**Programme Area:** Marine

**Project:** Tidal Modelling

# Title: Continental Shelf Model Requirements Document

## Abstract:

This deliverable is number 2 of 10 in the Tidal Modelling project and captures the requirements for two Continental Shelf hydrodynamics models (CSM). The report describes the technical specifications, assumptions, requirements and exploitation of both the Coarse- and Detailed-resolution versions of the CSM (CCSM and DCSM respectively). The technical specifications are primarily intended for model

developers, whereas the description of the assumptions, requirements and exploitation of the CSM are intended to inform potential users. 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)

**PM01.02**
## Continental Shelf Model Requirements Specification

13th January 2012

Version 3.0

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

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## CONTENTS

## TABLE OF FIGURES

# 1 EXECUTIVE SUMMARY

The *Energy Technologies Institute* (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). B&V has a very broad and in-depth experience of both tidal range and tidal current projects, including resource assessment and project development, technology development, due diligence, cost of energy and policy development. Through working on these projects, it has 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 flows using the TELEMAC system 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 HRW and other partners such as Electricité de France and the Federal Waterways Engineering and Research Institute of Germany (pertinent information related to the TELEMAC system and, in particular, to the 2D module used in this project is given in Section 3.2). HRW's expertise is acknowledged within the UK tidal modelling community as the only entity with an in-depth experience of TELEMAC and its tailoring to specific problems.

The 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 (RAE 2008), the School was ranked third in the UK for combined research quality and quantity.

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

- How will the impacts of tidal range and tidal current energy schemes positioned around the UK combine to form an overall effect?
- Will the extraction of tidal energy resources in one area affect the tidal energy resources at distant sites around the UK and Europe?
- What constraints might these interactions place on the design, development and location of future systems?

This is achieved through a series of work packages and, ultimately, 10 deliverables outlined below.

D01 – Tidal resource characterisation
D02 – Continental Shelf Model (CSM) requirements specification document
D03 – Scenarios modelling
D04 – Cost of Energy Model and supporting documentation
D05 – Interface specification for detailed tidal current model 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 forms D02 – Continental Shelf Model (CSM) Requirements Specification document. As such it describes the technical specifications, assumptions, requirements and exploitation of both the Coarse- and Detailed-resolution versions of the CSM (CCSM and DCSM respectively). The technical specifications are primarily intended for model developers; the description of the assumptions, requirements and exploitation of the CSM are intended to inform potential users. We can therefore confirm that the acceptance criteria for D02 – CSM Requirements Specification have been met.

The development of the CSM is presented here in three steps.

1. The first step in developing a Continental Shelf Model of the UK waters is model set-up: extent, resolution, seabed map, forcing.

   *CSM extent*

   In order to include all (potential) sites and to cater for long-range impacts and interactions between energy schemes, the CSM will not only cover the UK waters but will extend offshore slightly beyond the Northern European continental shelf (defined principally by the 300 m depth contour), including the coastlines of the United Kingdom, Ireland, the Channel Islands, France, Belgium, the Netherlands, Germany, Denmark, Sweden and Norway. It will include amongst others the Malin Sea, Irish Sea, Celtic Sea, English Channel and the North Sea. Recent publications (Burrows, 2009; Cornett, 2011) have indeed indicated that relatively small projects can affect very distant locations. The Baltic Sea will not be included in the model because of its very limited tidal range and maximum mean spring tidal current velocities (Carlsson, 1997). An annual mean discharge will, however, be imposed as an inflow in the model. The anticipated model coverage is illustrated in Figure 1.

   *Resolution and exclusions*

   The level of detail with which the coastline and islands are represented in the CSM depends largely on the local resolution. The resolution threshold is such that the perimeter of an island will have to be defined by a contour of at least 5 nodes (a pentagon of appropriate shape). In other terms, the perimeter should be at least 5 times the local resolution of the CSM. If the island is smaller it will only be represented in the CSM as a bump in the seabed, with bathymetric elevations averaged/interpolated over the CSM resolution. Similarly the resolution threshold is set such that a passage will have to be defined with at least 3 nodes (v- or u-shaped passage), and therefore that an opening of less than 2 times the local resolution of the CSM will be excluded from the CSM. Section 3.1.2.2 gives examples for clarity. Islands and water bodies excluded from the model because they are too small for the chosen local resolution are expected to have a negligible contribution to the tidal flows at the scale of the continental shelf.

   The resolution of the CSM will vary spatially. It is anticipated that:

   - The CCSM resolution will range from c. 50 km at the offshore boundary to c. 1 km at the locations of selected tidal range and tidal current energy schemes. The total number of prediction points should not exceed 50 thousand.
   - The DCSM resolution will range from c. 10 km at the offshore boundary to c. 200 m at energy scheme sites. The total number of prediction points should not exceed 5 million.

   It is noted that, while the resolution of the DCSM will provide more detailed predictions than that of the CCSM, its purpose, like the CCSM, is primarily to provide preliminary impact assessment results for the entire Northern European continental shelf. It should not be used in place of a refined local model when considering resources / impacts in specific areas.

