual (conventional)	160	2240	3.8
2050	Optimistic	Dymchurch	Dual (conventional)	110	1980	3.2
2050	Optimistic	Oxwich Bay	Dual (conventional)	16	352	0.6
2050	Extreme	Humber	Dual (Rolls-Royce)	200	1340	3.7
2050	Extreme	Thames	Dual (Rolls-Royce)	110	530	1.8
2050	Extreme	Cumbria	Dual (conventional)	70	1260	2.2
2050	Extreme	Morte Bay	Dual (conventional)	14	252	0.4
Never		Dee/Wirral	See text	0	0	0
Never		Duddon	See text	0	0	0

The project team would suggest that inclusion of the Dee/Wirral by sacrificing the Dee and Mersey schemes would be a subject suitable for investigation in one (or more) of the additional scenarios that the ETI can later request. A final indication of the scale of deployment of tidal range technologies that will be examined across the scenarios from no deployment to an envisioned 'full' deployment in the 2050 'extreme' case, are the figures associated with that overall deployment strategy; 2983 turbines, an installed capacity of 54599 MW and indicated energy output potential of 102.7 TWh/y (indicating an overall technology capacity factor of 21.47%, and energy generation equivalent to 27% of UK electricity demand in 2010).

5.16 Conclusion

Combining the various decisions that are embodied in the build order discussion, and definition of the sensitivity analysis, the tidal range scenario definition is now completed. The geographic alignment of all of the identified tidal barrage and lagoon developments has been provided to the project partners by lead partner B&V as shapefiles (i.e. geospatial vector data format) to enable exact prescription of preferred alignments within the CSM.

The energy generation potential of the various tidal range technology scenario configurations is summarised in Table 27. The steady increase in energy generation potential through the first half of the Table is obvious as the scenarios build on top of each other to provide a wide range of scenario test cases for implementation in the CSM ranging from low levels of generation to very significant energy generation contributions in the UK context (for reference, total UK electricity generation from all sources in 2010 was 381 TWh [DECC (2011b)]).

Table 27: Indicative tidal range energy output (TWh/y) of various scenario development combinations

Year	Case numbers	Optimism	Ebb (conventional)	Dual (conventional)	Dual (Rolls-Royce)	Total (TWh/y)
2020	2, 4, 21	Medium	0	6.9	0	**6.9**
2020	3	Optimistic	0	6.9	0.3	**7.2**
2030	5, 7	Medium	18.7	6.9	0.3	**25.9**
2030	6	Optimistic	18.7	6.9	1.7	**27.3**
2030	22	Special	0	45.0	1.7	**46.7**
2030	23	Special	0	23.9	1.7	**25.6**
2040	8, 9	Medium	18.7	15.4	12.2	**46.3**
2040	10	Optimistic	18.7	17.6	12.2	**48.5**
2050	11, 14, 15	Medium	18.7	56.1	12.2	**87.0**
2050	12	Optimistic	18.7	63.7	12.2	**94.6**
2050	16, 18	Extreme	18.7	66.3	17.7	**102.7**
2050	24, 25	Special	0	0	0	**0**
2050	19	Special	18.7	51.4	12.2	**82.3**
2050	20	Special	0	14.9	5.5	**20.4**
2050	26	Sensitivity	48.1	24.6	0.3	**73**
2050	27	Sensitivity	18.7	67.6	16.0	**102.3**
2050	28	Sensitivity	0	0	83.3	**83.3**
Multiple	9, 13, 29, 30	Pessimistic	0	0	0	**0**

However the total generation potential arising from simple summation of the indicative output from each of the projects in a scenario should be treated with caution. First of all, it is acknowledged that the simplified 0-D and 1-D model simulations used to inform deliverables D01 and D02 will be superseded by the outputs generated by the 2-D CSM, as the CSM will capture aspects of the dynamic interaction that are unresolved in the simpler model formats. It is also to be expected (and will be verified by the CSM) that the impacts of combined operation of multiple barrages will likely reduce the overall generation potential due to alterations of the tidal system in response to large scale deployment. Additionally, at the high levels of penetration indicated by the 2040 and 2050 scenarios in Table 27, it can be expected that integration of tidal range outputs into the electricity network will provide a significant challenge. The combination of a number of the larger barrage options has the potential to exceed instantaneous demand on the system which would require significant load shedding (or storage) with subsequent loss of revenue potential. Although it is beyond the scope of this project to examine these issues, the combination of provision of the CSM upon completion, and scenario descriptions provided herein will provide appropriate output data to enable future examination of these issues in conjunction with an appropriate model of the UK electricity system. If grid issues were to become a concern, then it would increase the value of the very low head technology approach, as this technology generation profile tends to be more prolonged across the tidal cycle, and therefore has less ‘spikes’ (although is still highly variable switching between zero output and generating at installed capacity very rapidly – the distinction is that the installed capacity tends to be lower for a similar level of overall energy generation). In this situation it would be realistic to assume that very low head technology solutions such as proposed by Rolls-Royce would displace more of the conventional selections made in the current scenario decision making process. The impact of such a decision is modelled in technology sensitivity case 28, where all the sites identified in the 2050 extreme case are switched to operating using the Rolls-Royce technology.

6 TIDAL CURRENT SCENARIO SELECTION

Deliverables D01 and D02 have extensively investigated potential locations and site development characteristics for tidal energy converter (TEC) technologies in UK coastal waters with peak power output greater than 60MW (see Table 28). Identification of locations with potential peak power output of greater than 100 MW was requested in the ETI RfP. Deliverable D01 has suggested the lower limit of 60 MW to include smaller but still significant overall resource locations. 60 MW is equivalent to just under 1% of the potential installed capacity identified within the Carbon Trust (2011) analysis adopted by deliverable D01 – as in D01 the Carbon Trust (2011) report will hereafter be referred to as 'CT 2011'. A brief summary of the relevant outputs from both deliverables is now presented.

Deliverable D01 utilises a methodology developed in the CT 2011 report for identifying simplified generic descriptions of the dominant site physics, and hence applying empirical expressions to determine the theoretical power available for extraction at a site, e.g. as in equation 1.

$$P_{Theoretical} = 0.2\rho g Q_{\max} a_o \qquad \text{(equation 1)}$$

These *theoretical* limits are identified as being the point at which attempting to extract more power from a location diminished the total resource available across the site, thus reducing the total overall power liberated. This relationship is defined graphically in Figure 7. Although the units of $P_{Theoretical}$ are Watts, the term refers to the losses felt by the tidal system, not electricity generated to the grid (the two would only be the same if the conversion was 100% efficient with no other losses associated with harnessing the energy, e.g. no support structure losses, etc.). This simplified

Table 28: UK Tidal Current sites with peak power greater than 60 MW as reported in CT 2011

Sites	Type of site	Area	Mean Sea Level (MSL)	Farm rated power (BASE CASE)	AEP Total Technical Resource (BASE CASE)	AEP Total Practical Resource (BASE CASE)	CoE based on technical resource, no learning
		km2	m	MW	GWh/y	GWh/y	p/kWh, dr15%
Pentland Firth Deep	HC	66.0	62	2,525	10,067	6,431	17
Race of Alderney	TS	15.3	31	626	2,253	1,595	26
Carmel Head	TS	38.3	38	590	1,948	1,504	29
South Jersey	TS	42.7	20	529	1,904	1,348	75
East Casquets	TS	37.7	22	526	1,891	1,339	62
Pentland Firth Shallow	HC	20.1	30	483	1,230	1,230	24
West Islay	TS	25.4	31	411	1,164	1,046	36
North East Jersey	TS	24.9	21	324	1,165	825	72
Islay / Mull of OA	TS	17.0	37	318	869	811	25
Westray Firth	TS	5.7	27	277	750	706	35
Bristol Channel - Minehead	RES	11.9	30	170	633	433	34
North of N. Ronaldsay Firth	TS	10.2	39	153	409	389	38
West Casquets	TS	11.1	23	145	522	370	61
Ramsey Island	TS	7.9	42	139	807	355	25
Mull of Kintyre	TS	6.8	116	128	444	326	23
Isle of Wight	TS	8.5	29	117	490	297	57
Mull of Galloway	TS	7.6	29	104	306	264	59
South Minquiers (Jersey)	TS	7.7	16	82	294	208	90
N. Ronaldsay Firth	TS	5.7	17	75	399	191	74
Rathlin Island	TS	3.6	102	65	172	166	25

understanding of the relationship between the power extracted with consequent velocity reduction (at least in channel geometry situations) enabled the application of a *technical* limit that could be imposed to ensure physical environmental impacts in the far field were constrained (e.g. as indicated in Figure 7 where the level of energy extraction for a given velocity reduction in the tidal system is identified).

Deliverable D01 acknowledges limitations of the input data to the site identification activity, and notes that additional sites may well be highlighted in the CSM due to the improved resolution of the model over existing publically available data sources. Deliverable D01 also has some specific guidance to inform the scenario development work regarding:

- The need for detailed prescription of the sites for which the Crown Estate has issued Agreements for Lease (particularly in and around the Pentland Firth) in terms of 2020 deployment. It may therefore be prudent for the scenario modelling work package to further split the Pentland Firth (and surrounding area) sites into the specified Crown Estate sites so that they can be appropriately modelled in the various CSM scenario runs (in Table 28, the Pentland Firth is just considered as two larger regions, ‘shallow’ and ‘deep’).

- The need to consider practical constraints on development reported in deliverable D01. Some of these practical constraints are reported directly (i.e. the combination of shipping routes, fishing and designated conservation site which for the identified sites around the UK reduces the energy extraction potential by 25% on average (base case)). Some constraints, such as grid accessibility are acknowledged as being out of scope. Others are identified but their impact is not explicitly defined (e.g. wave and tidal range characteristics, competition for sites between tidal range and tidal current technologies). Some of these factors can be incorporated as constraints on the development timeline (e.g. avoidance of sites with high annual mean, or extreme significant wave heights by focussing on early deployment sites that are more sheltered).

- Detailing various practical and design constraints that should be imposed or considered, a list of which is presented in Table 29.

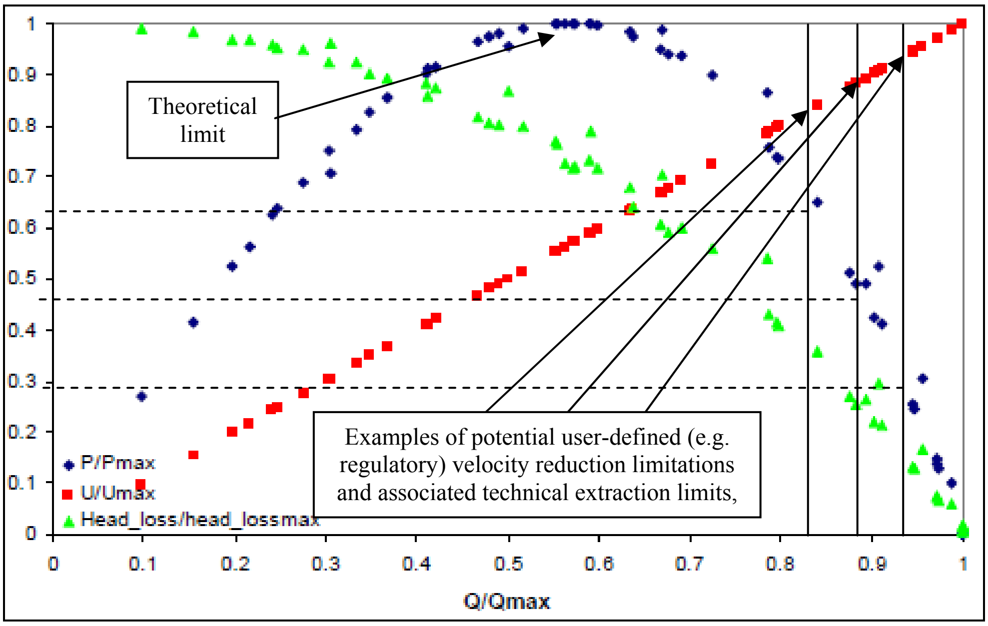


Figure 7: Non-dimensional response of simulated hydraulic current channels (source: [Carbon Trust (2011)]). *P* is power, *U* is velocity magnitude, Head loss refers to alteration of the free-surface immediately up– and downstream of the extraction device.

Table 29: Practical and design constraints provided by deliverable D01 output.

Constraint	Guidance provided
Cost of energy:	Only sites with a mean annualised power density in excess of 1.5kW/m^2 are considered to have a realistic energy/cost benefit to be worth considering as suitable for deployment
Clearance of turbines:	The clearance of turbines is based on EMEC and draft IEC Standard documents; with a top clearance of 5m at LAT and sea-bed clearance of 25% of the depth applied. For a 10 m turbine this implies a minimum water depth of 22.5 metres below LAT.
Spacing of turbines:	The farm spacing is also based on EMEC and draft IEC standards, with a staggered spacing of 2.5 diameters by 10 diameters assumed (hence the geographic footprint of the device varies as 25D02 m^2).
Rated velocity and rotor diameter:	The assumption of a limited number of design classes of TEC in terms of rated velocity and rotor diameter.
Environmental acceptability:	Highlights the potential for significant environmental response in terms of altered tidal dynamics. This raises the potential need to impose limitations of the scale of energy harvested in relation to alteration of the far field tidal system dynamics. Constraints using the technical limitations already introduced in conjunction with the theoretical limit in equation 1 have been used to define the resource in Table 28.
Structural drag:	Proposes a range of structural drag losses with respect to the total amount of energy harvested (5-25%).
Wake mixing losses:	Proposes a range of wake mixing losses to account for the unresolved sub-grid scale mixing between the free-stream and decelerated flow in the device wake with respect to the amount of energy harvested (5-20%).

Finally, deliverable D01 presents a summary of the CT 2011 report. The base case technical resource in UK waters is projected as being equivalent to 29 TWh/y (+/- 40%) of generation utilising an installed capacity of just over 8 GW. Alternative scenarios imposing or releasing various constraints also generated scenarios representative of generation between 15.5 – 50.4 TWh/y (+/- 40%). This wide array of potential scenario options indicates the various uncertainties in the data, methodologies applied, and interpretation of what will be deemed an acceptable level of environmental impact arising from the deployment of farms of TEC devices.

Deliverable D02 provides a methodology for parameterising the energy lost from the system from the tidal dynamics perspective, and enables these energy losses to be interpreted as the power generated to the grid, and power potentially available for generation but lost due to device conversion inefficiencies, support structure drag and wake mixing effects. The methodology is based upon defining the power (or thrust) curve relationship with respect to upstream flow velocity for the installed TEC device as a fifth-order polynomial function, knowing the device cut-in and rated velocity, and prescription of the cross-sectional surface area and drag coefficient associated with the device support structure.

6.1 Existing scenario development proposals

A wide range of government agencies, stakeholder interest groups and third sector organisations have presented vision documents, road-maps and growth forecasts relating to future prospects for electricity generation from tidal current energy development in UK coastal waters [e.g. ETSU (1993), Carbon Trust (2005), The British Wind Energy Association (BWEA – now RenewableUK) (2006), MacKay

(2009), UK Energy Research Centre (2009), ETI & UK Energy Research Centre (2010), European Ocean Energy Association (2010), The Climate Change Committee (2010), Offshore Valuation Group (2010)]. A major focus of these documents and assessments has been on predictions of the roll out of technology with restrictions imposed due to external factors such as supply chain inadequacy and hence bottlenecks. A common thread therefore emerges in these assessments in focussing on a particular aspect of the problem without sufficient acknowledgement of the complexity of the issues. For instance, a common failing is to neglect the importance and restrictions imposed by the fundamental availability of tidal current energy resource (the pre-requisite for any TEC farm site is strong enough currents to produce a viable amount of power [Roc *et al.* (2011)]), or of the eroding of the resource that comes from increasing deployment (e.g. Offshore Valuation Group [2010])). Other common failings are lack of consideration of the economic viability of proposals presented, over-selling of the commercial readiness of the technology providers and supporting supply chain, and a lack of understanding of the importance of matching tidal current energy converter (TEC) technology with the available resource. This is reflective of the general immaturity of the sector, and hence the lack of existing projects from which to extrapolate forward from.

Hence, assessments of TEC industry development from as recently as 2006 forecast that the combined wave energy converter (WEC) and TEC sectors would have leapt from less than 1 MW installed capacity to approximately 200 MW by 2011 (today) on the way to achieving 3 GW installed capacity in 2020 and hence making a meaningful contribution to the UK governments 2020 renewable energy generation goals [BWEA (2006)]. With 2 months left until the end of 2011, there is substantially less than 10 MW installed capacity even when counting both WEC and TEC technologies. This collective misinterpretation of the industry position has led to a number of false-starts that has potentially slowed progress towards commercialisation and mass TEC technology uptake. An example is the now withdrawn Marine Renewable Deployment Fund (MRDF) that was put in place in 2004/5 (quote from [RenewableUK (2011)]:

> “The Marine Renewables Deployment Fund (MRDF) was established by the UK Government in 2004 to support the first arrays of devices operating at sea. Due to the stage of technology development that the industry was at in 2004, it was difficult for all involved to properly quantify the true cost of the first demonstration arrays.
>
> The MRDF was positioned in exactly the right space, allowing marine energy technology to develop from full-scale prototypes to pre-commercial arrays. However, the wide perception developed by the industry that the technology was at a more advanced stage of development, compounded with the lack of private finance as a result of the global economic downturn, resulted in MRDF being created prematurely. This could have been rectified by restructuring the fund to support different activities, but industry and government both recognised the need for funding of these projects.
>
> In reality, interim funding was needed to assist the deployment of pre-commercial test units. This is why the Marine Renewables Proving Fund, allocated via the Renewable Energy Strategy, was so successful.”

More representative interpretations (although still ambitious) begin to emerge as the experience of lack of progress in the latter half of the 2000’s began to hit home. The Marine Energy Group branch of the Forum for Renewable Energy Development in Scotland (FREDS) proposed the deployment scenarios presented in Table 29 with a view toward 2020 deployment of WEC and TEC technology in Scotland [FREDS (MEG) (2009)]. What was considered a ‘low’ scenario just two years ago now seems much more realistic or even ambitious (75 MW by 2013 looks highly unlikely today). Developing the approach of the original UKERC Marine Energy

Table 29: FREDS (MEG) marine energy deployment scenarios for Scotland in 2020.

Scenario	Profile	Economic Impact
Low Scenario	**500 MW installed by 2020:** • steady early installation rate; • culminating in ~75 MW installed capacity by the end of 2013; • rapid growth in installed capacity rate of 30% per annum thereafter	▪ 1,500 direct Scottish jobs ▪ 2,850 direct jobs overall ▪ Up to £687m total expenditure in Scotland ▪ £1.3bn expenditure overall
Medium Scenario	**1000 MW installed by 2020:** ▪ rapid early installation rate; ▪ culminating in over 150 MW installed capacity by the end of 2013; ▪ rapid growth in installed capacity rate of 30% per annum thereafter	▪ 2,600 direct Scottish jobs ▪ 5,000 direct jobs overall ▪ Up to £1.3bn total expenditure in Scotland ▪ £2.4bn expenditure overall

High Scenario	**2000 MW installed by 2020:**
	• rapid early installation rate;
	• three year delay to ramp up – could be due to several factors, including:
	  ○ technology or supply chain problems
	  ○ lack of investment confidence
	  ○ lack of grid access
	  ○ delays to planning and consenting
		▪ 5,300 direct Scottish jobs
		▪ 10,000 direct jobs overall
		▪ Up to £2.4bn total expenditure in Scotland
		▪ £4.7bn expenditure overall

Roadmap released in 2008, the ETI and UKERC collaborated to produce an updated roadmap [ETI & UK Energy Research Centre (2010)]. This is one of the few documents that makes explicit deployment predictions beyond 2020 (summarised in Figure 8) with an attempt to ground the predictions to a realistic future based upon understanding of the various drivers and constraints in the system (recall the Figures are for combined WEC and TEC deployment). The lower end of the expectations seem realistic for 2020, expectations for 2030 and beyond are ambitious but achievable given appropriate support and investment in development. Similar 2020 assessments (deployment of 1-2 GW of marine technology by 2020 with a central estimate of 1.5 GW) were presented by RenewableUK in 2010 [renewableUK (2010)]) in contrast to the organizations targets portrayed in 2006 that have already been referenced. The National Renewable Energy Action Plan [DECC,

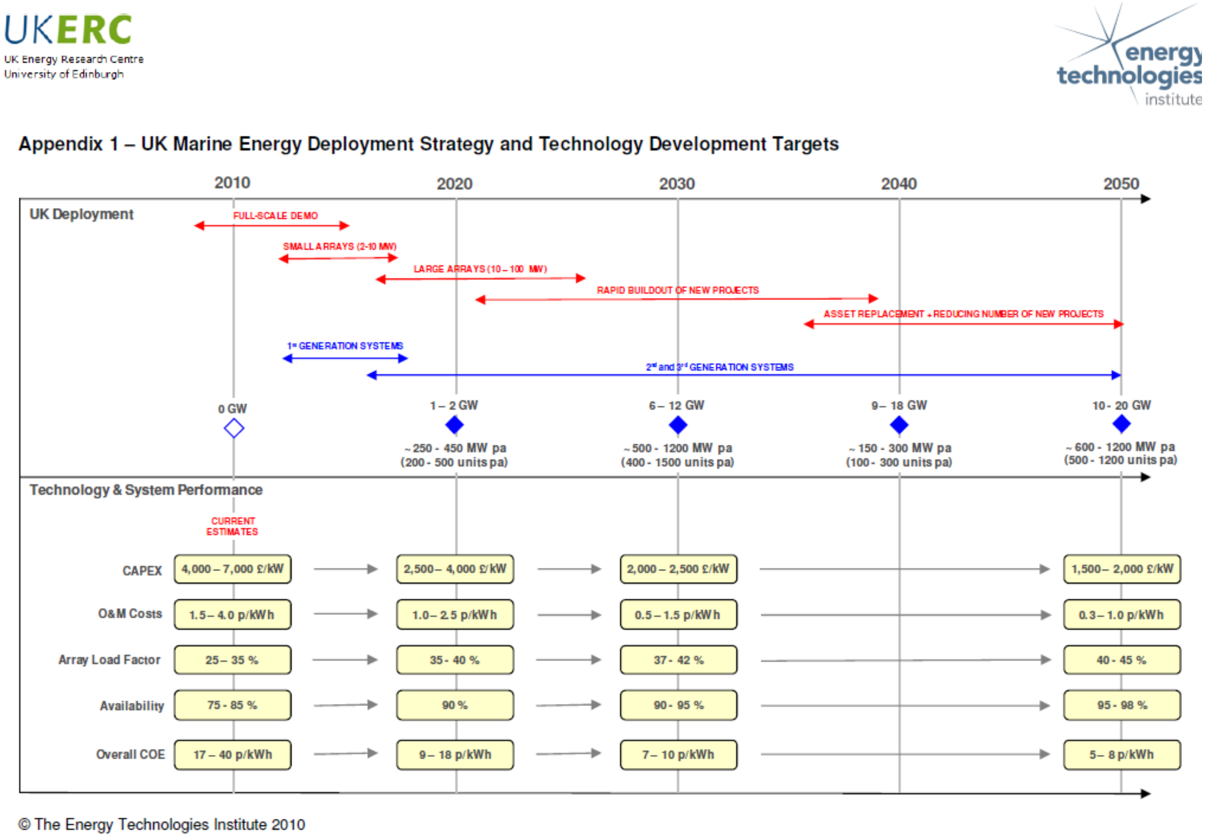


Figure 8: UK Marine Energy Deployment Strategy and Technology Development Targets (source: ETI & UK Energy Research Centre (2010))

(2010(b))] estimates that 1.3 GW of combined WEC and TEC technologies will be deployed around the UK by 2020. Finally, the most recent statements by a UK government agency make a further step-change in reducing expectations to more achievable goals [DECC (2011(a))]. [DECC (2011(a))] predicts:

> "up to around 400MW of installed capacity by 2020 under a high build scenario, ramping up to 2.2 GW by 2030. These are maximum build levels, and achieving them would require high levels of financial support."

It is interesting to note that the marine (WEC and TEC) industry has always been concerned by more realistic (pessimistic from their preferred perspective) medium term targets. [DECC (2011(a)] portrays the least ambitious vision statement for 2020 technology uptake, but the document is the basis for presenting a strong argument for increasing TEC Renewable Obligation Certificate payments (ROC's) by a factor of 2.5 for all projects of less than 30MW in operation by 2017. This sort of support regime is the kind of signal that could create the breakthrough move toward commercialisation and project development, as opposed to technology proving and testing as still dominates today.

The approach adopted in this report to informing the TEC deployment scenarios is to combine the know-how of the project team with the prevailing views embodied in the supporting literature listed (with a bias towards the most recent studies as they tend to be the most comprehensive). An issue is the lack of focus on projections beyond 2020. The CT 2011 study provides some reasonable bounds within which to operate.

6.2 Progressing the RfP methodology

The spatial variability of tidal currents is governed by complex non-linear physics and interaction with variable bathymetry and topography. Adding TEC devices creates an additional set of complex fluid interactions at a site of interest for tidal power development. For these reasons, interpolating spatially diffuse tidal data records will lead to inaccuracies, as will prescription of the characteristics of large areas using averaged single value representations (e.g. of velocity magnitude and direction).

The original intent of the RfP document released by the ETI was that the required scenarios would be pre-determined based upon existing understanding of the resource location, strength and variability. Since the project team have been engaged on this study, it has become obvious that this would be a counter-productive approach – effectively imposing 'old' coarse resolution resource understanding onto a new state-of-the-art tool designed to improve input data to the assessment process. The reliance on 'old' data to inform scenario design is therefore brought into question with respect to the overall intent of the project. Hence, an alternative solution has been proposed. This updated approach involves creating a set of scenario design and development criteria (as would be required in any case), but instead of deriving the answer using existing data inputs offline, the intention is now to wait until the new detailed CSM is complete and the 'base case' in existence and hence use outputs from the detailed CSM 'base case' as the key data input to inform final scenario decision-making. What is particularly novel about this approach is that the project team will agree the selection criteria prior to CSM development, and enable the CSM to 'self-select' using the criteria as guidance, hence minimising potential bias related to human intervention in the process by minimising the need for user intervention. This approach brings significant overall advantages to the project, some of which are listed below:

- Using higher resolution bathymetry and velocity input data:
  - Enables more accurate prescription of potential development sites and the physical extent of these sites;
  - Enables more accurate prescription of TEC device characteristics to best utilise the resource and therefore more accurately reflect the potential for future development and deployment;

  - Will provide better gradation of the extreme resource available for extraction (e.g. the smoothing effect of lower resolution input data would be to reduce the significance of resource 'hot-spots' in the dataset).
- The points raised above increase the realism of the scenarios considered as the input data will more closely resemble the actual tidal energy resource that would be uncovered by detailed site assessment during feasibility study of a real world project development.
- Removes potential for prescription of development (based upon 'old' data inputs informing scenario development) that presents a mismatch with the resource depicted by the new CSM output (for instance at higher resolution the location of the velocity magnitude 'hot spot' may for example be 1.8 km away from where previously identified (within the resolution of the most appropriate existing national data source [ABPmer, et al. (2008)] – the farm and device specific characteristics may therefore have been placed up to 9 mesh elements removed from the intended resource of interest for CSM application at the intended highest order resolution (200m)).
- The new approach will provide a much more usable product for the client after project completion as there will be a substantial increase in model flexibility and usability by non-experts as much of the key decision making becomes embodied in the numerical model as opposed to being off-line and requiring additional expert intervention. In simple terms, the evolved approach could be considered to be the provision of an informed decision support tool.

The ETI has accepted this advice with the caveat of requiring detailed prescription of 10 of the intended initial 30 scenario and sensitivity specifications to mitigate future risk in the project. It is on that basis that the study has proceeded. Hence, output from the CSM will identify appropriate development locations using the metrics and constraints defined in the sub-sections of chapter 6 to shape the level of technology innovation and build rate appropriately for the intended scenario objectives introduced.

6.3 'Decision-tree' approach procedure to be implemented during CSM scenario simulations

The 'decision-tree' approach advocated requires the operation to be broken down into two parts. The intent is to mimic within the numerical model operation the process that would be used offline to define the characteristics of a given scenario. It is therefore necessary to develop a standardised procedure that would duplicate how scenario development would be conducted offline and then embed these decision-making processes as appropriate into the modelling approach. The first part of the procedure (described in section 6.3.2) deals with decision making that requires derivation during post-processing of the outputs from the base case simulation (which could be seen as representative of provision of field survey data providing complete coverage of UK coastal waters). The second part of the procedure (described in section 6.3.3) is embedded in the CSM model architecture itself for application of the various scenarios detailed by the post-processing analysis in part 1. Many of these processes are easily represented in the numerical modelling and post-processing environment (e.g. identifying the suitability of local bathymetry for a particular generation of TEC technology would require a simple "IF THEN ELSE" statement within the model at the appropriate juncture). Others require further insight to develop a suitable method for automating the process (e.g. how to appropriately match TEC device characteristics (in particular rated velocity) to the local resource strength and variability).

6.3.1 Methodology for defining the limit to extraction in a region

Prescription of what an acceptable level of impact on tidal dynamics actually is will depend upon how these alterations to the system trickle down to impact other physical, chemical and biological oceanographic and marine science processes and organisms. Overly constraining development from the perspective of the ETI-TRM project is undesirable. What is required to inform the ETI-TRM project goals is investigation of a wide sample of energy extraction levels, system responses and interactions that spans from minor levels through potentially normal modes of future operation through to extreme cases. Only then will the project deliver outcomes that inform the wider debate relating to the economic and environmental benefits and impacts of large scale deployment of tidal range and current technologies.

A methodology for assessing the theoretical limit to energy extraction from different tidal regimes was presented in deliverable D01 and summarised in brief in section 6.3.1. These concepts have been adopted from CT 2011 by D01 as application of existing best practice. Similar approaches are being adopted to quantify the theoretical resource in the United States in national scale assessments being conducted for the US Department of Energy. Dependent upon the tidal regime, the theoretical extraction limit is achieved by reducing the far field velocity in the region by the order of 40-50%. This is representative of an environmental impact level that is unlikely to be acceptable in terms of gaining regulatory consent for project development and deployment.

CT 2011 additionally presented a methodology for determining an (imposed) technical limit to energy harvesting, summarised in deliverable D01. The technical limit to energy extraction is a further restriction placed on the theoretical limit, selected to constrain far field environmental impacts. As the purpose of this study is to investigate varying levels of impact and interaction between projects, imposing a restrictive constraint in an attempt to minimise impact and interaction is seen as counterproductive. Therefore the CT2011 technical limits will only be imposed in a specific scenario test case.

However if some limits to extraction are not placed on local levels of deployment, there is the potential that farms will be prescribed that are severely sub-optimal (e.g. where the Q/Q_{max} term is substantially less than 0.5 in Figure 7), indicative of the farm design causing more blockage to the flow than it allows to pass through (and hence limiting power generation). A farm design with these characteristics will cause unnaturally extreme environmental impact and interaction potential. This describes the inherent difficulty of the detailed project design thought processes that must be embodied in a national scale assessment. Optimising these aspects of project design for an individual project remains a subject of intense debate as opposed to encompassing existing knowledge – and the difficulty experienced when conducting national scale assessment is therefore magnified.

A methodology that ensures that a wide range of interesting energy extraction cases will be generated while ensuring that the design of the tidal farm remains on the optimal right hand side of Figure 7 will be to impose an ‘acceptable’ extraction coefficient (C_E),, which will be introduced as a user defined variable. Using certain simplifying assumptions regarding the prescription of the $P_{theoretical}$ term (to remove the a_1 term from the hydraulic current analysis), the power available for energy harvesting in this analysis for all tidal regimes and locations will be referred to as $P_{acceptable}$, where:

$$P_{acceptable} = C_E \times P_{theoretical} \qquad \text{(equation 4)}$$

Where C_E is the user imposed acceptable extraction coefficient. For application in the UK context, the value of C_E adopted in the scenarios will be 20% for ‘medium’ cases, 40% for ‘optimistic’ cases, and 80% for ‘extreme’ cases. These values of C_E obviously imply a constraint on tidal farm design equivalent to 20%, 40% and 80% of the theoretical upper limit on energy harvesting. This simplified approach using just one formulation and three prescribed values of the coefficient C_E across all the test cases also benefits the application of the automated approach introduced in section 6.3.2. The application of this approach is additionally beneficial as it ensures that two identical farms operating in two different bodies of water will be subject to the same constraint conditions. The CT 2011 technical limit varied across a range of tidal regimes – further validation of that approach is desirable given the limited application experience. Selection of one arbitrary technical limit was also a criticism raised regarding the CT 2011 outcomes, the ability in this study to test a range of limits is seen as advantageous.

This section has developed a simple means for prescribing constraints on the level of deployment in a particular region that will be taken forward for application in the procedure detailed in section 6.3.2.

6.3.2 Post-processing the base case (scenario 1) CSM simulated output

Once the detailed CSM model has been constructed and undergone validation testing against known datasets, the scenario 1 'base case' can be simulated. The results of this scenario provide the basis (encapsulating the existing 'no development' tidal dynamics around the UK) against which all the other simulations will be compared to determine variation from the simulated existing 'norm'. The scenario 1 base case will additionally be used through post-processing of the output data generated by the CSM simulation to provide input data to the scenario definitions. An example of this would be interrogating the output data to determine mesh elements within the domain that demonstrate certain characteristics of interest. This process will now be detailed in a step-wise procedure that is appropriate for implementation and application in conjunction with the CSM:

Step 1. Interrogate the model to identify and rank mesh elements by their mean kinetic power density when above a pre-determined threshold (e.g. 1.5 kW/m^2) and set-up a new data record for each mesh element identified.

Commentary: The mean kinetic power density enables the quantification of power potential. It is calculated as follows – the instantaneous kinetic power density is defined as:

$$P_{KE}(t) = \frac{1}{2}\rho\left(\sqrt{\left(U^2 + V^2\right)}\right)^3 \qquad \text{(equation 2)}$$

The mean kinetic power density is then derived by averaging the kinetic power density over a Spring-Neap tidal cycle:

$$P_{KE}(m) = \frac{1}{T}\int P_{KE}(t)dt \qquad \text{(equation 3)}$$

Deliverable D01 has identified that long-term economic viability at a site requires a mean kinetic power density of 1.5 kW/m^2 or more.

For the scenario test cases, Table 30 defines the target and absolute minimum mean kinetic power density required for consideration as a potential site within that time horizon (2020 scenarios are not defined using this approach as they will be detailed in sections 7.1 and 7.2). Further discussion of the use of the target and absolute minimum values will be presented in step 9.

Table 30: Target and absolute acceptable minimum mean kinetic power densities required for a location to be considered as a potential deployment site.

Basis of the scenario timeline	Target minimum acceptable mean kinetic power density (kW/m^2)	Absolute minimum acceptable mean kinetic power density (kW/m^2)
2030 'medium' scenarios	3.00	2.25
2030 'optimistic' scenarios	2.25	2.00
2040 'medium' scenarios	2.00	1.80
2040 'optimistic' scenarios	1.80	1.65
2050 'medium' scenarios	1.65	1.5
2050 'optimistic' scenarios	1.5	1.5
2050 'extreme' scenarios	1.5	1.5

This approach is taken to represent the overarching economic drivers that will encourage development of the most productive sites early in the build order. Selection of these values is to some extent arbitrary but has been based upon the project team's experience of real velocity time-series at sites of interest for development of tidal current energy. Without pre-knowledge of the final solution, the overall resource at each time horizon will be additionally constrained by the minimum and maximum installed capacities associated with each time horizon as indicated in Table 31. These values are informed by the discussion presented in section 6.1. Indicative energy output estimates (to the nearest TWh/y) are also included to provide the user rough guidance as to the relevant potential of each case under the assumption that the average capacity factor is c. 30%.

Table 31: Minimum and maximum installed capacity limits imposed on the scenario deployments

Basis of the scenario timeline	Minimum installed capacity (MW) and indicative energy output (TWh/y)	Maximum installed capacity (MW) and indicative energy output (TWh/y)
2030 'medium' scenarios	2000 (5)	3000 (8)
2030 'optimistic' scenarios	3000 (8)	4000 (10)
2040 'medium' scenarios	4000 (10)	8000 (21)
2040 'optimistic' scenarios	5000 (13)	10000 (26)
2050 'medium' scenarios	8000 (21)	15250 (40)
2050 'optimistic' scenarios	10000 (26)	20000 (52)
2050 'extreme' scenarios	15250 (40)	40000 (105)

.

Step 2. Beginning with the highest ranked mesh element from step 1, identify the depth associated with the mesh element under consideration, and append this information to the new data record.

Commentary: The local bathymetry (depth) defines the technology suitability at that location.

Step 3. Determine whether the identified mesh element is suitable for 1st or 2nd generation technology, or is too shallow to be of further interest, and append this information to the new data record.

Commentary: The local bathymetry (depth) is compared against the following criteria:

- If the depth across the mesh element is less than 20 metres, then it is considered unsuitable for deployment of farm scale devices (e.g. the available swept area for a horizontal-axis TEC would be uneconomic in large scale deployments). These locations offer a niche development potential for alternative TEC designs with different capture surface characteristics. The amount of economically and practically exploitable resource in such shallow water is considered to make only a marginal contribution towards national TEC energy generation potential. Furthermore, the occurrence of such depths with the extreme tidal current velocities of interest for economic exploitation is not expected to produce any sites that provide an overall contribution of more than the 60 MW minimum farm size threshold identified for this study.
- If the depth is greater than 20 metres, but less than 50 metres, the location is suitable for deployment of 'first generation' technologies. First generation technologies are defined as representative of existing TEC device undergoing at sea pre-commercialisation testing and iterations of these technologies. These devices are considered to be limited by their support structure type (sea-bed mounted) in terms of suitable operating depths and issues relating to installation difficulties in deeper water.
- If the depth is greater than 50 metres, the site is considered suitable only for deployment of 'second generation' technologies. Second generation technologies are defined as being suitable for depths greater than 50 metres. This class is representative of technologies utilising more radical support structures (e.g. floating anchored, neutrally buoyant anchored). Some second generation technologies approaches are at the early stages of development in terms of technology readiness levels. The project team also envisages that earlier stage TEC farm deployments will favour shallower water than is appropriate for second generation technologies as these sites are generally not as far from shore. This would mirror the experience of offshore wind technology development where increased

mobilisation costs, and particularly undersea cable costs, negatively impact the economics of projects developed further offshore.

Table 32 outlines the development timeline and deployment restrictions associated with the availability and capability of first and second generation TEC technologies to be used in the scenario definitions.

Table 32: TEC technology evolution timeline adopted in this study

Basis of the scenario timeline	Maximum depth permitted for deployment	Restriction on the deployment of 2nd generation technology (MW installed)	Depth beyond which further restriction are place on the deployment of 2nd generation technology (depth, permitted installation in MW)
2020 ‘medium’ scenarios	50 m	n/a	n/a
2020 ‘optimistic’ scenarios	50 m	n/a	n/a
2030 ‘medium’ scenarios	100 m	500 MW	n/a
2030 ‘optimistic’ scenarios	100 m	1500 MW	n/a
2040 ‘medium’ scenarios	120 m	3000 MW	100 m (500 MW)
2040 ‘optimistic’ scenarios	120 m	5000 MW	100 m (1000 MW)
2050 ‘medium’ scenarios	150 m	Unrestricted	Unrestricted
2050 ‘optimistic’ scenarios	150 m	Unrestricted	Unrestricted
2050 ‘extreme’ scenarios	150 m	Unrestricted	Unrestricted

Step 4. Determine the plan area of the mesh element. Append this information to the new data record.

Commentary: The plan area is important in defining the number of devices that can be located in that mesh element (dependent upon the packing density).

Step 5. Generate a velocity exceedance curve for the identified mesh element. Append this information to the new data record. An exemplar exceedance curve is presented in Figure 9.

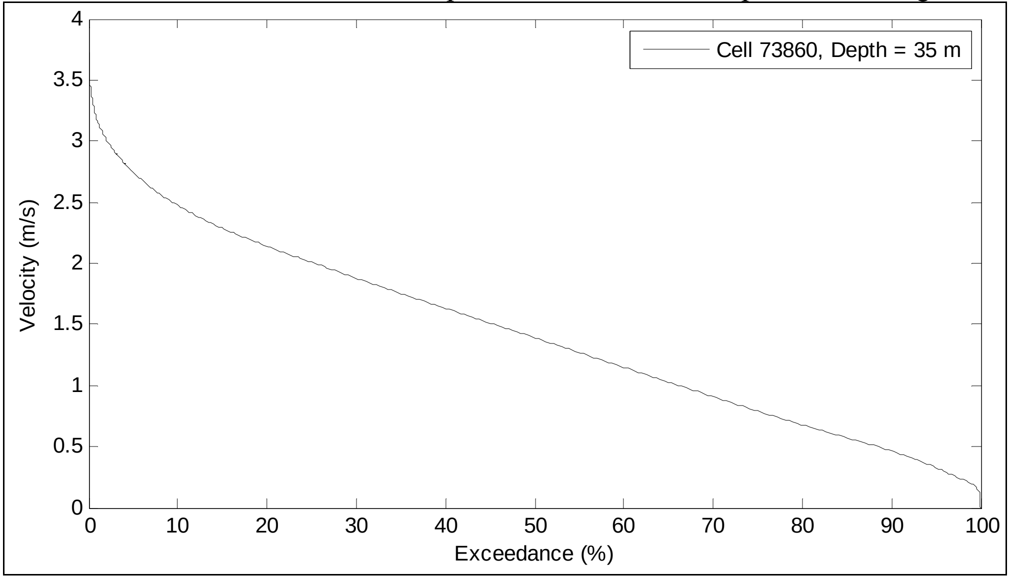


Figure 9: Exemplar velocity exceedance curve derived as explained in section 6.4 (Ness of Duncansby, (site of the Scottish Power Renewables Crown Estate lease in the Pentland Firth))

Commentary: The velocity exceedance curve is used in the next step to determine the appropriate rated velocity for the mesh element. The velocity exceedance curve is also an excellent way to compare between the characteristics of different mesh elements of interest for deployment. For instance, it is immediately clear how much time the device is above and below cut-in from a simple glance at the exceedance curve. Additionally, an exceedance curve is what is proposed by the current draft version of the IEC Tidal Resource Characterisation as being a desired output to inform yield assessment calculations.

Step 6. Interrogate each exceedance curve to determine the appropriate rated velocity to match device characteristics for that location. Append this information to the new data record.

Commentary: Selection of the rated velocity and hence rated power of a TEC device is a complicated design process considering the local flow characteristics, device characteristics and economic analysis. Conducting a rigorous assessment of the rated velocity to identify the exact optimal condition is beyond the scope of this study. A shortcut to achieving a representative approximation is therefore desirable. Simple approaches such as selecting the velocity based upon a percentage of the maximum velocity at a site are a reasonable starting point, but fail to account for the variability from site to site experienced in the relative magnitude of Spring and Neap tides for that particular location. Iyer (2011) recommends a simple approach using the exceedance curve for the site as the basis of assessment. By selecting the rated velocity at a certain stage on the exceedance curve, the user can expect to achieve a capacity factor for their device at any site with overall accuracy of the order ±5%. The capacity factor is the theoretical energy that a device will generate in a set period given a particular input resource divided by the total energy that the device would generate if operating at full load throughout the given period. The capacity factor is a good metric to utilise as a simplified control used to optimise the economic productivity of an installed renewable energy device against the cost of the device in terms of investment in power plant machinery and ability to withstand environmental loadings. Selection of the desired cut-off point on the velocity exceedance curve will be a user-defined variable. For the purposes of this study, the value will be set at 10% exceedance level. This generally delivers a capacity factor in the range 28-34% if the undisturbed flow regime is maintained. This range of capacity factors is deemed a realistic target for a portfolio of TEC farm deployments.

Readers note: Some of the earliest pre-commercialisation testing deployments will likely decide upon selecting a higher representative velocity exceedance than identified here as it de-risks the project by reducing the thrust acting on the device at (and above) rated velocity. For instance, this is why the MCT 'Seagen' device installed at Strangford Narrows is reporting capacity factors well above 60% - the device is rated at a relatively low velocity for that particular location in terms of optimising the energy/cost rating (although as Strangford offers such an extreme tidal resource, the actual rated velocity of the device is highly representative of the likely rated velocity when deployed in locations suitable for the deployment of large farms). The overall benefit of this approach is that for the purposes of technology testing, demonstration and evolution, the device is operating more regularly at the design rated power output.

Step 7. Interrogate the available technology types available for deployment in the period of interest and select the most appropriate. Append this information and the various parameters associated with the identified device to the new data record.

Commentary: User-defined technology types and characteristics for the time period of interest can be input to the model. Within this study we are assuming that for each time horizon there is a restricted suite of available device typologies representative of the 'off-the-shelf' market in that timeframe. The turbine typologies available in the different timeframes are presented in section 6.6.

The most appropriate technology will be identified by selecting the greatest available turbine diameter to maximise device swept area available after accounting for the limits recommended by deliverable D01 (surface clearance at LAT of 5 metres and sea-bed clearance of 25% of the overall depth). Then the appropriate rated velocity/power will be identified. To do so, the instantaneous kinetic power that the device would generate if operating at the preferred velocity identified in step 5 and 6 is derived using equation 2 and multiplying by the swept area associated with the now defined turbine diameter and the equivalent coefficient of performance of the device (assumed to be 0.4 at rated velocity throughout this study from information provided in deliverable D02). This identifies the preferred rated power for this mesh element. Selection between the available TEC devices on offer in that timescale is then a simple process of selecting the rated velocity that provides the closest rated power (either rounding up or down) to the preferred rated power for the mesh element. This is a more appropriate method than selecting the closest velocity to rated velocity. Having finalised device selection, the characteristic parameters of the device should be appended to the new data record.

Step 8. Derive the number of devices within a mesh element by comparing the plan area with the imposed device packing density. Append as a non-integer real number in the new data record.

Commentary: The plan area of the mesh element has been determined in step 4. The maximum packing density for the TEC device identified in step 7 will have will have been identified as part of the appended data record. Packing densities are derived from assumptions relating to wake persistence and distance downstream required to enable the wake to recover. Deliverable D01 recommends a base case device spacing of 2.5 turbine diameters laterally, and 10 turbine diameters in the downstream direction. This equates to a farm packing density of 1 rotor per $25D^2$ m^2, where D represents the rotor diameter. Hence the packing density for a 20 metre diameter turbine is one every $10000m^2$ (or 100 every square kilometre). Increased packing density would likely increase the interaction between devices and hence reduce the efficiency of each device, whereas decreased packing density will decrease the number of device that can be installed in a given plan area. As the footprint of strong tidal flow velocities of most interest for economic installation of turbines is finite, there is a strong driver to maintain an increased packing density. There are also economic benefits from reducing the inter-farm undersea cabling by increasing packing density. The issue is obviously of significance to the overall economics of a TEC farm. These issues are currently areas of intense research. It is likely that the evidence and experience from a number of arrays of multiple devices in the open sea will be necessary to gain a fuller understanding of these issues.