Previous modelling experience related to various areas of interest for tidal currents, by all members of the project team, has shown that the resolution outlined above should allow a good representation of the tidal flows and therefore of the interactions between tidal energy schemes, as well as a technically robust yet accessible and useable tool. It may become opportune to adjust the resolution of the CSM during its development to match the fact that the CCSM is intended to be run on a standard desktop computer while the DCSM will require the use of a high performance cluster of computers.

*Seabed map and datum*

Admiralty Chart data will be processed and provided by SeaZone of HRW to develop the CSM seabed map up to *Mean High Water Springs* (MHWS). This will enable the CSM to adequately predict the volumes of water leaving and entering estuaries/inlets on ebb and flood flows. The level of detail included in the charts is deemed sufficient for the purpose of the CSM, given its resolution.

The CSM will be developed in the spherical coordinate system (Latitude, Longitude), Ellipsoid WGS84. The vertical datum will be *Mean Sea Level* (MSL).

*Tidal forcing*

The CSM will be driven by spatially varying time histories of water levels along the model boundaries. The time histories will be derived from tidal synthesis based on the harmonic constituents available from the TPXO dataset. The TPXO dataset is one of the most accurate global models of ocean tides (OSU, 2008). It is based on a best-fit of tidal levels measured along remote sensing tracks from the TOPEX/POSEIDON satellite project in operation since 2002. The 13 constituents derived from complex harmonic analysis of observed levels (8 primary, 2 long-period and 3 non-linear constituents) are by definition clean of atmospheric and surge variations, as these variations would not be part of the astronomical periods against which the tidal harmonics are being predicted. A refined version of the TPXO dataset exists for the Northern European continental shelf, which has been validated against the available tide gauge data. This dataset is deemed adequate to define tidal levels in deep water, in the Atlantic Ocean.

A long period (between 45 and 90 days) will be used to validate the CSM against available (published and measured) data. A 20-year average spring-neap 15-day cycle will be used to model the scenarios (details in Section 3.1.7.3).

2. The second step in developing a CSM of the UK waters is validation.

   At this stage, it is envisaged that tidal levels recorded as part of the UK tidal gauge network (UKTGN, 2011) and those made available through the *Système d'Observation du Niveau des Eaux Littorales* (SONEL) programme outside the UK will be used to calibrate and validate the CSM. Although data are available for more stations, it is anticipated that in the order of 20 stations could be used in this project to keep model calibration manageable. Additional comparisons with satellite altimeter data may be presented, in particular in terms of spatial maps of tidal range / current speed, but these comparisons can only be regarded as secondary validation. Time records of observed current velocity are harder to find and often proprietary. They would, however, provide a valuable contribution to the model verification and confidence in the CSM predictions for tidal currents. Efforts will therefore be made to identify suitable current velocity time records and use them to further validate the CSM.

A base case of the model, referred to as base case scenario, will be developed where the existing environment is represented in the CSM. This version will not include the implementation of future or proposed energy schemes, but will include existing energy schemes such as La Rance tidal power plant, based on known information and / or assumptions made on operating procedures. Harmonic constituents will be extracted from the CSM outputs (levels) and compared to constituents at observation sites. This approach is particularly relevant, as opposed to that consisting in comparing water levels directly, when validating the model against observed data, which include the effects of atmospheric and surge events. Harmonic constituents are, by definition, clean of these external factors.

The number of harmonic constituents that can sensibly be extracted from a time record, and the reliability of those constituents, largely depend on its length. As a guide, five constituents can be obtained from a one-day record; 15 from 15 days; 26 from 29 days; 54 from 6 months and 60 from one year of data (Vassie, 1986). In this study, it is expected that the CSM will be run for calibration periods between 45 and 90 days, and will predict tidal levels with a higher number of harmonic constituents than that imposed at the boundary as shallow water and friction effects will introduce non-linear constituents at sites near the coast. It is noted that the IEC, a standard recognised by the marine renewable energy industry, TC114 August 2011 draft technical specification recommends that model and calibration data be compared on the basis of harmonic constituents for all constituents applied on the model driving boundary (13 in this case).

The development of the CSM will comply with the most recent international guidance from the IEC. In cases where the EMEC guidance is more stringent, it will be followed in place of the IEC TC114 August 2011 draft technical specification. In particular, there are no clear performance criteria to be met in the IEC TC114 August 2011 draft technical specification. The EMEC guidance considers a 20% error in peak velocities acceptable at pre-feasibility stage. This criterion could be used to assess the model performance where current data are available (bearing in mind the fact that for sites with rapid spatial variation in currents there will often be a significant difference between a spot measurement and a c. 200m cell-averaged prediction).