The number of devices per mesh element is recorded as a non-integer real number as the imposition of the mesh element arrangement is itself arbitrary. When a number of clustered mesh elements are identified as a potential farm layout, then the overall number of devices in a farm will be corrected to an integer number (see step 17).

Step 9. Repeat steps 2-8 throughout the model domain until one of the following hierarchy of conditions is met:

1) If the maximum installed capacity as prescribed in Table 31 in step 1 for that particular scenario timeline is exceeded, then the procedure is complete (even if mesh elements remain that have mean kinetic power density higher than the prescribed target minimum level of interest for that scenario as prescribed in step 1, Table 30).
2) If there are no more available mesh elements for analysis above the target mean kinetic power density identified in Table 30, and the minimum installed capacity as also prescribed in Table 31 for that particular time scenario has been exceeded, then the procedure is complete.
3) If the minimum required installed capacity as prescribed in Table 31 for that particular scenario timeline has not yet been exceeded, then the analysis is allowed to continue until either this minimum installed capacity is exceeded, or the mean kinetic power density of the available mesh elements reaches the absolute limited identified in Table 31.

Commentary: This part of the procedure is a little more involved than most other stages so far.
Without pre-knowledge of the CSM base case simulation output, it is difficult to impose deployment restrictions. The identified approach selects the highest ‘value’ deployment locations based upon the local (mesh element) mean kinetic power density. Imposing appropriately loose bounds on overall levels of deployment at each timescale to allow the CSM base case to inform development is considered representative of the market forces that will be exhibited as the technology evolves – if sufficient sea-bed areas can be identified with high resource density, the economics of that area in terms of development prospects are enhanced. Maximum installed capacity criteria are imposed to mimic supply chain constraints. The minimum installed capacity criteria is used to ensure that a meaningful total energy yield is reached in each scenario while still

maintaining some credibility in terms of a developing build order at an appropriate energy/cost benefit. These minimum criteria are also used to try and ensure that there is sufficient differentiation between the cases being examined in consideration of the remit of scenario development within the ETI-TRM project.

Step 10. Identify clusters of mesh elements indicative of a potential array of devices that can be characterised as a farm. A new ‘farm number’ data flag should be established. This information should be appended to each individual data record to enable grouping of adjacent mesh elements to be identified.

Commentary: Within TELEMAC, identification of whether mesh elements share boundaries can be easily investigated by checking whether the mesh element of interest shares a node or nodes with similarly flagged mesh elements in the record. It is possible that several smaller farms may be identified within an area that could be developed into a single larger farm in reality. However, this is dealt with in Step 16.

Step 11. Derive the overall installed capacity of each identified farm and breakdown into sub-groupings of identical TEC devices.

Commentary: When neighbouring mesh elements are identified, the total installed capacity of the farm and sub-totals of the installed capacity of each typology of TEC device should be assessed.

Step 12. Toggle energy extraction limitation on/off.

Commentary: If the user wants to employ the energy extraction limitations introduced in section 6.3.1, then proceed to step 13. Otherwise proceed forward to step 16.

Step 13. Determine the angular orientation and width of the widest cross-section through the farm perpendicular to the main flow direction.

Commentary: The inputs required from the base case CSM simulation output to inform application of equation 4 in step 14 of the procedure may require user interaction to help identify the appropriate definition of the variables about to be introduced. As the procedure is more involved that the other steps (which can each be defined in a line or two of computational code), it may be more efficient to involve the user to conduct some of the required operations. Whether this process is handled automatically within the computer code by additional development within the CSM, or with need for in-line user input, it is conducted in two parts.

An assessment of the maximum discharge through the cross-sectional area defined by each farm is required. The input variables in terms of velocity and depth will already be associated with each individual cell. What has to be derived is the angular orientation of the cross-section, and the width of the cross-section.

Part 1: The angular orientation of the cross-section is defined as the bearing perpendicular to the mean principal current direction through the widest extent of the farm (which may need to be defined separately in part 2 if being conducted manually).

Part 2: Identify the widest extent of the cross-section perpendicular to the flow direction identified in part 1 of the operation.

Whether this stage is fully automated or requires user input, identifying the angular orientation and width of the cross-section enables the derivation of equation 4 in the next step.

Step 14. For each farm region identified, assess whether limitations need to be applied to the extent of the deployment due to user-defined energy extraction limits by deriving $P_{acceptable}$ (equation 4) and comparing with the proposed installed capacity of the farm.

Commentary: The methodology for evaluating constraints on the energy extracted by a farm with respect to its cross-sectional area (embodied in the variable Q_{max}) was introduced in section 6.3.1. For each farm, it is necessary to apply equation 4 to provide some means of constraining the development of an individual project to a level below which it exceed the theoretical extraction limit and hence creates excessive blockage impacts (even in isolation without any potential interaction effects with other projects). There is also an underlying economic aspect to the application of equation 4 with appropriate values of the coefficient C_E as described, as limiting the energy extracted from the tidal system ensures that the resource available to the farm for exploitation is not reduced to levels below which the project economics are severely impacted.

As the value $P_{acceptable}$ refers to the total overall losses from the tidal systems perspective, not just that converted and delivered to the grid connection point, it is necessary to account for losses when comparing the installed capacity against $P_{acceptable}$. Therefore an assumed overall efficiency is required. This is a value that the user will be able to define if desired. A value of 60% will be assumed for the purposes of this study (this value will only be applied in 2030 cases and beyond as the 2020 developments are prescribed explicitly). This is considered a conservative assumption reflective of the efforts that TEC device manufacturers will make to optimise overall device-resource efficiency (from the resource perspective) once the technology reaches maturation. The first devices to market are unlikely to reach this level of device-resource efficiency (energy delivered to the grid) / (overall energy lost to the system).

Providing evidence of the potential and magnitude of interactions between projects is one of the major output objectives of the ETI-TRM project. Hence, purposefully trying to avoid such interactions would reduce the value of the project in terms of meeting the project objectives.

If the farm does require to be constrained, then proceed to step 15. Otherwise proceed to step 16.

Step 15. As the farm needs to be constrained, reduce the packing density in line with the required reduction in overall power extraction in the system.

The simplest method from a CSM operation perspective is considered to be to reduce the packing density in response to the need to limit farm installed capacity due to extraction limits. Hence the existing identified number of devices per mesh element in the farm (still stored as a real number) should be reduced by a factor equal to the ratio of $P_{acceptable}$ (MW) to (overall farm installed capacity (MW)).

Step 16. Identify and remove all farms or isolated mesh elements where the overall installed capacity (which is equal to the peak power output) is less than the 60 MW limit of interest identified by the ETI for the TRM project. A list of all these mesh elements and summary statistics relating to their characteristics (mesh elements, mean kinetic power density, depth, velocity exceedance curve, plan area and list of neighbours that also meet timescale deployment criteria) will be recorded in an additional output file.

Commentary: To avoid needlessly excluding mesh elements from the scenario, for each mesh element or group of mesh elements identified as failing to meet the minimum combined installed capacity limit of 60W, conduct a search within a 1 km radius from each mesh element to assess whether or not near neighbours exist. There is strong potential for instance that two or more disparate arrays of TEC devices could be separated by a band of shallow water or flow velocities that just fail to meet the imposed criteria. If the combination of two (or more) neighbouring arrays separated by not more than 1 km can be demonstrated, then the arrays can be retained within the analysis and treated as one farm. If this additional criteria cannot be met, then the mesh element or group of elements is removed from further consideration for that scenario.

This exclusion is not meant to indicate that a particular deployment is being highlighted as inappropriate for that time horizon, rather that it is not relevant to the particular scenario under investigation due to the minimum 60 MW installed capacity cap. The devices excluded from consideration in the CSM simulations are still considered as counting towards the overall minimum/maximum installed capacities in a particular scenario timeline as identified in Table 31.

Step 17. The pre-processing analysis is complete. The new data records for each of the identified mesh elements shall be appropriately stored. A list of all the identified mesh elements and summary

statistics relating to their characteristics (mean kinetic power density, depth, velocity exceedance curve, plan area and list of neighbours that also meet timescale deployment criteria) will be recorded in an additional output file.
Commentary: It is at this stage that non-integer device numbers within a farm are rounded down to the nearest whole number. This reduction is considered at a farm level as opposed to a mesh element level. For example, if two mesh elements were each contributing '2.5' devices of the same characteristics within a farm then the combined total within the farm would be that 5 devices were retained. If alternatively both mesh elements were contributing '2.4' devices, then if no other mesh element in the farm has devices with the same characteristics (with a 'part' device left over to contribute), then the overall contribution would only be 4 devices – 'part' devices cannot be retained.

Scenarios must be developed from the bottom up (2020 through 2050) as development in an earlier timeframe carries over to development in a later timeframe (medium scenarios have their own separate timeline for consistency, as do optimistic scenarios, and extreme scenarios utilise the final optimistic case developed).

6.3.3 Implementation required for scenario incorporation to each run of the CSM

The output for each scenario from the procedure detailed in section 6.3.2. is then used as input to the appropriate individual scenario simulation when implemented in the CSM. A standardised procedure is also necessary within the model to implement this information and to ensure that the appropriate energy extraction modelling impacts are imposed. The parameterisation approach for modelling energy extraction impacts has been presented in deliverable D02. Appropriate application of the recommended energy extraction modelling formulation in the TELEMAC model as additional terms in the momentum equations is required. After implementing the energy extraction parameterisation, the simulation results can then be used to consider the potential impact of each development, and the interaction of each development on its neighbours as well as considering the cumulative national scale impact. Similar to in section 6.3.2 a step-wise approach is recommended as follows:

<u>Step 1.</u> (Prior to time-stepping operation) Identify mesh elements where energy extraction is to be implemented as representative of the deployment of TEC devices and generate a 'mask' or similar identifier within the computational system.
Commentary: To speed up computational operation it is beneficial to generate a 'mask' used to identify whether energy extraction is potentially required in each particular mesh element. Energy extraction can then be set at zero for all other mesh elements which can then be ignored for the rest of the procedure outlined in the following steps.
<u>Step 2.</u> (Prior to time-stepping operation) For each mesh element identified, read in the output file generated for that particular location within the post-processing procedure. This will include information relating to the characteristics of the representative devices installed (e.g. number of devices, power curve, support structure drag area and drag coefficient).
Commentary: The information should be stored in an appropriate form to aid computational efficiency.
<u>Step 3.</u> At each time-step during assessment of the momentum equation components, the local velocity condition and overall water column depth necessary to perform the assessment of energy extraction are provided by the CSM. The application of the energy extraction terms will follow the procedure presented in deliverable D02.
Commentary: At each time-step it is desirable to assess and maintain a cumulative count of the energy harvested (Wh) from the tidal system for each contributing component (energy harvesting force, device drag force and wake mixing force) during an ensemble interval.
<u>Step 4.</u> At each prescribed output step (ensemble intervals generally of the order 10, 15 or 30

minutes for tidal model data), output the instantaneous values of power loss (W) for each term, and the cumulative sum of the energy harvested (Wh) during the period of that output step alongside the other variables stored by the CSM.
Commentary: These output values provide a means of assessing the relative magnitude, variability and, in conjunction with the more traditional free surface elevation and velocity vector components of the model, the impact of deployment of TEC devices in a particular CSM scenario. The energy harvested can also be used to derive the energy output to the grid.
Step 5. The CSM simulation should run its course as per any other model application with the energy extraction terms operating as any other part of the model system.

6.4 Methodology for explicitly prescribing tidal current scenario selection

Although the process presented in section 3 is intended to be automated in conjunction with the CSM, it is also possible to manually apply the procedure using alternative data sources. An example

In order to explicitly prescribe a tidal current scenario without utilising the CSM, the same 'decision-tree' procedure intended for automation as outlined in 6.3.2 can be applied manually assuming suitable inputs are available. For the purposes of this study, the data inputs used are similar to what was adopted in CT 2011. The major input data sources therefore are the UK Marine Renewable Energy Atlas (ABPmer, *et al*. (2008)) (hereafter referred to as the 'MEA'), and the Admiralty 'TotalTide' navigation software dataset (United Kingdom Hydrographic Office, 2004). The MEA data is presented on a regular grid structure. Hence, when reference is made in section 6.3.2 to a 'mesh element', when applied in the context of the MEA data the terminology 'grid cell' is used. In order to generate a reliable long-term time-series for applying the 'decision-tree' approach:

- The spring peak velocity at each cell was extracted from the MEA (which provides better spatial coverage and resolution, but no temporal resolution), and
- Time-series were extracted from Totaltide and then local data was interpolated to each cell using the inverse distance-weighting approach [Shepard, (1968)]. Variability of tidal phasing varies spatially much more slowly than the velocity magnitude and direction (although the method is considered to be an approximation as opposed to accurate).
- The 'new' time-series generated is then scaled to the spring peak velocity from the MEA.

Extracting time-series from TotalTide is a laborious process, therefore the amount of data that had to be captured and processed was substantially reduced by swapping the order of the first two steps in the 'decision-tree' procedure (although more appropriate for manual processing, the original procedure is better suited for digital processing). Figure 10 is a plot of the area identified as having appropriate bathymetric depths for consideration in the 2020 timescale scenarios (between 20 m and 50 m) based upon data from the MEA. Figure 11 presents the area identified as over-lapping with the bathymetry in Figure 10 where mean kinetic power densities greater than 1.5 kW/m2 were reported by the MEA. It is immediately apparent that the combination of these two conditions identifies highly dispersed and very specific regions that have potential for development of first generation technologies as identified by the input source data.

Figures 10 and 11 highlight that the MEA data indicates that only 0.14% of UK coastal waters exhibit a mean kinetic power density greater than 1.5 kW/m^2 and depth range of 20-50 metres (and therefore can potentially be developed using 'first' generation technologies in the scenarios out to 2050 (for comparison, the MEA reports that only 0.15% of the UK continental shelf experiences a spring peak velocity greater than 3 m/s). A similar analysis of regions with depth greater than 50 metres identifies

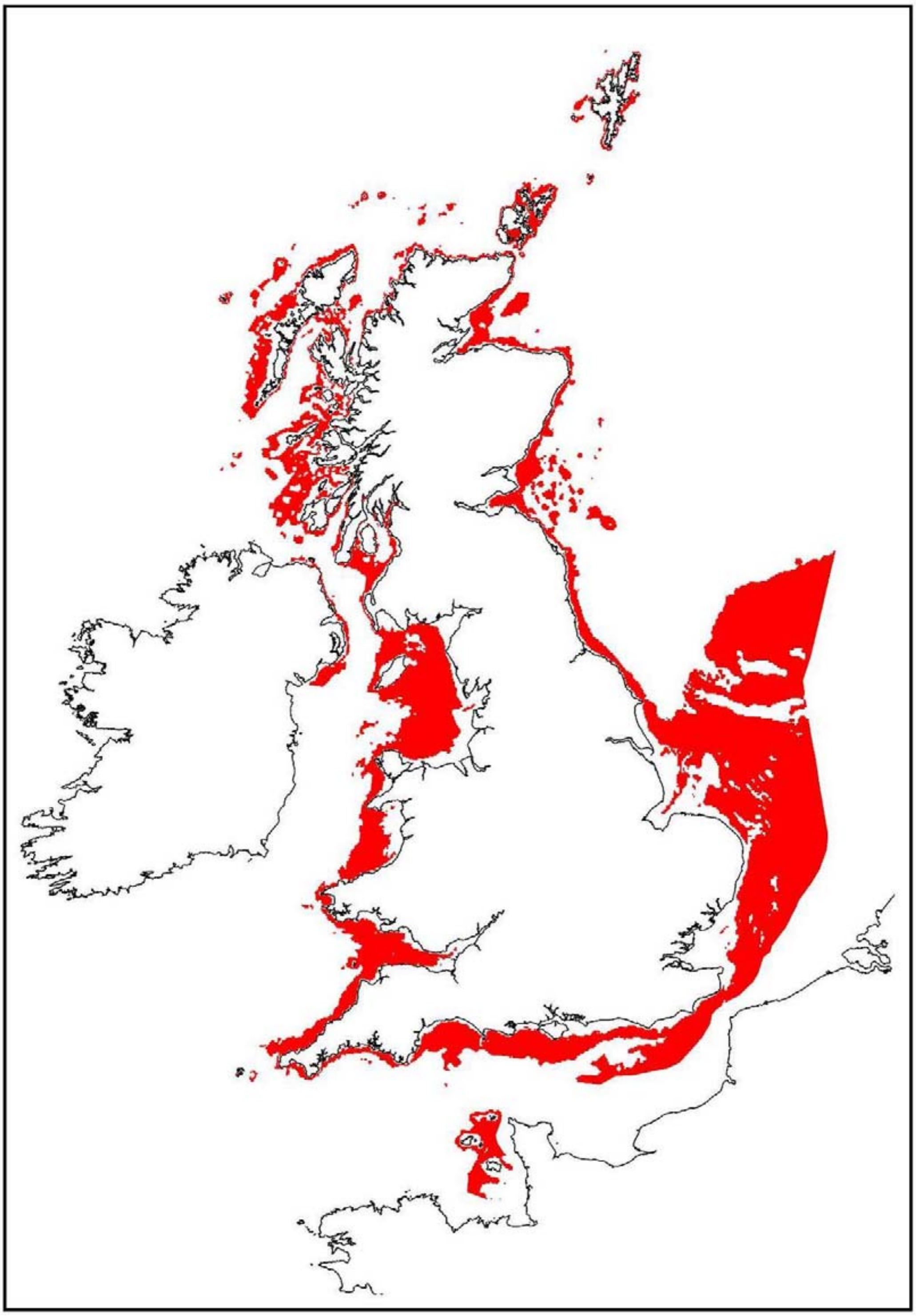


Figure 10: Areas in UK coastal waters identified as having depths in the range 20-50m.

that only 0.049% of UK designated international waters identified with these depth characteristics also have an ‘acceptable’ mean kinetic power density of greater than 1.5 kW/m^2. The combined areas identified as exhibiting a mean kinetic power density greater than 1.5 kW/m^2 in depths of more than 20 metres was identified in Figure 2.

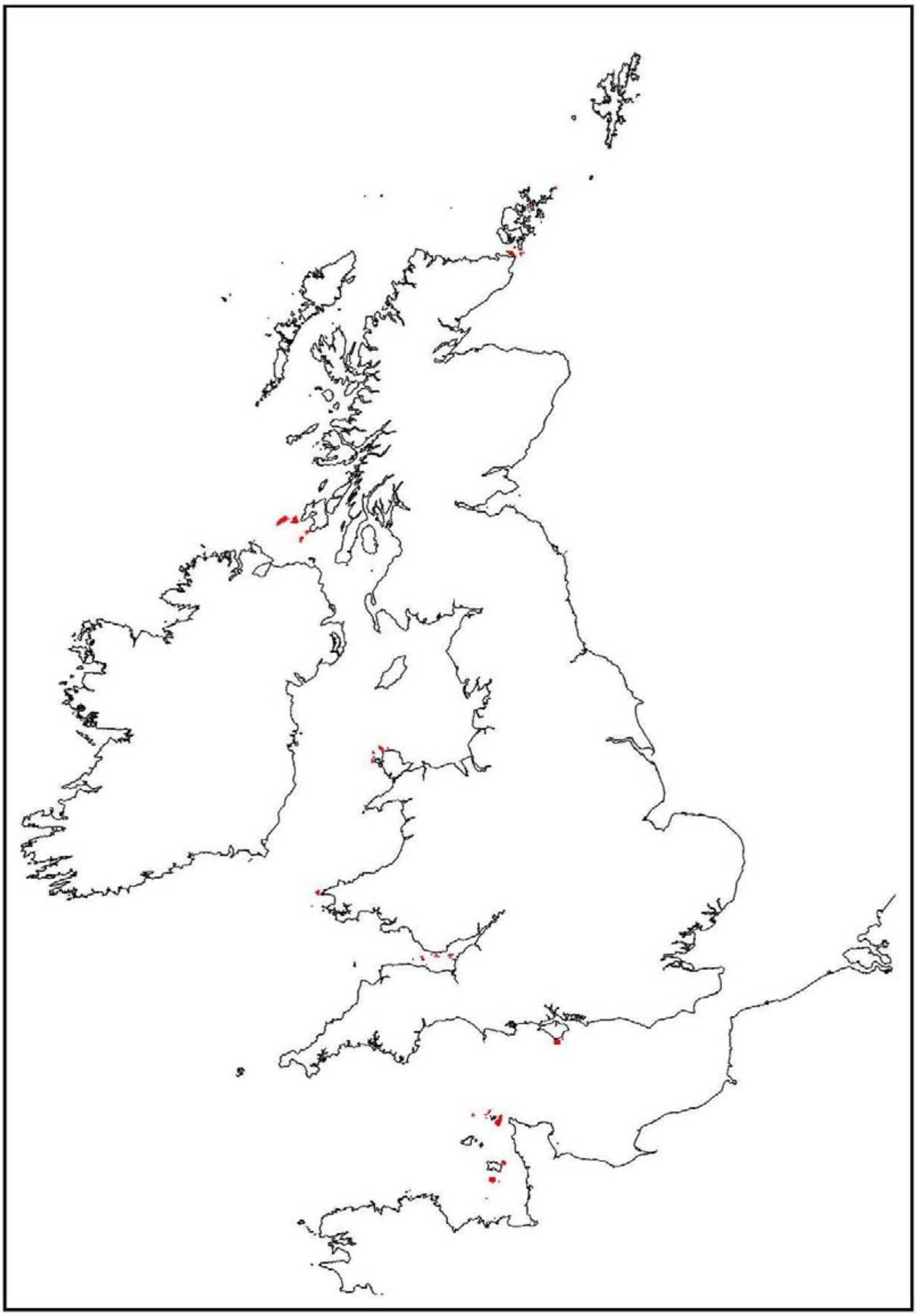


Figure 11: Areas in UK coastal waters identified as having depths in the range 20-50m and mean kinetic power density > 1.5 kW/m^2.

Apart from the use of different source data, the 'decision-tree' procedure outlined earlier can then be applied exactly as described in section 6.3.2 to determine an appropriate deployment strategy to underpin scenario development. This will be discussed further in the section 7 discussing the results informing prescription of the manually derived TEC technology deployment scenarios.

6.4.1 Use of the explicit methodology or input data in further scenario developments

A number of additional tidal current deployment scenarios of interest for implementation in the CSM analysis utilise existing approaches presented in the literature (some of the 'special' cases to be examined) or rely on commercially sensitive data associated with real projects that are currently undergoing early stages of commercial development (these projects are used to define most of the potential early development stages (e.g. 2020 'medium' case)).Both approaches will be presented in the detail required for CSM implementation in section 7. These cases fall into two categories, (i) those that can be populated using the data described in section 6.4 and manual application of the procedure outlined in section 6.3.2, and (ii) those that rely on input data associated with the scenario being provided by or inferred from the source material. In order to populate the second category, the decision-tree procedure is not appropriate. It will instead be necessary to apply a different approach where the scenario is populated by outputs of methodological approaches that differ from those that have been developed throughout section 6 of this document. Hence the limiting of energy extraction, consideration of practical constraints, etc. are not considered within the analysis specific to these cases unless specifically incorporated within the source material.

6.5 Competing for use of resource with other renewables

An external factor that may impact on the build order of TEC farms is competition for resources with other offshore renewable energy technologies. Regions of interest for development of tidal current energy tend to exclude interest for offshore wind energy projects due to the severe functional loads imparted on wind energy installations by extreme tidal currents. Hence it is likely that there will be little or no direct conflict between these two technology approaches regarding geographic footprint (this does not preclude the fact that the existence of a number of tidal current energy and wind energy projects in a distinct region may impact on each other through alteration of the underlying tidal system). Similarly the design complexity induced by a significant wave regime acting on a tidal current device and for an extreme tidal current acting on a wave energy device tends to keep the interests of project developers focussed on different locations for the two technologies (e.g. compare Figures 6 (wave) and 2 (tidal current). However, there would be some potential for the two technologies to co-exist harmoniously in certain situations with limited resource interaction (e.g. shoreline or nearshore wave development inland of a tidal current farm). No additional restriction is applied to the deployment of tidal current farms due to these potential competing uses.

6.6 Technology availability

Within this study we are assuming that for each time horizon there is a restricted suite of available device typologies representative of the 'off-the-shelf- market in that timeframe. This is not unlike the wind energy manufacturers provision of a set of defined turbine ratings and dimensions that project developers can choose between – it is likely that TEC manufacturers will follow a similar approach (there is for example already a coalescing of the TEC devices undergoing pre-commercialisation testing around the rated power of 1 MW, with the technologies at earlier stages of development also viewing this as an aspirational target).

First generation technologies are assumed to be commercial versions of devices currently undergoing pre-commercialisation testing, with the ability through time to offer increased turbine diameters. Design consensus relating to second generation technologies has not as yet been reached. On the time horizon 2030-2050 when such devices are assumed to be market ready in this study, it is likely that second generation technologies will, as well as having enabled access to deeper water, also have increased the overall swept area available for power capture. This may be achieved by continuing to increase the turbine diameter, or may involve the deployment of multiple turbines using one common support structure. Hence as the overall swept area increases, the rated power of an individual device increases.

The frontal area of the support structure elements of each device is a required input to assess fluid losses associated with overcoming support structure drag. There is as yet a lack of consensus on design of first generation TEC device support structures, and even less consensus regarding potential second generation devices. Given the lack of credible input data, a simple approach has been developed. Under the simplifying assumption that the thrust acting on the overall TEC device is a major determinant of support structure requirements, it is assumed that the frontal area of the support structure elements will vary linearly with the thrust acting on the turbine rotor. The thrust force for a variable pitch device should peak at rated power. The thrust at rated power will either already be known (from a device thrust curve), or can be derived from knowledge of the device power curve. For this study, the power based calculation is applied, as what little TEC device performance information exists in the public domain is presented in the form of power curves as was discussed in deliverable
D02. The relationship used is of the form:

$$\left(S \times \frac{P_{rated}}{U_{rated}}\right)$$

Where *S* is a shape factor related to the device type. For application in this study, the value of *S* is set at 0.25 for first generation surface piercing devices, 0.15 for first-generation non-surface piercing devices, and assumed to be 0.2 for all 2nd generation devices. The empirical factor for first generation devices has been derived by back-calculating against known existing TEC device support structure architectures. Second-generation technologies will not necessarily require support structures that span the full depth of the water column; hence a median value between the two first-generation values is used given the lack of hard data on which to base an assessment. This approach produces the support structure frontal areas presented in Tables 33 and 34. If the support structure frontal area was already known for a particular device, then that data can be directly input to the CSM through the user interaction files.

6.6.1 2020 technology options

For the purposes of scenario development with respect to the provision of early stage Pentland Firth deployments, turbine manufacturers are already attached to the majority of projects. Therefore there is obvious guidance regarding the technologies that these companies may deliver to the commercial market between now and 2020 based on the prototypes undergoing testing. All are horizontal axis devices. Two classes are assumed, the first a standard one turbine per support structure set-up, the other offering two turbines per support structure (like MCT's Seagen 'S' design). The support structure of the 1st device type is assumed to span only half the water depth, whereas the 2nd device has a surfacing piercing structure. Both classes are available with turbine diameters of 15 metres or 20 metres, and have assumed rated velocity options of 2.2 m/s and 2.5 m/s. Basic device properties are summarised in Table 33 for all 4 'off-the-shelf' options for both classes of device.

Table 33: First generation TEC device properties available in 2020

Identifier	U_{rated} (m/s)	Diameter (m)	No. of turbines	Swept area (m^2)	P_{rated} (kW)	Drag coefficient	Support structure area m^2
PC20.1	2.2	15 m	1	176.7	378.6	1.0	25.8
PC20.2	2.5	15 m	1	176.7	562.5	1.0	33.8
PC20.3	2.2	20 m	1	314.1	673.1	1.0	45.9
PC20.4	2.5	20 m	1	314.1	1000.0	1.0	60.0
PC20.5	2.2	15 m	2	353.4	757.2	1.0	86.1
PC20.6	2.5	15 m	2	353.4	1125.0	1.0	112.5
PC20.7	2.2	20 m	2	628.2	1346.2	1.0	153.0
PC20.8	2.5	20 m	2	628.2	2000.0	1.0	200.0

6.6.2 Technology options in 2030 and beyond

To simplify options in 2030 and beyond, all first generation devices will be assumed to have undergone design evolution towards supporting two turbines on one support structure. These device are no longer considered to be surface piercing, as in large arrays this would cause exclusion of other users. This design decision, together with expected design evolution and increased installation experience extends the assumed depth range of first generation devices to 60 metres from 2030 onwards. An additional rated velocity condition (2.75 m/s) will be made available, obviously best suited to particularly energetic sites. This provides 6 different first generation device orientations for 2030 and beyond. Second generation devices will be assumed to follow a similar approach – they will be able to support 4 turbines with the same drive-train properties as first generation devices (see Table 34). Second generation technologies essentially represent a step-change in support structure, partly to facilitate accessing the energy resource in deeper water. Although technology may evolve along a different path, the overall intent of increasing swept area per support structure (and hence reducing installation costs) is considered a strong driver. Whether the increased swept area is achieved by increasingly large turbine diameters, supporting multiple turbines as supposed here, or using alternative turbine designs (e.g. large vertical axis TEC devices proposed by Salter (2009)), the overall impact is generically the same in terms of allowing access to deeper water and potentially reducing project lifetime cost over time through an increased capture area per unit installation

6.7 Summarising the outcomes of the build order/constraints scenario development approach

In order to define a framework around which to build scenario specifications, it has been necessary to define a series of constraints to ensure credible development strategies are proposed. The industry know-how of the project team and the limited existing scenario projections for TEC development has formed the basis of this assessment. Key inputs have been the CT 2011 report, government assessments of the potential for TEC development in UK waters and the limited existing project proposal definitions (i.e. Pentland Firth and Orkney Waters leasing round).

As detailed design of large scale TEC development projects has yet to be undertaken given the relative immaturity of the sector, it has been necessary to foresee the key drivers that will define project selection. In simple terms the scenario specification framework has been driven by the availability of

Table 34: First and second generation TEC devices available in 2030

Identifier	U_{rated} (m/s)	Diameter (m)	Max. Operating depth (m)	No. of turbines	Swept area (m^2)	P_{rated} (kW)	Drag (C_D)	Support structure area m^2
PC30.1	2.2	15	60	2	353.4	757.2	0.3	68.8
PC30.2	2.5	15	60	2	353.4	1125.0	0.3	90.0
PC30.3	2.75	15	60	2	353.4	1475.1	0.3	107.3
PC30.4	2.2	20	60	2	628.2	1346.2	0.3	122.4
PC30.5	2.5	20	60	2	628.2	2000.0	0.3	160.0
PC30.6	2.75	20	60	2	628.2	2622.4	0.3	190.7
PC30.7	2.2	15	150	4	706.7	1514.5	0.3	137.7
PC30.8	2.5	15	150	4	706.7	2250.0	0.3	180.0
PC30.9	2.75	15	150	4	706.7	2950.2	0.3	214.6
PC30.10	2.2	20	150	4	1256.4	2692.4	0.3	244.8
PC30.11	2.5	20	150	4	1256.4	4000.1	0.3	320.0
PC30.12	2.75	20	150	4	1256.4	5244.7	0.3	381.4

appropriate tidal energy resource for exploitation, so a hierarchy of factors has been identified:

1. The strength of the resource (the mean kinetic power density has been identified as being the most appropriate measure of the resource from a technology perspective in terms of identifying energy yield potential).
2. The suitability of the resource location for technology application. Depth is therefore a leading constraint (although this is expected to relax over time as technology suited to deployment in deeper water reaches commercialisation). Distance to shore also has economic implications.
3. Environmental impact constraints potentially limiting the extent and density of farm deployments.
4. Additional factors that would have a negative impact on project cost through increased design requirements (e.g. the local wave climate).

Overarching constraints underpinning development are also imposed to ensure that the proposed scenarios maintain credibility:

1. Supply chain and industry confidence: a band of minimum and maximum installed capacities is imposed in each scenario timeline to provide acceptable bounds within which the industry and supply chain can grow. This is in part reflective of economic constraints (e.g. appetite of public and private investors), and additionally engineering constraints (e.g. the ability to respond to required build rates given the inherent difficulties of weather windows, operational equipment availability, mass manufacture of device, and not least the project development timescales in terms of leasing and consent).
   This approach also has benefit from an ETI-TRM perspective as it ensures that a wide range of deployment levels will be examined across the suite of scenarios.
2. Technology capability also limits development in terms of accessing and exploiting resource. As the technology matures, a wider resource becomes potentially economic to develop in terms of opening up access to deeper water, and cost reduction through learning and development experience altering the economics of more marginal resource sites.

The final consideration in scenario specification has been considering the goals of the EI-TRM project itself. The project is intended to examine a wide range of TEC deployment levels and push the envelope in terms of the upper limits in order to better inform discussion of the potential future prospects of the technology.

Although a different methodology has been required, the approach described above is remarkably similar to the approach taken to define the tidal range scenario specification. The differences relate to the existing level of experience. Hence the tidal range scenarios are based upon existing project proposals. The tidal current scenarios are required to envision their own future project proposals.

6.8 Conclusions

The various approaches that have been presented to inform scenario specification for TEC development differ substantially from the tidal range approach. Although lacking final deployment experience, the major tidal range project locations in the UK have undergone substantial project feasibility and design development. Therefore a development history exists providing a foundation upon which scenario specification can readily be constructed. The same experiences are lacking from a tidal current energy specification perspective. The mismatch of a highly concentrated but spatially variable energy resource represented with coarse input data creates extra difficulties for TEC scenario prescription.

In order to overcome these difficulties, a new approach has been presented in line with the development of the CSM. The CSM itself provides a rich source of appropriate data upon which to build TEC deployment scenarios. It is therefore only logical to utilise this resource in the context of the ETI-TRM project. In order to do so, it has been necessary to develop a constraints framework that will be applied to the output of validated CSM simulations (referred to as the base case). The constraints framework has been developed to form a logical stepwise analysis procedure. This scenario selection procedure will be embedded in the CSM post-processing analysis tools. The procedure will generate output files that can be readily applied to the CSM. Parameterisations that enable simulation of energy extraction will be embedded in the core architecture of the CSM to enable application of the specified scenarios. The stepwise procedure for scenario selection can also be readily applied manually if appropriate data is available to inform the assessment.

Finally, in order to make use of the limited body of existing scenario specifications for TEC development and deployments, the source material has been utilised to explicitly derive the inputs necessary to represent these cases in the CSM.

7 TIDAL CURRENT RESULTS

The following sections provide the outcomes of the scenario definition for tidal current technologies, along with supporting commentary and summary tables detailing the combined characteristics and parameters used to describe each scheme as it is introduced. Section 6 of this document has provided a means of defining tidal current project proposals thereby internally generating a site selection and build order preference around a set of user defined constraints.

Section 6 (Table 31) has provided indicative build rates under the ‘medium’ support case and ‘optimistic’ support case that are summarised in Figure 12. Decisions are presented in ‘build order’ (the medium case first, then optimistic case for each timeframe). Unlike the tidal range scenarios, the constraints framework applied to tidal current scenario definition will generate slightly different cases for each timeframe of interest. There will be substantial overlap, but as some of the constraints are relaxed, the scenarios generated will each evolve slightly differently. All scenario test cases will still be directly comparable. Each timeframe will just be indicative of a slightly different incremental build phase.

The first 15 scenarios defined (as for the tidal range cases) describe incremental industry development timeframes spanning through to 2050. A number of ‘special cases; that do not follow directly follow the incremental build approach are then examined. These include simulations of projects that already hold leases for development from the Crown Estate, and more radical development proposals presented in the literature. Two technology sensitivity test cases are also presented, examining the impact of development of ‘third-generation’ technology solutions.

The various scenarios are now presented in order as indicated in table 1.

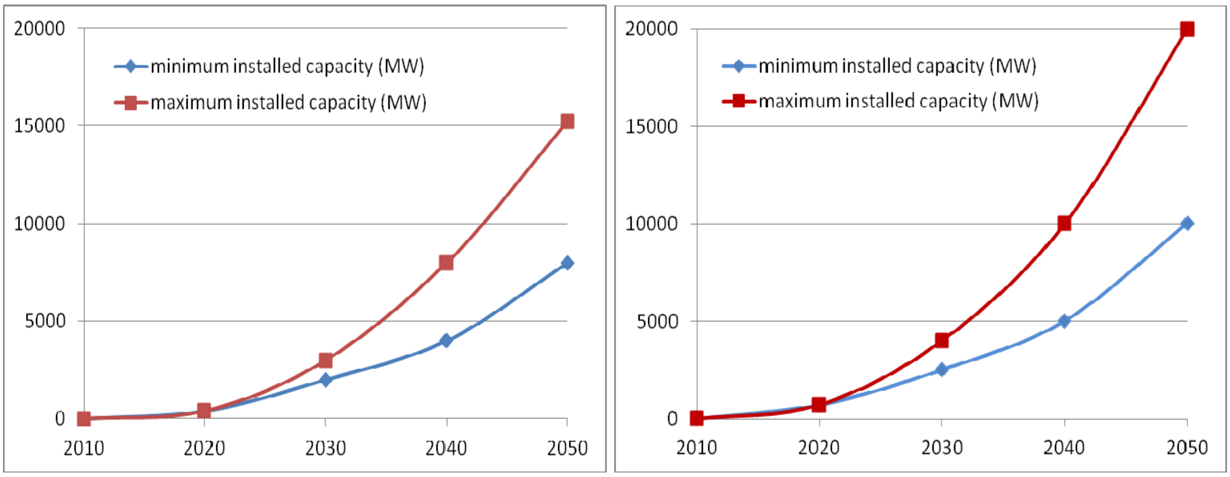


Figure 12: Imposed installed capacity limits, ‘medium’ case (left), ‘optimistic’ case (right). The ‘extreme’ case is not shown but builds upon the 2050 optimistic specification.

7.1 Identifying preferred build order (2020 medium case)

The 2020 ‘medium’ case assumes an installed capacity of 400 MW following the most recent UK government prediction of TEC deployment on that timescale [DECC (2011(a))]. Given the provision of leases for 1GW of TEC installations by the Crown Estate in the Pentland Firth and Orkney Waters region, it is considered reasonable to further constrain the 2020 development timeline geographically to match the existing lease locations. This is also in agreement with the recommendations of deliverable D01 for both scenario development and CSM specification:

> "The sites for which the Crown Estate has issued Agreements for Lease (particularly in and around the Pentland Firth) should be considered by the scenario modelling work package in terms of 2020 deployment, and the CSM should be created such that its high resolution areas fundamentally cover all of these sites and those in and around the Pentland Firth. It may therefore be prudent for the scenario modelling work package to further split the Pentland Firth (and surrounding area) sites into these specified Crown Estate sites so that they can be appropriately modelled in the various CSM scenario runs."

This means that the Pentland Firth 'deep' and 'shallow' designations presented in Table 28 need to be further developed for 2020 scenario prescription.

7.1.1 Manual scenario specification using the MEA data

The 2020 'medium' case will be used to provide an example of the outputs from manual application of the scenario specification framework. This will also highlight the deficiencies in the available national databases that can be used to inform this procedure. This provides additional justification for the provision and application of the automated approach using CSM simulation outputs to provide more reliable data upon which to base scenario definitions. It is recommended for implementation in the CSM that the automated procedure constrained to the particular geographic locations is still applied to generate a more appropriate scenario that best matching device properties with characteristics of the in-situ resource.

First of all, it is necessary to identify the projects that have been issued Agreements for Lease (see Table 35). Then the match between existing data and the lease areas needs to be established (summarised in Figure 13). Source data from the MEA is selected where the footprint of a particular lease area best matches with one of the grid cells. In cases where the farm straddles two or more cells fairly evenly, then the cell with the highest mean Spring peak velocity is utilised (representative of 'cherry-picking' the best locations within a lease area for initial development). Exceedance curves for each of the MEA grid cells that coincide with Pentland Firth and Orkney Waters lease sites and where the MEA data indicates mean Spring peak velocities above 2.5 m/s are presented in Appendix B. These exceedance curves were generated following the procedure discussed in section 6.4.

Table 35: Agreements for Lease issued by the Crown Estate in round 1 for the Pentland Firth and Orkney Waters region (source: [Crown Estate (2011)]).

Developer (Technology)	Site	Capacity
Wave		
SSE Renewables Developments Ltd	Costa Head	200 MW
Aquamarine Power Ltd & SSE Renewables Developments Ltd (Oyster)	Brough Head	200 MW
Scottish Power Renewables UK Ltd	Marwick Head	50 MW
E.ON Climate and Renewables UK Developments Ltd	West Orkney South	50 MW
E.ON Climate and Renewables UK Developments Ltd	West Orkney Middle South	50 MW
Pelamis Wave Power Ltd (Pelamis)	Farr Point	50 MW
Tidal		
SSE Renewables Developments Ltd	Westray South	200 MW
SSE Renewables Holdings (UK) Ltd & OpenHydro Site Development Ltd (OpenHydro)	Cantick Head	200 MW
Marine Current Turbines Ltd	Brough Ness	100 MW
MeyGen Ltd	Inner Sound	400MW
Scottish Power Renewables UK Ltd	Ness of Duncansby	100 MW

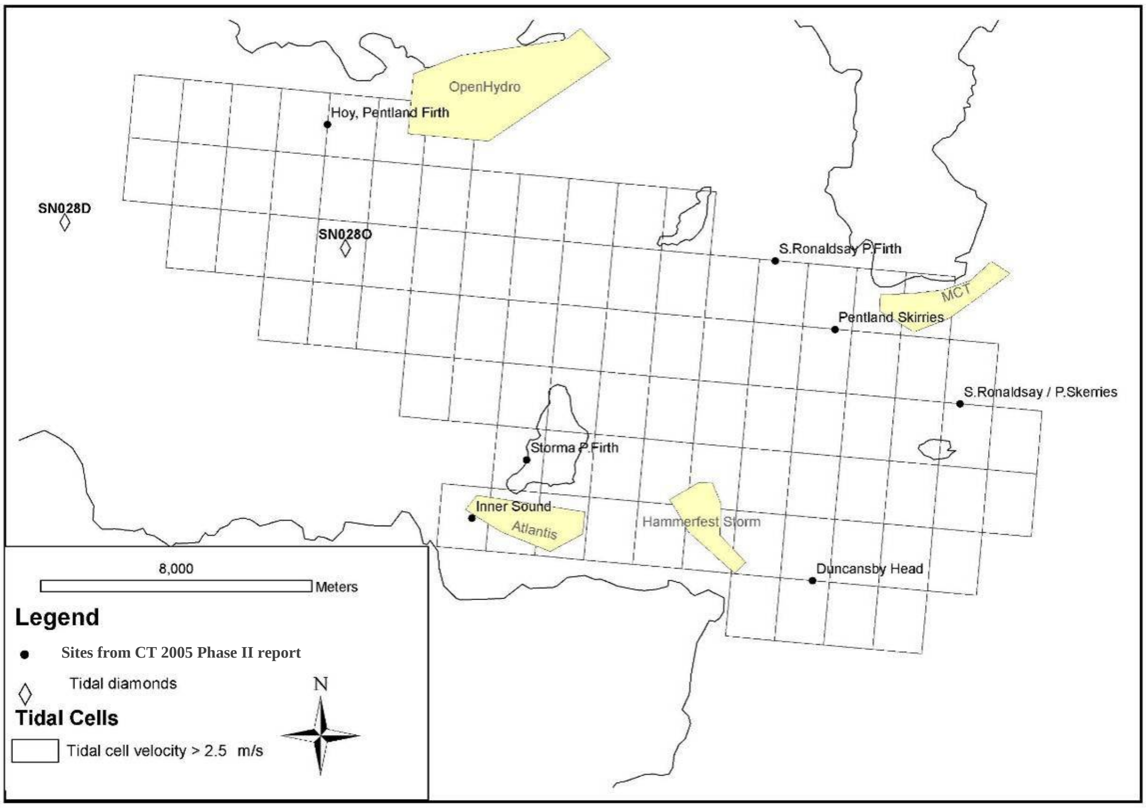


Figure 13: Layout of the Pentland Firth Crown Estate round 1 tidal energy leasing activities overlain on the MEA data grid (only those grid cells with Spring peak velocity greater than 2.5 m/s are outlined).

A difficulty emerges in applying the MEA data in terms of the Inner Sound region leased to Meygen Ltd. The MEA reports that both the grid cells that the Meygen footprint straddles have average depths of only 19 metres. Hence the Inner Sound region is deemed unsuited to development using the project constraints that are to be applied. As the Inner Sound is already undergoing project development, higher resolution representations of the region are already entering the public domain. In the Environmental Impact Assessment (EIA) scoping document provided to the regulator, Meygen identify that around half of the Inner Sound region is a channel of depth 34-38 metres [Rollings (2011)]. Numerical modelling simulation data is also included in [Rollings (2011)] that indicate that velocities during Spring peak flow conditions are highly variable across the Inner Sound (not surprisingly), and that peak values observed are significantly higher than reported in the MEA (See http://www.scotland.gov.uk/Resource/Doc/295194/0121858.pdf, specifically Figure 9). The pragmatic approach for this ETI TRM study is to utilise the higher resolution bathymetry data interpretation provided in the literature verified by cross-checking with Admiralty Charts. The velocity data from the MEA will be retained as there is no verification presented of the Meygen model output, and highly resolved peak velocities are not representative of the site-wide condition (still being considered in the wider context of the analysis as a 1.8 x 1.8 km grid cell). This Inner Sound case is an example of where coarse input data resolution would severely undermine the assessment procedure, and hence why the updated scenario selection procedure using higher resolution CSM outputs is both necessary and a significant improvement. It is likely that detailed site analysis or modelling data will identify deficiencies in the MEA data at all the Pentland Firth lease locations (e.g. the resolution of the MEA means that the two islands in the Pentland Firth (Stroma and Swona) are not included as part of the model grid bathymetry/topography).

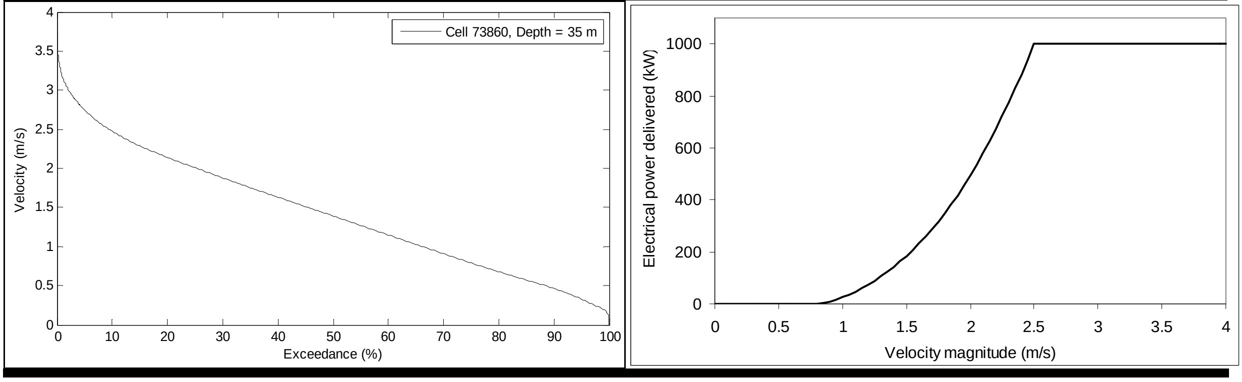
The approach adopted to achieving 400MW installed is to envisage that each project in Table 35 will be developed in phases. Therefore, for the 4 sites in the Pentland Firth, deployment of 100MW is the target farm size to achieve the overall installed capacity desired in the 2020 scenario (even although some of the project development organisation have obtained leases for higher levels of deployment). Manually following the procedure described in section 6.3.2, and applying a maximum installed capacity in each case of 100 MW produces the identified farm characteristics summarised in Tables 36-39, which describe each of the individual project sites.

7.1.2 Ness of Duncansby site

The characteristics of the Ness of Duncansby site leased to Scottish Power Renewables UK Ltd. derived using the MEA and TotalTide data as described in section 6.4 are presented in table 36. The data suggests that a 1 MW device with a rated velocity of 2.50 m/s would be appropriate. For a 100 MW installed capacity deployment, this obviously implies installation of 100 devices at the site. The indicative farm capacity factor of 29.54% derived using the exceedance curve and power curve shown is very closely to the intended design capacity factor.

Table 36: Ness of Duncanby scenario 2 development fact-sheet

Farm location:		Ness of Duncansby (SPR)	
Cell depth:	35 m	Cut-in velocity:	0.8 m/s
Device constrained depth:	22.5 m	10% exceedance velocity:	2.484 m/s
Device diameter:	20 m	Annual peak velocity:	3.73 m/s
Packing density ratio:	10000:1	Rated velocity:	2.50 m/s
Farm area (plan)	3.24 km^2	Rated power:	1 MW
Cross-sectional area (streamwise)	63000 m^2	Number of devices in farm	100
Farm rated power:	100 MW	Estimated farm *AEP*:	0.2588 TWh/y
Estimated farm load factor:	0.2954	Efficiency factor (E_f):	0.7225
Drag area (C_DA):	60.0 m^2	Wake mixing factor (E_w)	0.15

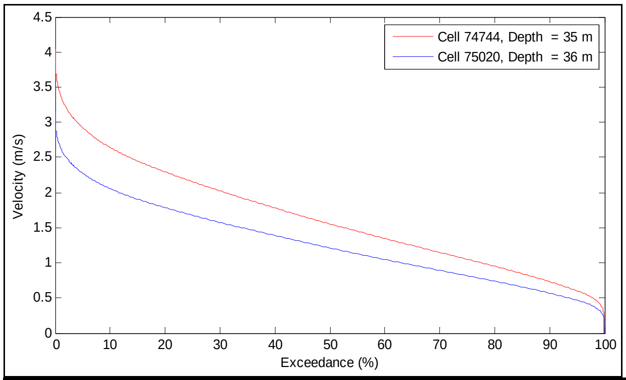


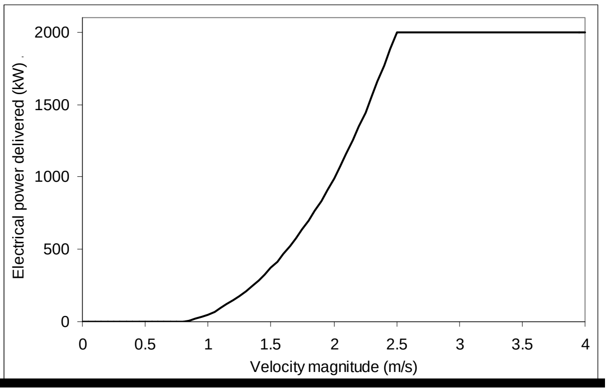
7.1.3 Brough Ness site

The characteristics of the Brough Ness site leased to Marine Current Turbines Ltd. derived using the MEA and TotalTide data as described in section 6.4 are presented in table 37. The Brough Ness site spans 2 MEA grid cells, both of which are indicated in the exceedance curve in table 37. The data from the more energetic grid cell seems best suited to a twin-turbine 2 MW device with a rated velocity of 2.50 m/s. For a 100 MW installed capacity deployment, this obviously implies installation of 50 devices at the site. The indicative farm capacity factor of 35.8% derived using the exceedance curve and power curve shown is indicative of the fact that the 10% exceedance velocity at the site of 2.65 m/s suggests a very energetic resource and potential under-prescription of the preferred turbine rated velocity – this relates to the constraints of technology availability discussed in section 6.6..

Table 37: Brough Ness scenario 2 development fact-sheet

	Farm location:	Brough Ness (MCT)	
Cell depth:	35 m	Cut-in velocity:	0.8 m/s
Device constrained depth:	22.5 m	10% exceedance velocity:	2.65 m/s
Device diameter:	2 x 20 m	Annual peak velocity:	4.04 m/s
Packing density ratio:	20000:1	Rated velocity:	2.50 m/s
Farm area (plan)	3.24 km^2	Rated power:	2 MW
Cross-sectional area (streamwise)	63000 m^2	Number of devices in farm	50
Farm rated power:	100 MW	Estimated farm *AEP*:	0.3137 TWh/y
Estimated farm load factor:	0.3580	Efficiency factor (E_f):	0.7225
Drag area ($C_D A$):	200 m^2	Wake mixing factor (E_w)	0.15



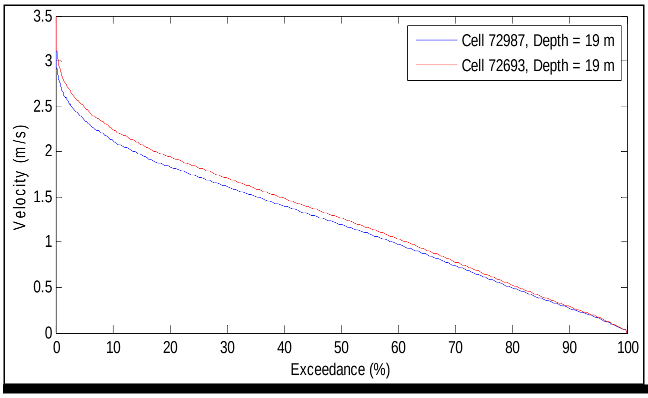


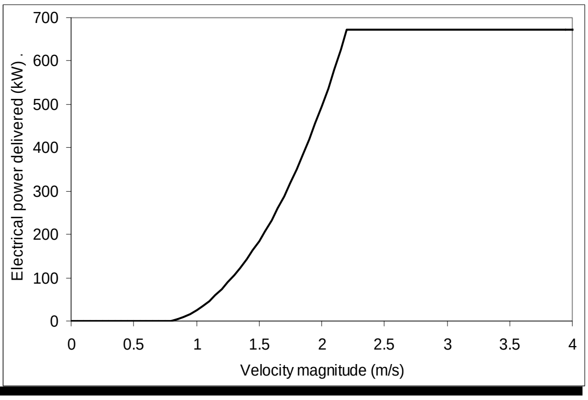
7.1.4 Inner Sound site

The characteristics of the Inner Sound site leased to Meygen Ltd. derived using the MEA and TotalTide data as described in section 6.4 is presented in table 38. The Inner Sound partially spans 2 MEA grid cells, both of which are indicated in the exceedance curve in table 38. The data from the more energetic grid cell seems best suited to a single turbine 0.673 MW device with a rated velocity of 2.20 m/s. For a 100 MW installed capacity deployment, this implies installation of 148 devices providing an installed capacity of 99.6 MW at the site. Recalling the bathymetric restrictions of the site indicated in section 7.1, the indicated grid cell only has spare capacity for around 14 more similar devices before the available site footprint will be full. The indicative farm capacity factor of 28.09% is derived using the exceedance curve and power curve shown. Discussion of discrepancies between the MEA resource data and higher resolution local project data has already been presented. What is important to recognise is that the MEA data should only be relied upon as a data source for TEC development appraisal in the absence of any other more reliable data sources.

Table 38: Inner Sound (E) scenario 2 development fact-sheet

	Farm location:	Inner Sound (E) (Meygen)	
Cell depth:	35 m	Cut-in velocity:	0.8 m/s
Device constrained depth:	22.5 m	10% exceedance velocity:	2.257 m/s
Device diameter:	20 m	Annual peak velocity:	3.31 m/s
Packing density ratio:	10000:1	Rated velocity:	2.20 m/s
Available farm area (plan):	1.62 km^2	Rated power:	0.6733 MW
Cross-sectional area (streamwise)	63000 m^2	Number of devices in farm	148
Farm rated power:	99.6 MW	Estimated farm *AEP*:	0.2680 TWh/y
Estimated farm load factor:	0.3075	Efficiency factor (E_f):	0.7225
Drag area ($C_D A$):	45.9 m^2	Wake mixing factor (E_w)	0.15



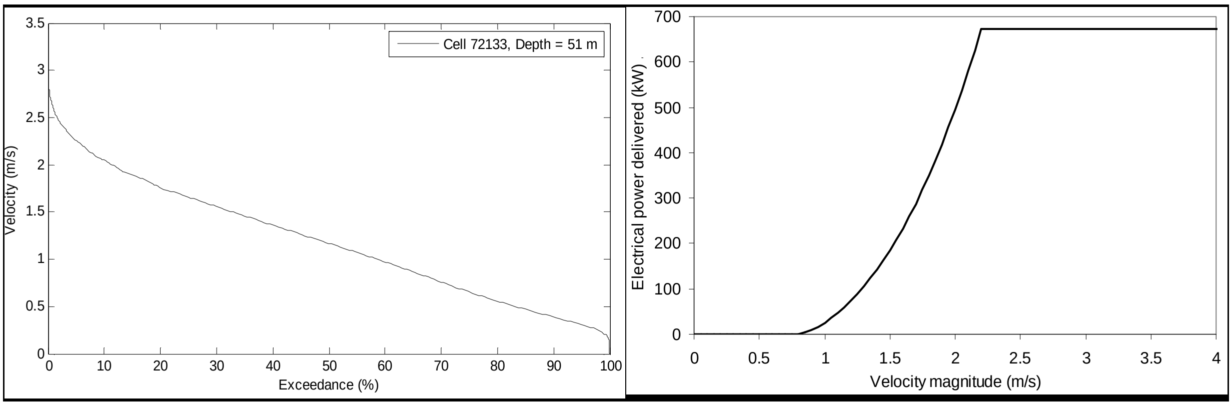


7.1.5 Cantick Head site

The characteristics of the Cantick Head site leased to SSE Renewable Holdings (UK) Ltd. and OpenHydro Site Development Ltd derived using the MEA and TotalTide data as described in section 6.4 is presented in table 39. The Cantick Head site partially spans multiple MEA grid cells, although only one of which is indicated as reaching peak Spring velocities in excess of 2.5 m/s as presented in the exceedance curve in table 39. The data seems best suited to a single turbine 0.673 MW device with a rated velocity of 2.20 m/s. For a 100 MW installed capacity deployment, this implies installation of 148 devices providing an installed capacity of 99.6 MW at the site. The indicative farm capacity factor of 24.69% is derived using the exceedance curve and power curve shown. The low capacity factor achieved is indicative of a low 10% exceedance velocity (2.0574 m/s) in comparison with the available commercial 2.2 m/s rated velocity device. Given that a lease has been granted for this site, in contrast with the relatively poor resource identified using the publically available data, it is suspected that the MEA may be under predicting the strength of the tidal energy resource in this region, The CSM will provide evidence to support this suspicion, or alternatively validate MEA performance in this region.

Table 39: Cantick Head scenario 2 development fact-sheet

Farm location:		Cantick Head (OpenHydro)	
Cell depth:	51 m	Cut-in velocity:	0.8 m/s
Device constrained depth:	33.25	10% exceedance velocity:	2.0574 m/s
Device diameter:	20 m	Annual peak velocity:	3.01 m/s
Packing density ratio:	10000:1	Rated velocity:	2.2 m/s
Farm area (plan)	3.24 km^2	Rated power:	0.6733 MW
Cross-sectional area (streamwise)	91800 m^2	Number of devices in farm	148
Farm rated power:	99.6 MW	Estimated farm *AEP*:	0.2155 TWh/y
Estimated farm load factor:	0.2469	Efficiency factor (E_f):	0.7225
Drag area ($C_D A$):	45.9 m^2	Wake mixing factor (E_w)	0.15



7.1.6 Automatic scenario specification using the CSM

The four locations detailed in sections 7.1.2-7.1.5 combine to provide the manually generated 400MW installed capacity 2020 medium scenario. As has already been intimated, it is preferred that the scenario specification implemented in the CSM is derived using the automated process that relies on CSM input data. The geographic footprint of the areas leased by the Crown Estate will be provided as shapefiles, and the automated process should be constrained to generate 100 MW worth of development in each of the 4 regions. This approach would for instance validate the availability of appropriate bathymetric depths in the Inner Sound, as well as provide more reliable representations of the velocity exceedance curves at each site which are used to inform device selection and specification,

7.2 Identifying preferred build order (2020 optimistic case)

A similar approach to the previous 2020 medium case has been utilised to generate a 2020 optimistic case using the manual scenario selection specification procedure with the combined MEA / TotalTide generated time-series as described in section 6.4 used as input data. Again, it is recommended that this data is updated during CSM application using the automated procedure and input data provided by the CSM base case.

The outcomes of the manual prescription are now presented. The intention of the 2020 optimistic scenario is to consider an accelerated development case related to the Pentland Firth and Orkney Waters leasing round that produces 700 MW of installed capacity (of the 1 GW overall leases granted). The extension to 700 MW is viewed as the addition of a second phase of development at the leased sites. This includes extension of the Inner Sound and Cantick Head sites up to 200 MW total build, and the introduction of 100MW of build at the fifth leasing site in Westray Firth. The Ness of Duncansby and Brough Ness sites are adopted from the 2020 medium scenario – these sites only hold leases for 100 MW installed capacity. Tables 40-43 summarise the updated and additional developments proposed by the manual application of the procedure using the MEA data.

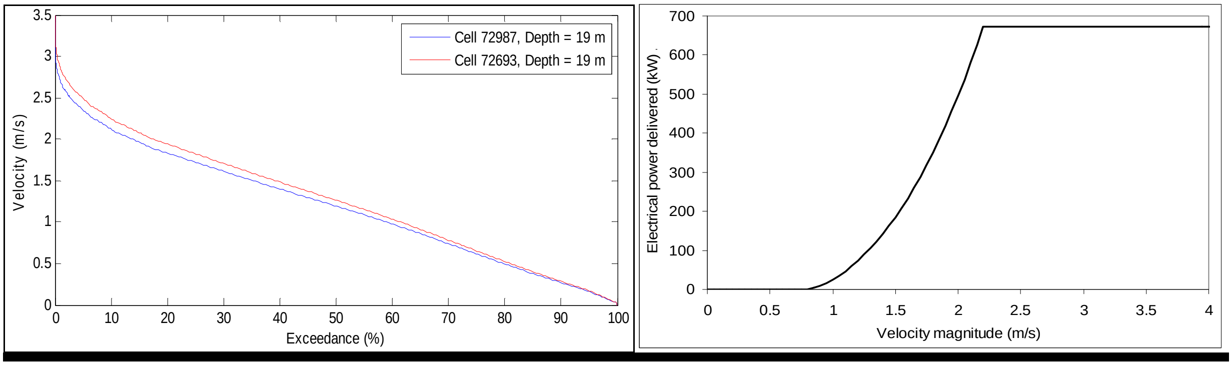
7.2.1 Inner Sound site

Extending the Inner Sound scheme is limited to a maximum of 162 total devices in the grid cell already partly developed in the 2020 medium scenario due to the available farm area for development being constrained (equivalent to an installed capacity of 109.07 MW – see table 40).

Table 40: Inner Sound (E) (Meygen 1) scenario 4 development fact-sheet

Farm location:		Inner Sound (E) (Meygen 1)	
Cell depth:	35 m	Cut-in velocity:	0.8 m/s
Device constrained depth:	22.5 m	10% exceedance velocity:	2.257 m/s
Device diameter:	20 m	Annual peak velocity:	3.31 m/s

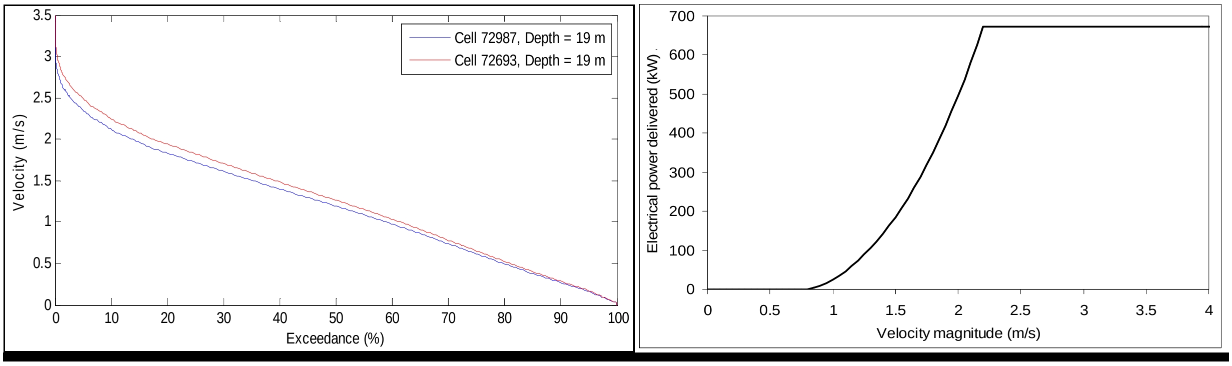
Packing density ratio:	10000:1	Rated velocity:	2.20 m/s
Available farm area (plan):	1.62 km^2	Rated power:	0.6733 MW
Cross-sectional area (streamwise)	63000 m^2	Number of devices in farm	162
Farm rated power:	109.07 MW	Estimated farm *AEP*:	0.2938 TWh/y
Estimated farm load factor:	0.3075	Efficiency factor (E_f):	0.7225
Drag area (C_DA):	45.9 m^2	Wake mixing factor (E_w)	0.15



The Inner Sound lease also spans a second slightly less energetic input data cell based on the MEA data. Therefore the remaining 2nd phase build that cannot be accommodated in the first cell (90.90 MW) takes place in this second cell as indicated in table 41

Table 41: Inner Sound (W) (Meygen 1) scenario 4 development fact-sheet

	Farm location:	Inner Sound (W) (Meygen 2)	
Cell depth:	35 m	Cut-in velocity:	0.8 m/s
Device constrained depth:	22.5 m	10% exceedance velocity:	2.131 m/s
Device diameter:	20 m	Annual peak velocity:	3.12 m/s
Packing density ratio:	10000:1	Rated velocity:	2.20 m/s
Available farm area (plan):	1.62 km^2	Rated power:	0.6733 MW
Cross-sectional area (streamwise)	63000 m^2	Number of devices in farm	135
Farm rated power:	90.90 MW	Estimated farm *AEP*:	0.2141 TWh/y
Estimated farm load factor:	0.2689	Efficiency factor (E_f):	0.7225
Drag area (C_DA):	45.9 m^2	Wake mixing factor (E_w)	0.15

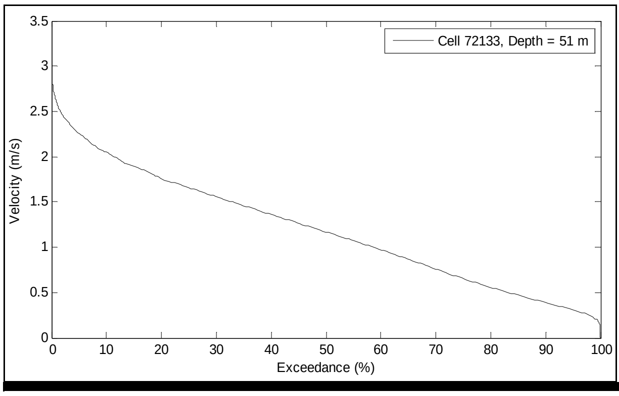


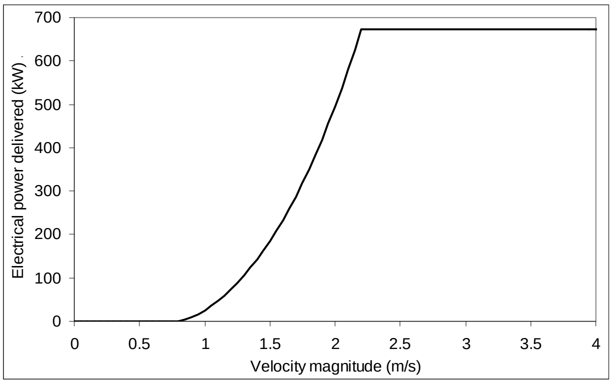
7.2.2 Cantick Head site

The Cantick Head site has no issues with accommodating an additional 100 MW of installed capacity. Hence all of the 1st and 2nd phase development (199.8 MW total) is prescribed using one set of input data applied uniformly across the farm (the mismatch between the resource input data spatial resolution and available data is again highlighted – 200 MW of installed capacity would span a footprint area of 2 km^2 – the scales of spatial variability characteristic of highly energetic coastal environments suggest that this is a gross simplification). As already highlighted, it is suspected that the resource identified is under predicted due to the lack of resolution of the input data. If the identified resource is demonstrated to be accurate by the CSM, then it is open to question whether this site location is best suited to early stage large scale TEC deployment (as the economics of the site implied by the strength of the resource are sub-optimal).

Table 42: Cantick Head scenario 4 development fact-sheet

	Farm location:	Cantick Head (OpenHydro)	
Cell depth:	51 m	Cut-in velocity:	0.8 m/s
Device constrained depth:	33.25	10% exceedance velocity:	2.0574 m/s
Device diameter:	20 m	Annual peak velocity:	3.01 m/s
Packing density ratio:	10000:1	Rated velocity:	2.2 m/s
Farm area (plan)	3.24 km^2	Rated power:	0.6733 MW
Cross-sectional area (streamwise)	91800 m^2	Number of devices in farm	297
Farm rated power:	199.8 MW	Estimated farm *AEP*:	0.4324 TWh/y
Estimated farm load factor:	0.2469	Efficiency factor (E_f):	0.7225
Drag area ($C_D A$):	45.9 m^2	Wake mixing factor (E_w)	0.15





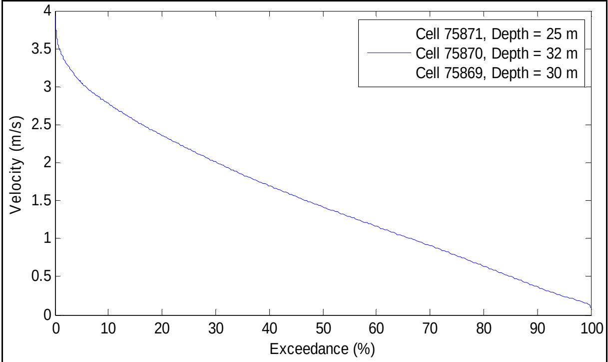
7.2.3 Westray Firth site

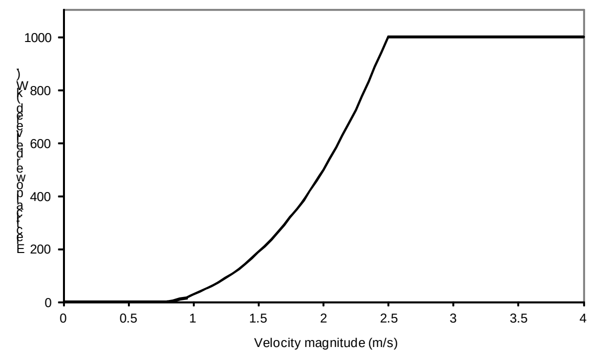
The characteristics of the Westray Firth site leased to SSE Renewables Developments Ltd. derived using the MEA and TotalTide data as described in section 6.4 are presented in table 43. The data suggests that a 1 MW device with a rated velocity of 2.50 m/s would be appropriate. For a 100 MW installed capacity deployment, this obviously implies installation of 100 devices at the site. The indicative farm capacity factor of 33.95% derived using the exceedance curve and power curve shown is a good indicator of the relative magnitude of the resource in this location as embodied by the 10% exceedance velocity of 2.78 m/s.

Table 43: Westray Firth scenario 4 development fact-sheet

	Farm location:	Westray Firth (SSE)	
Cell depth:	33 m	Cut-in velocity:	0.8 m/s
Device constrained depth:	20 m	10% exceedance velocity:	2.780 m/s
Device diameter:	20 m	Annual peak velocity:	4.18 m/s
Packing density ratio:	10000:1	Rated velocity:	2.5 m/s
Available farm area (plan):	3.24 km^2	Rated power:	1.00 MW
Cross-sectional area (streamwise)	59400 m^2	Number of devices in farm	100
Farm rated power:	100 MW	Estimated farm *AEP*:	0.2974 TWh/y
Estimated farm load factor:	0.3395	Efficiency factor (E_f):	0.7225

Drag area (C_DA):	60 m^2	Wake mixing factor (E_w)	0.15





7.3 Identifying preferred build order (2030 medium case)

The various constraints to be imposed in the automated scenario selection framework have already been introduced and discussed in depth in section 6 of this document. Table 44 summarises the constraints identified for the 2030 medium case, bringing all the relevant factors together in one simple fact-sheet representation. Incremental development is enabled from the 2030 medium case through to the 2050 extreme case be relaxation of the various constraints to 'encourage' development within the different timeframes under consideration. The installed capacity limitations are representative of achieving just under half of the lower installed capacity target identified for this timescale by [ETI & UK Energy Research Centre (2010)] for combined WEC and TEC deployment.

Table 44: 2030 medium case scenario selection constraints fact-sheet

Tidal current developments (CSM defined):	Political will:	Medium
Minimum average power density:	Target: 3.0 kW/m^2	Absolute 2.25 kW/m^2
Minimum depth (m):	20 m	
Maximum depth (m):	100 m (only 500 MW greater than 60 m)	
Maximum distance from shore:	6000 m	
Maximum annual mean significant wave height:	1.5 m	
Minimum total installed capacity:	2000 MW (approx. 5 TWh/y @ CF 0.3)	
Maximum total installed capacity:	3000 MW (approx. 8 TWh/y @ CF 0.3)	
Maximum site extraction factor (c_e)	20%	

7.4 Identifying preferred build order (2030 optimistic case)

The various constraints to be imposed in the automated scenario selection framework have already been introduced and discussed in depth in section 6 of this document. Table 45 summarises the constraints identified for the 2030 optimistic case, bringing all the relevant factors together in one simple fact-sheet representation. Incremental development is enabled from the 2030 medium case through to the 2050 extreme case be relaxation of the various constraints to 'encourage' development within the different timeframes under consideration. The installed capacity limitations are representative of achieving over half of the lower installed capacity target identified for this timescale by [ETI & UK Energy Research Centre (2010)] for combined WEC and TEC deployment.

Table 45: 2030 optimistic case scenario selection constraints fact-sheet

Tidal current developments (CSM defined):	Political will:	Optimistic
Minimum average power density:	Target: 2.25 kW/m^2	Absolute 2.00 kW/m^2
Minimum depth (m):	20 m	
Maximum depth (m):	100 m (only 1500 MW greater than 60 m)	

Maximum distance from shore:	8000 m
Maximum annual mean significant wave height:	1.5 m
Minimum total installed capacity:	3000 MW (approx. 8 TWh/y @ CF 0.3)
Maximum total installed capacity:	4000 MW (approx. 10 TWh/y @ CF 0.3)
Maximum site extraction factor (c_e)	40%

7.5 Identifying preferred build order (2040 medium case)

The various constraints to be imposed in the automated scenario selection framework have already been introduced and discussed in depth in section 6 of this document. Table 46 summarises the constraints identified for the 2040 medium case, bringing all the relevant factors together in one simple fact-sheet representation. Incremental development is enabled from the 2030 medium case through to the 2050 extreme case be relaxation of the various constraints to 'encourage' development within the different timeframes under consideration. The installed capacity limitations are representative of achieving just under half of the installed capacity target range identified for this timescale by [ETI & UK Energy Research Centre (2010)] for combined WEC and TEC deployment.

Table 46: 2040 medium case scenario selection constraints fact-sheet

Tidal current developments (CSM defined):	Political will:	Medium
Minimum average power density:	Target: 2.0 kW/m^2	Absolute 1.8 kW/m^2
Minimum depth (m):	20 m	
Maximum depth (m):	120 m (only 500 MW > 100 m, 3000MW > 60 m)	
Maximum distance from shore:	10000 m	
Maximum annual mean significant wave height:	1.75 m	
Minimum total installed capacity:	4000 MW (approx. 10 TWh/y @ CF 0.3)	
Maximum total installed capacity:	8000 MW (approx. 21 TWh/y @ CF 0.3)	
Maximum site extraction factor (c_e)	20%	

7.6 Identifying preferred build order (2040 optimistic case)

The various constraints to be imposed in the automated scenario selection framework have already been introduced and discussed in depth in section 6 of this document. Table 47 summarises the constraints identified for the 2040 optimistic case, bringing all the relevant factors together in one simple fact-sheet representation. Incremental development is enabled from the 2030 medium case through to the 2050 extreme case be relaxation of the various constraints to 'encourage' development within the different timeframes under consideration. The installed capacity limitations are representative of achieving over half of the installed capacity target range identified for this timescale by [ETI & UK Energy Research Centre (2010)] for combined WEC and TEC deployment.

Table 47: 2040 optimistic case scenario selection constraints fact-sheet

Tidal current developments (CSM defined):	Political will:	Optimistic
Minimum average power density:	Target: 1.8 kW/m^2	Absolute 1.65 kW/m^2
Minimum depth (m):	20 m	
Maximum depth (m):	120 m (only 1000 MW > 100 m, 5000MW >60m)	
Maximum distance from shore:	12000 m	
Maximum annual mean significant wave height:	1.75 m	
Minimum total installed capacity:	5000 MW (approx. 13 TWh/y @ CF 0.3)	
Maximum total installed capacity:	10000 MW (approx. 26 TWh/y @ CF 0.3)	
Maximum site extraction factor (c_e)	40%	

7.7 Identifying preferred build order (2050 medium case)

The various constraints to be imposed in the automated scenario selection framework have already been introduced and discussed in depth in section 6 of this document. Table 48 summarises the constraints identified for the 2050 medium case, bringing all the relevant factors together in one simple fact-sheet representation. Incremental development is enabled from the 2030 medium case through to the 2050 extreme case be relaxation of the various constraints to 'encourage' development within the different timeframes under consideration. The installed capacity limitations are representative of achieving approximately three-quarters of the installed capacity target identified for this timescale by [ETI & UK Energy Research Centre (2010)] for combined WEC and TEC deployment.

Table 48: 2050 medium case scenario selection constraints fact-sheet

Tidal current developments (CSM defined):	Political will:	Medium
Minimum average power density:	Target: 1.65 kW/m^2	Absolute 1.5 kW/m^2
Minimum depth (m):	20 m	
Maximum depth (m):	150 m	
Maximum distance from shore:	15000 m	
Maximum annual mean significant wave height:	2 m	
Minimum total installed capacity:	8000 MW (approx. 21 TWh/y @ CF 0.3)	
Maximum total installed capacity:	15250 MW (approx. 40 TWh/y @ CF 0.3)	
Maximum site extraction factor (c_e)	20%	

7.8 Identifying preferred build order (2050 optimistic case)

The various constraints to be imposed in the automated scenario selection framework have already been introduced and discussed in depth in section 6 of this document. Table 49 summarises the constraints identified for the 2050 optimistic case, bringing all the relevant factors together in one simple fact-sheet representation. Incremental development is enabled from the 2030 medium case through to the 2050 extreme case be relaxation of the various constraints to 'encourage' development within the different timeframes under consideration. The installed capacity limitations are representative of achieving the installed capacity target identified for this timescale by [ETI & UK Energy Research Centre (2010)] for combined WEC and TEC deployment.

Table 49: 2050 optimistic case scenario selection constraints fact-sheet

Tidal current developments (CSM defined):	Political will:	Optimistic
Minimum average power density:	Target: 1.5 kW/m^2	Absolute 1.5 kW/m^2
Minimum depth (m):	20 m	
Maximum depth (m):	150 m	
Maximum distance from shore:	20000 m	
Maximum annual mean significant wave height:	2 m	
Minimum total installed capacity:	10000 MW (approx. 26 TWh/y @ CF 0.3)	
Maximum total installed capacity:	20000 MW (approx. 52.5 TWh/y @ CF 0.3)	
Maximum site extraction factor (c_e)	40%	

7.9 Identifying preferred build order (2050 extreme case)

The various constraints to be imposed in the automated scenario selection framework have already been introduced and discussed in depth in section 6 of this document. Table 50 summarises the constraints identified for the 2050 extreme case, bringing all the relevant factors together in one simple fact-sheet representation. Incremental development is enabled from the 2030 medium case through to the 2050 extreme case be relaxation of the various constraints to 'encourage' development within the different timeframes under consideration. The installed capacity limitations are representative of achieving as much as double the installed capacity target identified for this timescale by [ETI & UK Energy Research Centre (2010)] for combined WEC and TEC deployment. The purpose of the extreme scenario is as it is titled to consider an extreme deployment case. This proposed scale of installation is still well within the bounds of the more radical upper bound scenarios presented in the literature (e.g. [The Offshore Valuation Group (2010)].

Table 50: 2050 extreme case scenario selection constraints fact-sheet

Tidal current developments (CSM defined):	Political will:	Extreme
Minimum average power density:	Target: 1.5 kW/m^2	Absolute 1.5 kW/m^2
Minimum depth (m):	20 m	
Maximum depth (m):	150 m	
Maximum distance from shore:	25000 m	
Maximum annual mean significant wave height:	2 m	
Minimum total installed capacity:	15250 MW (approx. 40 TWh/y @ CF 0.3)	
Maximum total installed capacity:	40000 MW (approx. 105 TWh/y @ CF 0.3)	
Maximum site extraction factor (c_e)	80%	

7.10 Introducing the 'special' scenario cases (scenarios 21, 24 and 25)

Various additional scenarios that do not fit strictly into the build order discussion or framework are now presented to examine specific cases of interest. These scenarios are referred to as 'special' to designate that they are not part of the core scenarios introduced to date that have been constructed through the incremental build approach previously discussed. Ten 'special' cases are introduced across the scenario analysis, five of which involve or are specific to tidal current projects.

7.11 Scenario 21

Scenario 21 intends to replicate the CT 2011 base case scenario discussed in deliverable D01. To recap, the CT 2011 scenarios were desk based assessments using input data such as the MEA. The development of theoretical and technical constraints was informed by numerical modelling of simplified idealised cases that identified generic responses to energy extraction stimuli. The base case scenario provides an assessment of the technical resource potential of full UK wide deployment under specified development constraints. These include limiting the physical environmental impact of each individual project to a maximum of either 10% velocity reduction or 10% reduction of tidal range (or 0.2 metres in regions with small tidal ranges). The constraints are applied to each project individually, under the assumption of no interaction between projects. The scenario uses 8061 MW worth of installed capacity to generate 29.0 TWh/y under the imposed constraints.

7.12 Scenario 24

Salter (2009) presents radical proposals for the development of a massive farm of third-generation TEC devices in the Pentland Firth in the interest of encouraging debate regarding the future potential of tidal current energy development and deployment (see Salter, 2009 (specifically, figure 10)). The proposals involve the deployment of over 1200 closely packed, 140-metre diameter, 70 MW vertical-axis turbines placed in double rows (an installed capacity of the order 85 GW). Although only limited details are presented regarding the proposed technology, it is possible to infer a rough estimation of the intended performance of the 70 MW devices. Using the generic fifth-order power curve relationship used throughout the rest of this study as a basis and the information in Salter (2009), it is assumed that a rated velocity of 3.5 m/s and swept area of 11000 metres is necessary to achieve 70 MW generation. It is not clear whether the required 78 metres depth these values imply are available across all of the indicated deployment cross-sections – the CSM bathymetry will be used to constrain where necessary. With the layout already dictated, and assumed device performance characteristics, the proposed development scenario for the Pentland Firth can be implemented in the CSM.

7.13 Scenario 25

MacKay (2009) has also presented radical proposals for the future development of tidal current energy in UK water in the interest of stimulating debate. The deployment proposals summarised in Mackay, 2009 (specifically, see figure G.7) are generated using the 'farm' approach to TEC deployment – an assumption that the devices have little or no impact on their surrounding environment, and hence can be deployed in very large farm arrangements. The proposal suggests that the development strategy would generate of the order 200 TWh/y. No information is provided about how energy is to be harvested other than by tidal stream farms. The intention with this scenario is to provide shapefiles defining the deployment regions identified, and then allow the CSM to specify turbines appropriate to the resource identified in the base case in each region and maintaining the device spacing requirements. As this scenario will likely see specification of many farms with lower target rated velocities than previously examined, two additional tidal turbine velocity ratings will be introduced, 2.0 m/s and 1.6 m/s that will be better suited to marginal resources (providing a smallest rated power device of 131 kW (15 m diameter @ 1.6 m/s)). Otherwise all other constraints will be ignored for the purposes of prescribing this scenario test case.

7.14 Introducing the tidal current sensitivity analysis cases (scenarios 29 and 30)

As TEC technologies are as yet immature and relatively untested, it is difficult to properly characterise the potential performance differences between technology alternatives. What is more insightful therefore is to consider the practical impact of technology evolution. There has already been some attempt to characterise such development throughout the scenario test cases by the designation of existing pre-commercial devices undergoing full scale open sea testing as representative of a 'first generation' technology solution. 'Second generation' technologies were introduced to the scenarios to facilitate access to tidal energy resources in deeper waters. A potentially envisaged focus area for third generation technology developments is cost reduction. The practical application of this from the scenario development perspective is that what has previously been considered uneconomic or marginal value tidal energy resources would potentially become cost competitive. How these step change cost reductions are practically achieved is not of particular importance. How the impact of third generation technologies will be tested in the CSM will be to release or remove some of the development constraints previously imposed as replacement economic filters in the absence of a historic database of project proposals. Both sensitivity scenarios still use the assumption of first and second generation device characteristics in terms of matching resource and technology. The difference is implicit that the technology has now undergone a step-change in cost so has an increased scope in terms of opening up previously marginal value development sites.

7.14.1 Scenario 29

The various constraints to be imposed in the automated scenario selection framework have already been introduced and discussed in depth in section 6 of this document. Table 51 summarises the constraints identified for the scenario 29 technology sensitivity test, bringing all the relevant factors together in one simple fact-sheet representation. As this scenario will likely see specification of many farms with lower target rated velocities than previously examined, two additional tidal turbine velocity ratings will be introduced, 2.0 m/s and 1.6 m/s that will be better suited to marginal resources (providing a smallest rated power device of 131 kW (15 m diameter @ 1.6 m/s)).

Table 51: Third generation technology sensitivity test-scenario 29 constraints fact-sheet

Tidal current developments (CSM defined):	Political will:	n/a
Minimum average power density:	Target: 1.40 kW/m^2	Absolute 1.2 kW/m^2
Minimum depth (m):	20 m	
Maximum depth (m):	150 m	
Maximum distance from shore:	25000 m	
Maximum annual mean significant wave height:	2 m	
Minimum total installed capacity:	30000 MW (approx. 77 TWh/y @ CF 0.3)	
Maximum total installed capacity:	unrestricted	
Maximum site extraction factor (c_e)	80%	

7.14.2 Scenario 30

The various constraints to be imposed in the automated scenario selection framework have already been introduced and discussed in depth in section 6 of this document. Table 52 summarises the constraints identified for the scenario 30 technology sensitivity test, bringing all the relevant factors together in one simple fact-sheet representation. As this scenario will likely see specification of many farms with lower target rated velocities than previously examined, two additional tidal turbine velocity ratings will be introduced, 2.0 m/s and 1.6 m/s that will be better suited to marginal resources (providing a smallest rated power device of 131 kW (15 m diameter @ 1.6 m/s)).

Table 52: Third generation technology sensitivity test-scenario 30 constraints fact-sheet

Tidal current developments (CSM defined):	Political will:	n/a
Minimum average power density:	Target = Absolute = 1.0 kW/m^2	
Minimum depth (m):	20 m	
Maximum depth (m):	150 m	
Maximum distance from shore:	25000 m	
Maximum annual mean significant wave height:	2 m	
Minimum total installed capacity:	Not specified	
Maximum total installed capacity:	unrestricted	
Maximum site extraction factor (c_e)	80%	

7.15 Conclusions

Specification of scenario constraints for 30 cases has been presented (summarised in table 53). The manual application of the scenario specification framework detailed in section 6 has been implemented. This activity has demonstrated the inadequacy of the available national resource databases for application in the ETI-TRM project. It is therefore strongly recommended that the automated procedure is endorsed and becomes the basis of scenario design using the constraints provided in conjunction with data from the initial CSM test case. The constraints necessary to enable the automated procedure in conjunction with the CSM are presented. The scenarios proposed cover a wide range of developments, first at a regional scale, and then enabling and examining national scale development potential and patterns. Scenarios that push the barriers of acceptable environmental impact are presented to enable the ETI-TRM project outcomes to aid in help defining the boundaries of what will and will not be considered acceptable levels of tidal current energy development and consequent impact.

Table 53: Summary of overarching tidal current energy scenario constraints

			Installed capacity (MW)		Mean kinetic power density (kW/m^2)	
Year	Case	Optimism	Minimum	Maximum	Target	Absolute

	numbers				value	value
2010	1, 17	n/a	0	0	n/a	n/a
2020	2, 3	Medium	400	400	n/a	n/a
2020	4	Optimistic	700	700	n/a	n/a
2020	21	Special	1000	1000	n/a	n/a
2030	5, 6, 22, 23	Medium	2000	3000	3.0	2.25
2030	7	Optimistic	3000	4000	2.25	2.0
2040	8, 9, 10	Medium	4000	8000	2.0	1.80
2050	11, 12, 13	Medium	8000	15250	1.65	1.50
2050	14	Optimistic	1000	20000	1.50	1.50
2050	16, 18	Extreme	15250	40000	1.50	2.50
2050	24	Special	85000	85000	n/a	n/a
2050	25	Special	Unlimited	Unlimited	n/a	n/a
2050	29	Sensitivity	30000	Unlimited	1.4	1.2
2050	30	Sensitivity	Unlimited	Unlimited	1.0	1.0
Multiple	15, 19, 20, 26, 27, 28	Pessimistic	0	0	n/a	n/a

8 KEY FINDINGS

- New methodologies (based on existing knowledge and approaches used in the project team) were required to develop an appropriate framework for specifying deployment scenarios (and the sites within them) for tidal range and current technologies that are grounded in realism.
- The methodologies developed have been used to generate thirty energy extraction scenarios for implementation in the CSM. The scenarios include various combinations of tidal range and tidal current energy developments around the UK coastline.
- Application of the methodology for scheme specification within scenarios has created a decision-support tool that will be implemented in the CSM. This will provide enhanced flexibility and usability of the final product for the ETI.
- Scenario specification demonstrates the potential to generate over 100TWh/y of electricity from a combination of tidal barrage and lagoon developments (more than 25% of UK electricity demand in 2010).
- Additional electricity contributions from tidal current farms also have the potential to generate in the region of 100TWh/y of electricity, although it is already understood that achieving these levels of electricity generation has adverse measurable impact on the underlying tidal system.
- The physical overlap between identified sites for tidal range and tidal current deployment in UK waters is identified as being minimal, but this does not mean that there will not be hydrodynamic interactions between sites.
- The CSM, in conjunction with the scenario specifications, will provide the tools required to assess site interactions and the effects of various energy extraction scenarios on the wider environment, and whether these upper levels of energy extraction are practically achievable.

9 CONCLUSIONS AND RECOMMENDATIONS

A technical report of the work undertaken in Work Package 2 has been presented. The report provides an explanation and justification of

1. The framework for selecting scenarios.
2. The selection of schemes within each scenario.
3. The design and choice of the scenarios.
4. The design and choice of the technology sensitivity analysis scenarios.

A consistent method has been developed to provide a framework for scenario selection for tidal range and tidal current technologies. A two-dimensional matrix is used to prescribe the varying timeframe being considered (in ten year increments from 2010 to 2050), and the degree of alignment of external support to facilitate industry development in those years (optimistic, medium and pessimistic)). Additional scenarios that ignore this incremental development approach are also considered to enable assessment of projects that may have otherwise been ‘blocked’ by earlier development choices and to consider some of the most radical proposals that exist in the literature. These radical alternatives are included to ensure that all views are represented across the suite of scenario test-cases

A hierarchical decision making procedure is used to select schemes assuming early development of the most economic resource constrained by restrictions relating to technical feasibility, build rate and environmental impacts. Within the scenarios, the deployment of installed capacity is related to decisions made in the (proposed) preceding years.

The selection of schemes within a scenario required the development of a new automated procedure for tidal current technology specification due to the identified lack of input data appropriate to meet the needs of the ETI-TRM program. The automated approach will rely on data generated by the CSM to ensure that the input data imposed on the energy extraction modelling scenarios is of an appropriate resolution. The scenario specifications evolve from the proposed base case where no energy extraction is simulated, and grow incrementally towards maximum theoretical deployment of both technology options.

The scenario design and choices has been described in detail for thirty scenario specifications. The scenarios span a wide range of energy extraction levels for both tidal range and current technology approaches from zero deployment through to cases with the potential to meet over half of the existing UK annual electricity demand (although interaction effects at these levels of energy extraction are expected to be significant).

Finally, the provision of the scenario fact-sheets presents easy to use building blocks that can readily be re-arranged to generate additional scenarios. The fact-sheets provide a key mechanism for scenario implementation in the CSM.

NOTATION

a_0 = Amplitude of tidal height variation
a_1 = Amplitude of driving head in a hydraulic current regime
A = Cross section area
$A_{1sluice}$ = Sluice throat area
$A_{0sluice}$ = Sluice exit area
$A_{0turbine}$ = Turbine exit area
$A_{9m\ t}$ = Turbine swept area for 9m dia. Rolls-Royce turbines
$A_{14m\ t}$ = Turbine swept area for 14m dia. Rolls-Royce turbines
B_1,B_2,B_3,B_4 = Turbine discharge/head characteristics for head less than intermediate head
C_1,C_2,C_3,C_4 = Turbine discharge/head characteristics for head between intermediate head and rated head
C_E = Tidal current energy extraction coefficient
D = Turbine rotor diameter
E_1,E_2,E_3,E_4 = Turbine discharge/head characteristics for head above rated head
F_1,F_2,F_3,F_4 = Turbine power/head characteristics for head below rated head
g = Gravitational acceleration
h = Depth of water
H_{min} = Minimum operating head
H_{int} = Intermediate head
H_{rated} = Rated head
K = Free-running Rolls-Royce turbine discharge coefficient
L_1-L_{12}, H_1-H_{12} = Table of turbine starting heads (12 data pairs)
N_{sluice} = Number of sluices
$N_{turbine}$ = Number of turbines
$P_{acceptable}$ = Acceptable TEC related energy extraction limit
$P_{Theoretical,}$ = Theoretical TEC related energy extraction limit
P_{max} = Turbine power at rated head / generator capacity including turbine and shaft (gearbox) losses
$P_{KE}(m)$ = Mean kinetic power density
$P_{KE}(t)$ = Instantaneous kinetic power density
Q_{max} = Maximum flow discharge through a cross-sectional area
R_1,R_2,R_3,R_4 = Turbine discharge/head characteristics for 9m dia. Rolls-Royce turbines
S_1,S_2,S_3,S_4 = Turbine power/head characteristics for 9m dia. Rolls-Royce turbines
SCW = Width of sluice caisson
TCW = Width of turbine caisson
T = Period (of 1 or more complete Spring-Neap tidal cycles)
T_{start} = Turbine starting time
U = Depth-averaged velocity magnitude
U_{rated} = Rated velocity of a TEC device
U_1,U_2,U_3,U_4 = Turbine discharge/head characteristics for 14m dia. Rolls-Royce turbines
V_1,V_2,V_3,V_4 = Turbine power/head characteristics for 14m dia. Rolls-Royce turbines
α_{ebb} = Sluice discharge coefficient on ebb tide
α_{flood} = Sluice discharge coefficient on flood tide
β_{ebb} = Free-running turbine discharge coefficient on ebb tide
β_{flood} = free-running turbine discharge coefficient on flood tide
ρ = Fluid density

GLOSSARY

0-d model – zero-dimensional / flat estuary model. A 0-d model uses only two water levels (sea level and basin level). Sea level is a user defined input and, as such, the effect of barrage operations on sea levels is not represented. The basin level is calculated assuming that the water level upstream of the impoundment line is uniform.

1-d model – one-dimensional model. A 1-d model represents water levels in an estuary using a series of cross-sections. Hence water levels can vary moving upstream or downstream from the impoundment line but levels are uniform across the estuary. This means that the effect of a barrage/lagoon on downstream sea levels is represented to some extent.

2-d model – two-dimensional model. A 2-d model uses a mesh or grid to represent the sea and coastline. Water levels can vary both parallel and perpendicular to the coastline. As such, a 2-d model represents the constriction and expansion as water flows into and out of the basin, through the turbine and sluice caissons.

ADP – Acoustic Doppler Profiler.

AEP – Annual Energy Production.

Barrage – an impoundment line across an estuary comprising embankment, turbines and usually sluices. Electricity is generated by creating a water level differential across the barrage between the impounded basin and the open sea. Barrages and (coastal) lagoons are similar.

Basin – the impounded area, usually landside, within the barrage/lagoon alignment.

Capacity Factor - The capacity factor is the theoretical energy that a device will generate in a set period given a particular input resource divided by the total energy that the device would generate if operating at full load throughout the given period.

Cavitation – the formation and immediate implosion of cavities in water as it passes through turbines. Cavitation can cause significant damage to turbines and is prevented by providing adequate submergence (installing the turbines deep enough below low tide level).

CD - Chart Datum. This is the datum used to show levels on Admiralty charts and usually corresponds to lowest astronomical tide level.

CoE – Cost of Energy.

Cp – Device coefficient of performance, i.e. mechanical efficiency at which the device extracts energy from the incoming flow.

Dual mode generation – power generation on both the ebb and flood tides.

Ebb tide – the seaward flow of water as the tide level falls.

Embankment – an artificial bank used to intercept and prevent the passage of water, forcing it through the turbine and sluice caissons whilst they are open.

Energy yield – the amount of energy generated by a scheme, usually quoted as an annual total in watt hours.

Flood tide – the landward flow of water as the tide level rises.

Free-wheeling – when tidal range turbines are not generating power but the turbine passage is kept open, which aids filling and emptying of the basin.

Generator capacity – maximum power output from each turbine unit, which usually includes an allowance for generator losses applied to the raw turbine power output.

GW – gigawatt, unit of power equal to one billion (109) watts.

GWh – gigawatt hours, unit of energy equal to one billion (109) watt hours. For constant power, energy in watt hours is the product of power (in watts) and time (in hours).

HAA – Horizontal Axis Axial flow turbine.

HAC – Horizontal Axis Cross flow turbine.

HC – Hydraulic current system.

Head – the hydraulic head, which is equal to the elevation plus velocity head (v^2/2g), where v is velocity and g is gravitational acceleration. Head is often used to indicate the total head difference across the barrage/lagoon structure.

Headloss – loss of energy experienced by the water flow as it moves through a constriction. Headlosses will occur as water passes through turbines and sluice gates channels or where bed levels are shallow.

Hill chart – turbine performance chart relating head, flow and efficiency, usually shown in non-dimensional form.

Impoundment length – the total length of the barrage/lagoon alignment including embankments, turbine and sluice caissons.

Installed capacity – the total peak power output of the turbine generators (equal to number of turbines multiplied by unit generator capacity).

Intertidal area – seabed of estuary or coastline exposed at low tide but submerged at high tide.

Lagoon (coastal) – similar to a barrage except that the impoundment line can be connected to any coastline rather than specifically across an estuary. A lagoon, therefore, will usually require a longer embankment than a barrage to give the same impounded area.

Lagoon (offshore) – an impoundment that is not connected to the coastline. An offshore lagoon must, therefore, be enclosed on all sides by an artificial embankment.

Majoration – increased efficiency for tidal range turbine due to larger turbine size (compared to the scale model on which the turbine hill chart is based). The increasing efficiency with increasing turbine size is due to larger gaps between the blades and fixed parts within the turbine.

MSL – Mean Sea Level.

MW – megawatt, equal to one million (106) watts.

MWh – megawatt hours, unit of energy equal to one million (106) watt hours.

Outages – times when turbines are unavailable for power generation. This may be due to routine maintenance or malfunction of some or all of the turbines.

PD – Power Density.

Pmax – The maximum total mean power harvested across the tidal cycle considered for a specified tidal system.

Practical Resource – The energy (which is a proportion of the technical resource) that can be harvested after consideration of external constraints (e.g. grid accessibility, competing uses such as MOD, shipping lanes, etc.). This level of assessment fundamentally requires detailed project design and investigation on a case-by-case basis. The practical resource is hence a proportion of the technical resource.

Qmax – The mean of the local maximum volume fluxes (m^3/s) for a particular tidal system over the tidal cycle considered.

Rated head – the lowest head difference across tidal range turbines for which the power output is equal to the generator capacity.

RES – resonant (basin) system.

Runner – the rotating part of a turbine. Energy is transferred from the water flowing through the turbine by the force on the turbine blades spinning the runner and driving the turbine generator.

TEC – Tidal Energy Converter, a device which captures energy from tidal currents.

Technical Resource – The energy that can be harvested from tidal currents using envisaged technology options and restrictions (including project economics) without undue impact on the underlying tidal hydrodynamic environment. The technical resource is hence a proportion of the theoretical resource.

Theoretical Resource – Maximum energy that can be harvested from tidal currents in the region of interest without consideration of technical, economic or environmental constraints.

Tidal Current – where Tidal Stream is referred to in the Scope of Works it is replaced with Tidal Current within the Tidal Resource Modelling reporting. This is due to a general acceptance that there are three hydraulic mechanisms which, combined, accurately define the hydraulics. Tidal Stream is one of the three hydraulic mechanisms, therefore to complete the Tidal Resource Modelling credibly and accurately, Tidal Current will be used and referred to.

Tidal Prism – the volume of water within an area (such as an estuary) between low and high tide level.

Total Resource – Total energy that exists within a defined tidal system.

TS – Tidal streaming.

TW - terawatt, equal to one trillion (1012) watts.

TWh – terawatt hours, unit of energy equal to one trillion (1012) watt hours.

Vmnp (m/s) – Mean neap peak velocity as defined by the Admiralty charts for a particular site, 5 m below the surface.

Vmsp (m/s) – Mean spring peak velocity as defined by the Admiralty charts for a particular site, 5 m below surface.

Vrated (m/s) – Rated velocity of tidal stream device. Rated velocity is the velocity at which the device reaches maximum (rated) output.

REFERENCES

ABPmer (2011); "WEBvision Renewables (Tide)" http://vision.abpmer.net/renewables/map_default.phtml.

ABPmer, The Met Office & Proudman Oceanic Laboratory (2008); "BERR Atlas of UK Marine Energy Resources". http://www.renewables-atlas.info/.

Binnie, Black & Veatch in association with IT Power Ltd (2001); "The Commercial Prospects for Tidal Stream Power". *ETSU T/06/00209/REP. DTI/Pub URN 01/1011*.

Burrows, R., Walkington, I.A., Yates, N.C., Hedges, T.S., Wolf, J. & Holt, J. (2009); "The tidal range energy potential of the West Coast of the United Kingdom". *Applied Ocean Research*, **31**, pp, 229-238. doi:10.1016/j.apor.2009.10.002.

Carbon Trust (2005); "Tidal Stream - Phase II UK Tidal Stream Energy Resource Assessment: A Report by Black and Veatch to the Carbon Trust's Marine Energy Challenge".

Carbon Trust (2011(a)); "UK Tidal Current Resource and Economics". *Carbon Trust CTC799*, 163 pp. http://www.carbontrust.co.uk/Publications/pages/publicationdetail.aspx?id=CTC799.

Carbon Trust (2011(b)); "Accelerating marine energy: The potential for cost reduction – insights from the Carbon Trust Marine Energy Accelerator". *Carbon Trust CTC797*, http://www.carbontrust.co.uk/Publications/pages/PublicationDetail.aspx?id=CTC797.

Committee on Climate Change (2011); "The Renewable Energy Review". http://hmccc.s3.amazonaws.com/Renewables%20Review/The%20renewable%20energy%20review_Printout.pdf.

Crown Estate (2011); "Wave and tidal energy in the Pentland Firth and Orkney waters: How the project could be built: A report commissioned by The Crown Estate and prepared by BVG Associates". http://www.thecrownestate.co.uk/tcform/TandCsDialog?f=/media/71431/pentland_firth_how_the_projects_could_be_built.pdf&fn=Pentland+Firth+and+Orkney+-+How+the+projects+could+be+built&m=1.

Department of Energy and Climate Change (2010(a)); "Severn Tidal Power: Feasibility Study Conclusions and Summary Report" http://www.decc.gov.uk/assets/decc/What we do/UK energy supply/Energy mix/Renewable energy/severn-tp/621-severn-tidal-power-feasibility-study-conclusions-a.pdf.

Department of Energy and Climate Change (2010(b)) "UK National Renewable Energy Action Plan (NREAP)". http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/renewable%20energy/ored/25-nat-ren-energy-action-plan.pdf

Department of Energy and Climate Change (2011(a)); "Consultation on proposals for the levels of banded support under the Renewables Obligation for the period 2013-17 and the Renewables Obligation Order 2012". URN 11D/876, http://www.decc.gov.uk/media/viewfile.ashx?filetype=4&filepath=11/consultation/ro-banding/3235-consultation-ro-banding.pdf&minwidth=true.

Department of Energy & Climate Change (2011(b)); "Digest of United Kingdom Energy Statistics 2011". *The Stationary Office*, 258 pp. ISBN 9780115155277

ETI & UK Energy Research Centre (2010); "Marine Energy Technology Roadmap" http://www.energytechnologies.co.uk/Home/Technology-Programmes/marine.aspx.

ETSU (1993); "Tidal stream energy review". *Technical report ETSU-T-05/00155/REP, Harwell Laboratory, Energy Technology Support Unit, DTI.*

European Commission (1996); "The exploitation of tidal and marine currents. Wave energy. Project results. Technical report EUR 16683 EN, Commission of the European Communities. Directorate-General for Science, Research and Development.

European Ocean Energy Association (2010); "Oceans of energy: European Ocean Energy Roadmap 2010-2050". http://www.eu-oea.com/euoea/files/ccLibraryFiles/Filename/000000000827/ocean vectorise 10 mai 2010.pdf.

Forum for Renewable Energy Development in Scotland (FREDS) (2004); "Marine Energy Group (MEG) Report 2004: Harnessing Scotland's Marine Energy Potential". *Scottish Executive*, http://www.scotland.gov.uk/Resource/Doc/1086/0006191.pdf.

Forum for Renewable Energy Development in Scotland (FREDS) Marine Energy Group (MEG) (2009); "Marine Energy Roadmap". *Scottish Government*, ISBN 978 0 7559 9083 2 (web only publication). http://www.scotland.gov.uk/Resource/Doc/281865/0085187.pdf.

Korean Broadcasting Service (2011); "Ceremony held to commemorate Sihwa Tidal Power Plant operation". *KBS World*, http://world.kbs.co.kr/english/news/news_Dm_detail.htm?No=84144&id=Dm.

Korean Broadcasting Service (2011); "Tidal power generation, a new engine for green growth". *KBS World*, http://world.kbs.co.kr/english/news/news_issue_detail.htm?No=22469.

MacKay, D.J.C. (2009); "Sustainable Energy – Without the Hot Air" *UIT Cambridge*, 368 pp. ISBN: 978-0-9544529-3-3.

Myers, L.E. & Bahaj, A.S. (2010): "Experimental analysis of the flow field around horizontal axis tidal turbines by use of scale mesh disk rotor simulations". *Ocean Engineering*, **37**, pp. 218-227. doi:10.1016/j.oceaneng.2009.11.004.

Poyry (2011); "Analysing technical constraints on renewable generation to 2050". *A report to the Committee on Climate Change*, http://hmccc.s3.amazonaws.com/Renewables%20Review/232_Report_Analysing%20the%20technical%20constraints%20on%20renewable%20generation_v8_0.pdf.

renewableUK (2010); "Channelling the Energy: A Way Forward for the UK Wave & Tidal Industry Towards 2020". http://www.bwea.com/pdf/marine/RenewableUK_MarineReport_Channeling-the-energy.pdf.

renewableUK (2011); "SeaPower: Funding the Marine Energy Industry 2011-2015". http://www.bwea.com/pdf/marine/SeaPower_Fund_Paper.pdf.

Roc, T., Thyng, K., Conley, D. & Greaves, D. (2011) "Applying a numerical decision-making tool for tidal current turbine (TCT) planning – Early Results". *Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC) 2011, Southampton.*

Rollings, E. (2011); "MeyGen Tidal Energy Project EIA Scoping Document (revision 1.7)". *MeyGen Phase 2 Tidal Energy Project*, http://www.scotland.gov.uk/Resource/Doc/295194/0121858.pdf.

Salter, S. (2009); "Correcting the Under-estimate of the Tidal Stream Resource of the Pentland Firth". *Proceedings of the 8th European Wave and Tidal Energy Conference (EWTEC) 2009, Uppsala, Sweden.*

Sanakran Iyer (2011); "New methodologies and scenarios for tidal current energy in the UK". *University of Edinburgh PhD thesis*.

Shapiro, G.I. ("011); "Effects of tidal stream power generation on the region-wide circulation in a shallow sea". *Ocean Sci.*,**7**, pp.165-174. doi:10.5194/osd-7-165-2011.

Shepard, D. (1968); "A two-dimensional interpolation function for irregularly-spaced data". *Proc. ACM National Conference.*

Sustainable Development Commission (2007); "Turning the Tide, Tidal Power in the UK". http://www.sd-commission.org.uk/data/files/publications/Tidal_Power_in_the_UK_Oct07.pdf.
The British Wind Energy Association (2006); "The Path to Power: Delivering confidence in Britain's wave and tidal stream industry". http://www.bwea.com/pathtopower/.

The Offshore Valuation Group (2010); "The Offshore Valuation: A valuation of the UK's offshore renewable energy resource". *Public Interest Research Centre on behalf of The Offshore Valuation Group*, 108 pp. ISBN: 978-0-9503648-8-9.

UK Energy Research Centre (2009); "Decarbonising the UK Energy System: Accelerated Development of Low Carbon Energy Supply Technologies". UKERC Energy 2050 Research Report No. 2, Version 2. 156 pp. http://www.ukerc.ac.uk/Downloads/PDF/U/UKERCEnergy2050/TAcceleration_Draft.pdf.

United Kingdom Hydrographic Office (2004); "TotalTide Software".

GUIDE TO APPENDICES

Appendix A – Details of tidal range site identification and technology matching.

Appendix B – Exceedance curves for selected first generation tidal current energy locations.

APPENDIX A – DETAILS OF TIDAL RANGE SITE IDENTIFICATION AND TECHNOLOGY MATCHING.

Table A1 Summary of ebb-only conventional turbines scheme selection

					Turbine selection		Suggested installed capacity			Sluices		Min. tidal range inside basin		
	Location	Basin area (km^2)	Impoundment length (km)	Mean tidal range (m)	Turbine dia. (m)	Turbine unit capacity (MW)	No. of turbines	Total installed capacity (MW)	Indicative energy output (TWh/yr)	No.	Size		GWh/yr per turbine	GWh/yr per km impoundment
1	Solway Firth	814	28	5.6	9.0	29	200	5,800	12.1	226	12m x 12m	44%	61	426
2	Duddon	32	6	5.8	-	-	-	-	-	-	-	-		
3	Morecambe Bay	455	18	6.2	9.0	16	120	1,920	6.2	140	12m x 12m	39%	52	336
4	Mersey	56	2	6.5	8.0	25	28	700	1.3	18	12m x 12m	68%	45	700
5	Dee	103	8	5.9	8.0	21	40	840	1.6	40	8m x 12m	68%	39	189
6	Severn - outer	1060	20	7.0	9.0	40	370	14,800	28.9	320	12m x 12m	50%	78	1446
7	Severn - Cardiff-Weston	504	16	7.9	9.0	40	216	8,640	18.8	166	12m x 12m	49%	87	1177
8	Thames	160	8	4.2	9.0	20	32	640	1.1	32	12m x 12m	53%	35	138
9	Wash	650	19	4.8	9.0	23	120	2,760	5.1	140	12m x 12m	48%	42	264
10	Humber	292	7	4.3	9.0	20	60	1,200	2.2	80	12m x 12m	51%	37	307
11	Wigtown Bay lagoon	163	15	4.8										
12	Kirkcudbright Bay lagoon	16	4	5.1										
13	Cumbria lagoon	62	20	5.5										
14	Dee-Wirral lagoon	268	37	5.9										
15	Oxwich Bay lagoon	14	6	6.1										
16	West Aberthaw lagoon	30	13	7.5										
17	Rhoose lagoon	25	12	7.5										
18	Bridgwater Bay lagoon	90	16	8.3										
19	Morte Bay lagoon	12	5	5.5										
20	Rye Bay lagoon	103	25	5.2										
21	Dymchurch lagoon	103	23	5.2										

Table A2 Summary of dual mode, conventional turbines scheme selection

					Turbine selection		Suggested installed capacity			Min.		
	Location	Basin area (km^2)	Impoundment length (km)	Mean tidal range (m)	Turbine dia. (m)	Turbine unit capacity (MW)	No. of turbines	Total installed capacity (MW)	Indicative energy output (TWh/yr)	tidal range inside basin	GWh/yr per turbine	GWh/yr per km impoundment
1	Solway Firth	814	28	5.6	9.0	18	1100	19,800	31.0	83%	28	1092
2	Duddon	32	6	5.8	-	-	-	-	-	-		
3	Morecambe Bay	455	18	6.2	-	-	-	-	-	-		
4	Mersey	56	2	6.5	9.0	18	25	450	0.9	80%	34	478
5	Dee	103	8	5.9	9.0	18	60	1,080	2.2	80%	36	259
6	Severn - outer	1060	20	7.0	9.0	18	875	15,750	45.0	80%	51	2250
7	Severn - Cardiff-Weston	504	16	7.9	-	-	-	-	-	-		
8	Thames	160	8	4.2	-	-	-	-	-	-		
9	Wash	650	19	4.8	9.0	14	350	4,900	8.5	80%	24	440
10	Humber	292	7	4.3	-	-	-	-	-	-		
11	Wigtown Bay lagoon	163	15	4.8	9.0	14	160	2,240	3.8	80%	24	261
12	Kirkcudbright Bay lagoon	16	4	5.1	9.0	18	14	252	0.4	80%	27	95
13	Cumbria lagoon	62	20	5.5	9.0	18	70	1,260	2.2	82%	31	108
14	Dee-Wirral lagoon	268	37	5.9	9.0	18	250	4,500	9.0	80%	36	244
15	Oxwich Bay lagoon	14	6	6.1	9.0	22	16	352	0.6	80%	39	102
16	West Aberthaw lagoon	30	13	7.5	9.0	27	45	1,215	2.3	82%	52	174
17	Rhoose lagoon	25	12	7.5	9.0	27	40	1,080	2.0	82%	49	158
18	Bridgwater Bay lagoon	90	16	8.3	9.0	30	120	3,600	6.9	81%	58	435
19	Morte Bay lagoon	12	5	5.5	9.0	18	14	252	0.4	83%	31	88
20	Rye Bay lagoon	103	25	5.2	9.0	18	110	1,980	3.2	80%	29	126
21	Dymchurch lagoon	103	23	5.2	9.0	18	110	1,980	3.2	80%	29	137

Table A3 Summary of dual mode, Rolls-Royce turbines scheme selection

					Suggested installed capacity						
	Location	Basin area (km^2)	Impoundment length (km)	Mean tidal range (m)	No. of 14m dia. turbines	No. of 9m dia. turbines	Indicative max. output (MW)	Indicative energy output (TWh/yr)	Min. tidal range inside basin	GWh/yr per turbine	GWh/yr per km impoundment
1	Solway Firth	814	28	5.6	750	0	6,790	20.8	80%	28	732
2	Duddon	32	6	5.8	-	-	-	-	-		
3	Morecambe Bay	455	18	6.2	320	0	3,670	10.5	80%	33	568
4	Mersey	56	2	6.5	40	0	570	1.4	80%	35	767
5	Dee	103	8	5.9	55	0	740	1.7	81%	31	206
6	Severn - outer	1060	20	7.0	800	352	7,540	24.1	75%	21	1207
7	Severn - Cardiff-Weston	504	19	7.9	165	900	5,130	17.0	80%	16	912
8	Thames	160	8	4.2	90	20	530	1.8	80%	16	216
9	Wash	650	19	4.8	400	0	3,150	8.3	80%	21	431
10	Humber	292	7	4.3	200	0	1,340	3.7	80%	18	507
11	Wigtown Bay lagoon	163	15	4.8	140	0	1,160	3.2	80%	23	221
12	Kirkcudbright Bay lagoon	16	4	5.1	12	0	110	0.3	80%	25	75
13	Cumbria lagoon	62	20	5.5	60	0	450	1.6	80%	27	80
14	Dee-Wirral lagoon	268	37	5.9	220	0	2,360	6.9	80%	32	187
15	Oxwich Bay lagoon	14	6	6.1	16	0	190	0.5	82%	33	84
16	West Aberthaw lagoon	30	13	7.5	40	0	580	1.7	82%	42	124
17	Rhoose lagoon	25	12	7.5	30	0	410	1.3	80%	42	101
18	Bridgwater Bay lagoon	90	16	8.3	110	0	1,500	4.1	90%	37	257
19	Morte Bay lagoon	12	5	5.5	14	0	140	0.4	84%	27	76
20	Rye Bay lagoon	103	25	5.2	100	0	780	2.5	80%	25	102
21	Dymchurch lagoon	103	23	5.2	100	0	780	2.5	80%	25	110

APPENDIX B – EXCEEDANCE CURVES FOR SELECTED FIRST GENERATION TIDAL CURRENT ENERGY LOCATIONS.

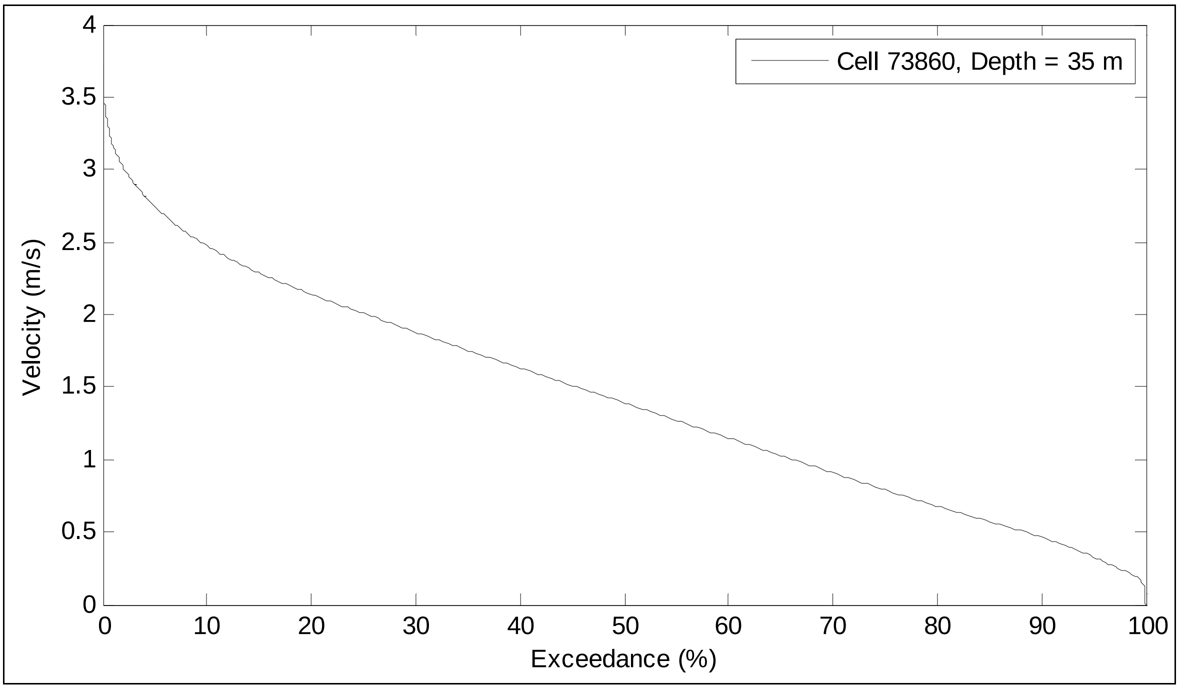


Figure B1: Ness of Duncansby (Scottish Power Renewables UK Limited)

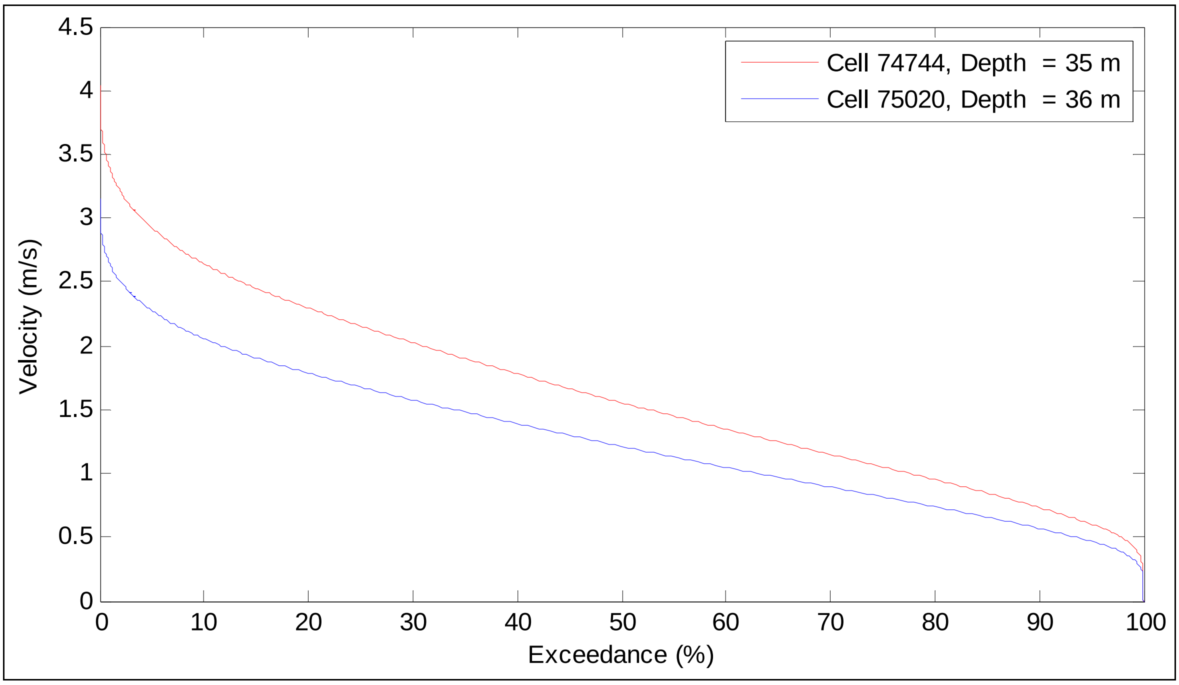


Figure B2: Brough Ness (SeaGeneration (Brough Ness) Ltd.)

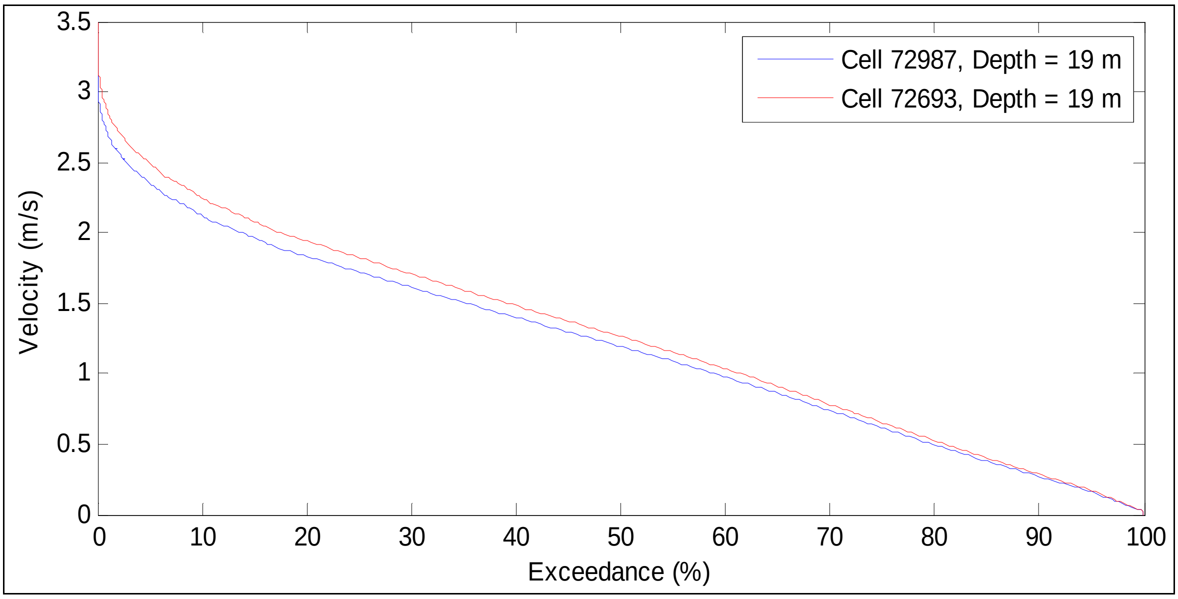


Figure B3: Inner Sound (Meygen Ltd.)

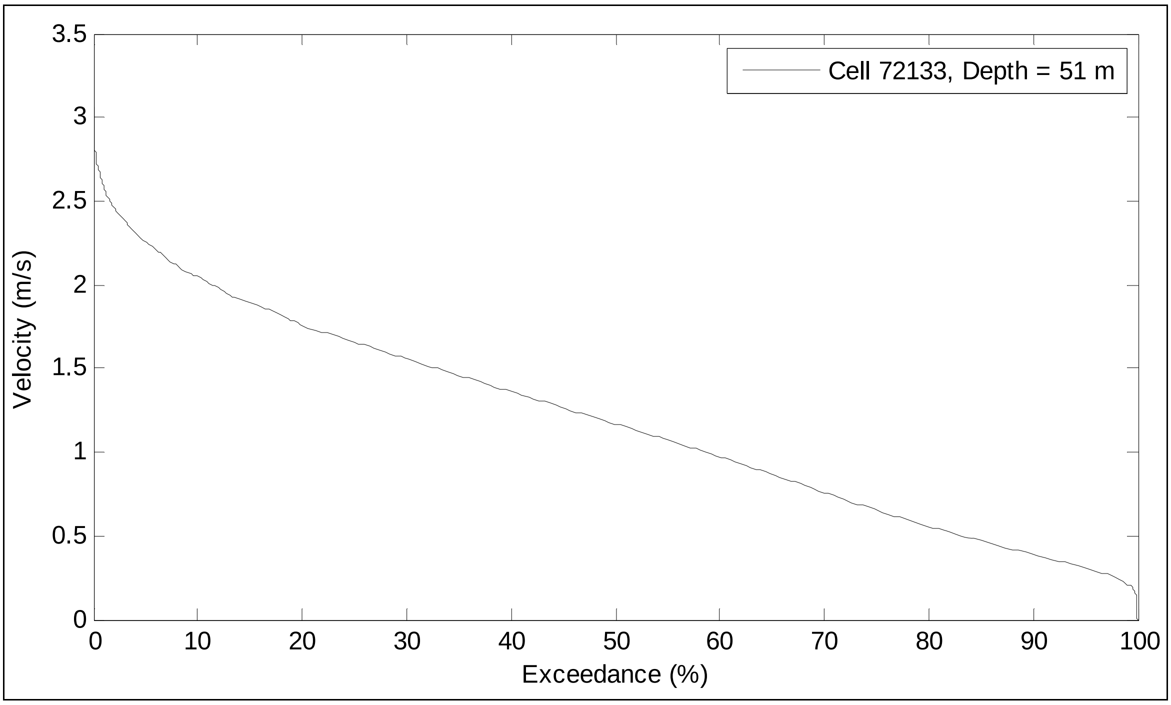


Figure B4 Cantick Head (Cantick Head Tidal Development Ltd.)

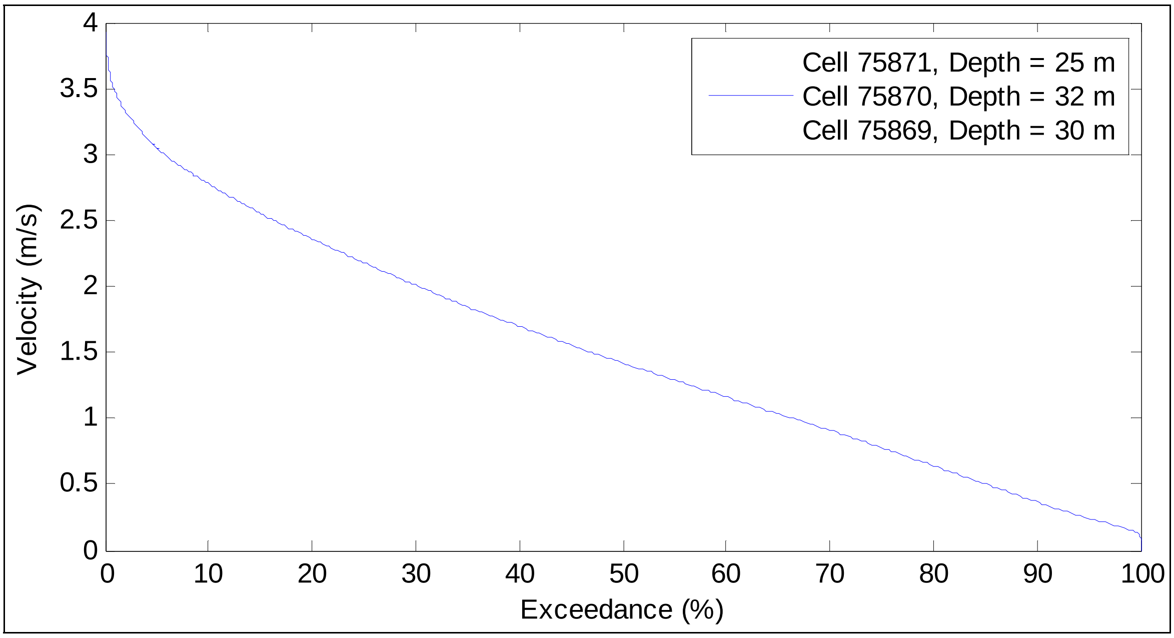


Figure B5: Westray Firth (central) (SSE Renewables Developments (UK) Limited)

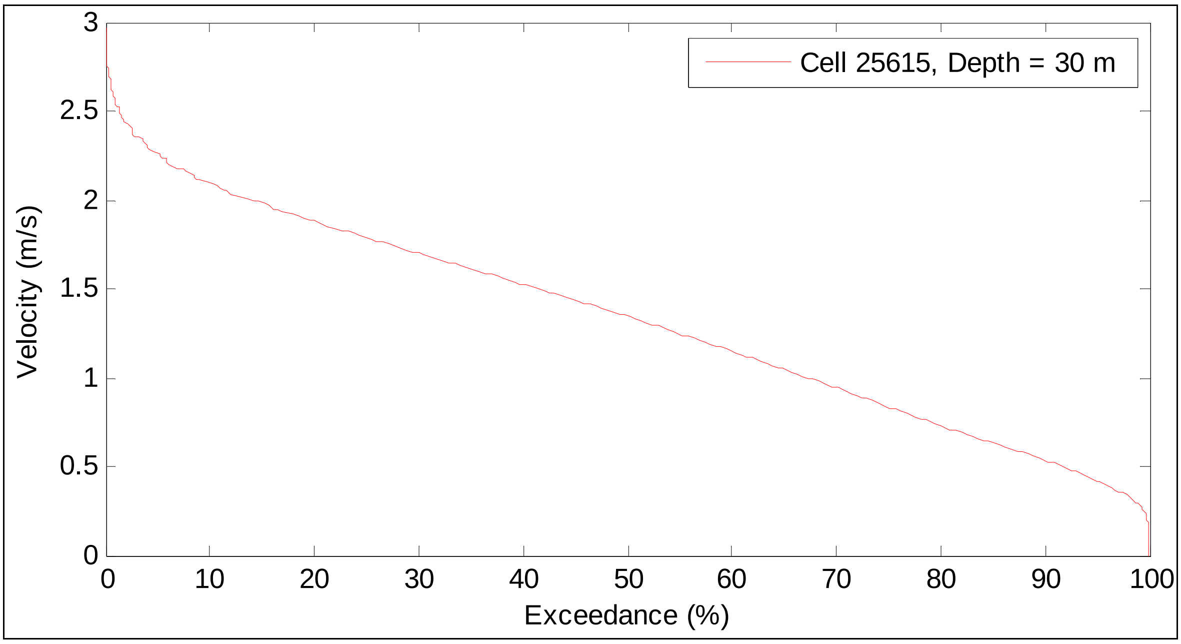


Figure B6: Islay/Mull of OA

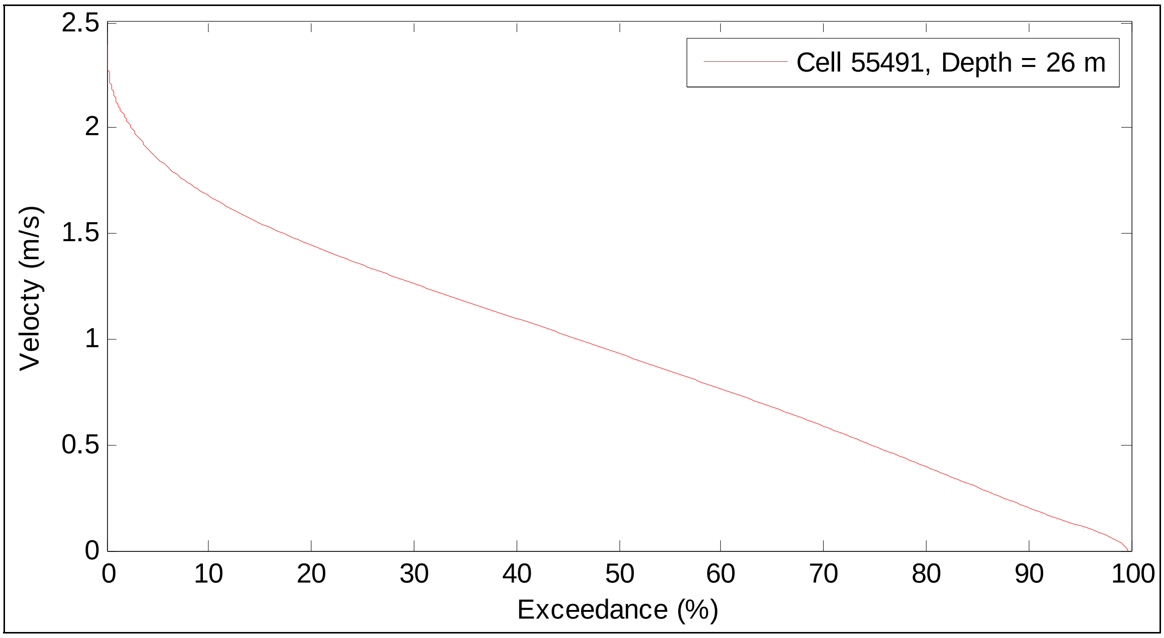


Figure B7: Carmel Head (Anglesey)

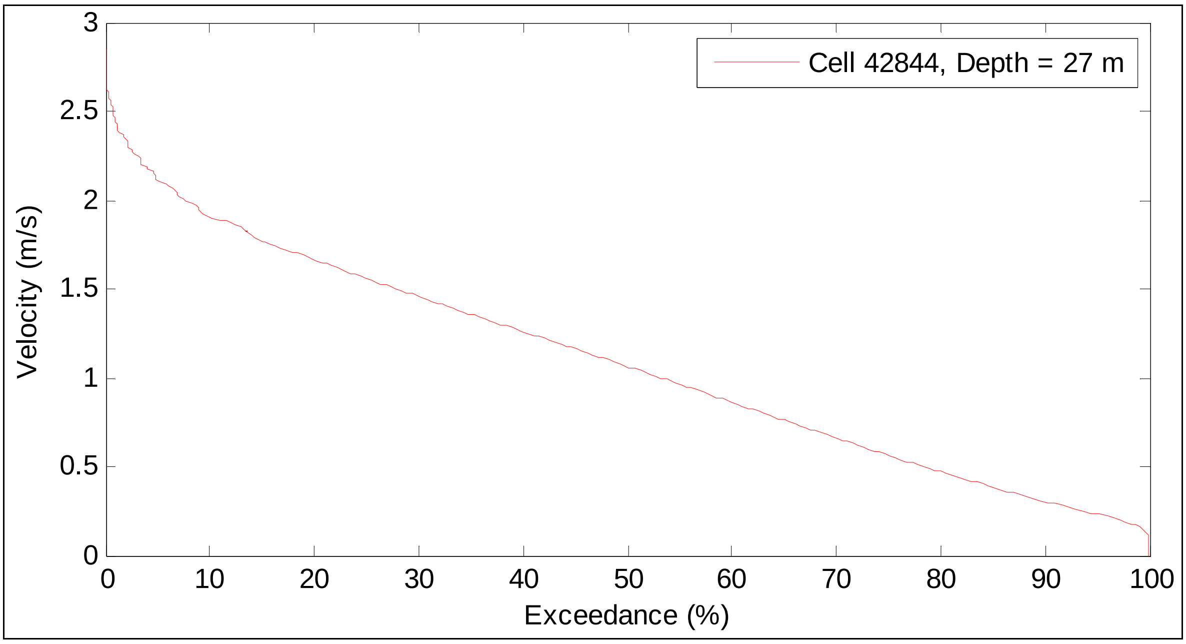


Figure B8: Ramsey Island

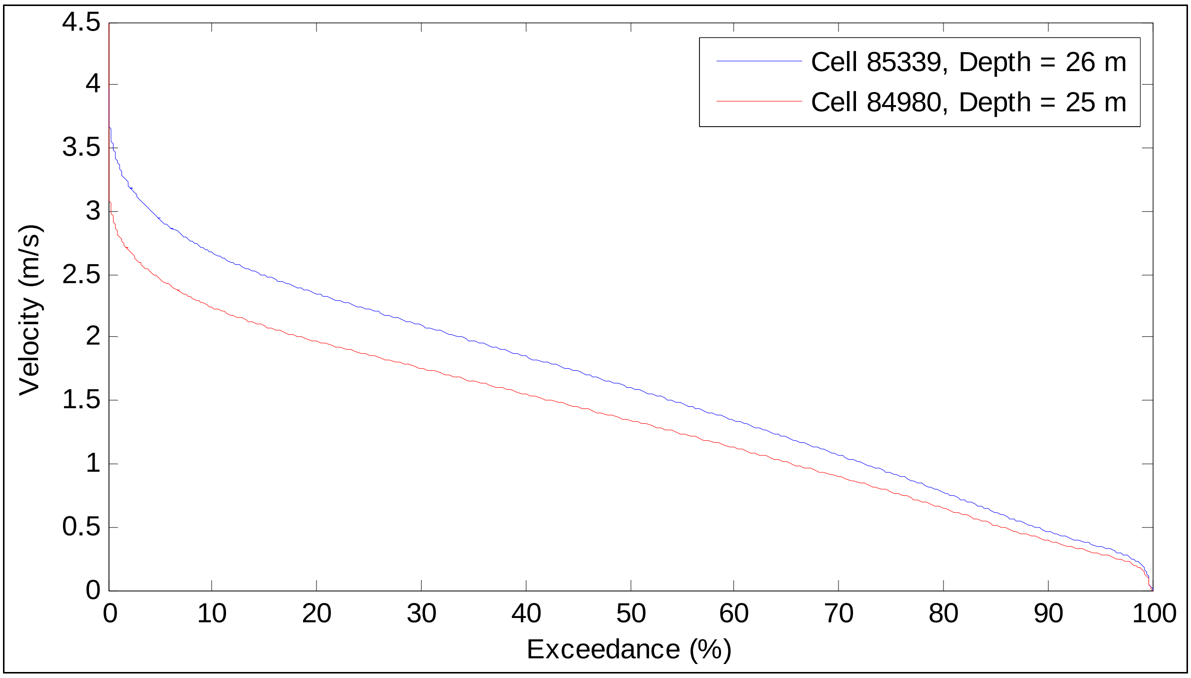


Figure B9: Race of Alderney