3. The third step in developing a CSM of the UK waters is the representation of tidal energy schemes in the model.

The CSM developed in this project is designed to be versatile. Implementation of various energy schemes by the end-user will be made possible by the use of generic parameterised formulations (details in Section 3.3) that represent tidal range and tidal current schemes at the scale and resolution of the CSM and cater for all types of technology, current and future. Similar (albeit less detailed) parameterised formulations have been used in the past and implemented in the TELEMAC system for practical applications.

The discharge through a tidal range scheme (by extension the power generated) is a function of the head and energy difference across the control structure and will be parameterised in the continuity equation as follows:

$$Q = D_1 + D_2\,\Delta h + D_3\,\Delta h^2 + D_4\,\Delta h^3 + D_5\,h\sqrt{\Delta h} + D_6\,\sqrt{\Delta h} + D_7\,\Delta u^2$$

where $Q$ is the discharge in m3/s, $\Delta h$ is the head difference in m, $h$ is the average water depth in m, $\Delta u^2$ relates to the energy difference and can be used to represent other energy losses, and where $D_1$ to $D_7$ are constants defined by the technology type, the operational procedures, the turbine capacity, the size, submergence and types of the openings and other key turbine parameters (refer Appendix B).

When tidal current devices are introduced in the hydrodynamic system, the system loses energy, whether the energy is extracted or whether drag forces are introduced. The various contributions for the loss of energy will be represented as additional body force terms, the sum of which will be $F_x$ and $F_y$ in the momentum equation presented in Section 3.2.3.1. These additional body force terms are a means of *parameterising* physical processes that occur at higher resolution than is used within the model. The parameterised terms replace small-scale physical processes (from the point of view of model resolution) with a continuous property applied across the area of the computational cell. Appendix A provides a detailed description of the parameterisation forms for modelling energy losses due to the introduction and operation of farms of TEC devices to be used in the CSM.

The model will incorporate a predefined method to produce maps that will allow the model/the user to identify tidal current sites and, subsequently, a similar method to identify tidal resource scenarios. A selection of scenarios around the UK coast (each representing a particular tidal energy extraction scheme) will be developed during the project, designed to help the user set up specific cases (see D03 – Scenarios modelling).

It is noted that, the formulations and associated parameters being generic, the user will be able to model other types of technologies in the CSM, even wind turbines (modelled as a drag force) should it be required to identify the likely impact of the civil works on the flow regime and its interaction with other schemes investigated in the CSM. Those users who acquire the CSM will also have access to the CSM source code and be able to modify the formulations as they see fit.

Finally users of the CSM will be able to include revisions to the seabed map representing dredging activities for example.

There will be two levels of graphical output produced by the CSM during the course of the project. The first level will include graphical outputs documenting primarily the validation of the CSM. The second level will include graphical outputs from the first level as well as those documenting the analysis of the interactions between selected scenarios around the UK coasts and of their potential impacts on European coasts.

The CSM results will be presented in the form of:

- Time histories of tidal levels (and where possible current velocity magnitudes and directions) at specific sites. Time histories illustrate the evolution of the level (speed) with the spring-neap tidal cycle as well as the comparison with validation data over the entire time period.
- Tidal ellipses. A tidal ellipse is a representation of the direction and strength of the flow throughout one or more tidal cycles and gives a good indication of the major current axis. These ellipses can highlight, for instance, the relative performance potential of the ebb and flood flows for a bi-directional turbine.
- Distributions of current velocities and exceedance curves. These plots are useful at the design/conception stage because they indicate the proportion of the time when (or probability that) the operational threshold of a turbine is exceeded, for instance.
- Colour contour maps at national or regional scale. These maps can be used to show spatial variations of maximum / mean depth-averaged current speeds, for example. They illustrate the impact resulting from the implementation of a tidal scheme (predicted depth-averaged current

speed and depth-averaged kinetic power density). They can also present the proportion of time when the predicted current speed exceeds a given threshold within the representative tidal period.

For tidal range energy schemes, a number of additional processed outputs will be generated specifically for use by the Cost of Energy (CoE) model (see D04 – Cost of Energy Model and supporting documentation). They will include, but may not be limited to, the following:

- Time histories of predicted free surface elevation for both spring and neap conditions, both upstream or downstream of the structure. They will inform the design and expected efficiency of the scheme.
- Bathymetric profiles showing the spatial variations of the seabed at the toe of the structure.
- Tables presenting estimates of the surface area covered by the water held behind a tidal range structure between *Mean Low Water Springs* (MLWS) and *Mean High Water Springs* (MHWS).
- Total energy yield for the average 15-day period.

All the outputs from the CSM are described in detail in Section 4, and those outputs required for the CoE model are provided in Appendix C.

It should be noted that spatially varying model output and processed outputs will be interpreted as contours in Shape File form (SHP) as published by the Economic and Social Research Institute and as Portable Network Graphic (PNG) picture form. Further, plots based on time histories will be extracted at specific locations of interest as comma separated value format (CSV) not necessarily related to the mesh node locations.

It is noted that the development of the tidal power industry is still at an early stage, particularly tidal current (although also technologies such as the Rolls-Royce tidal range turbine). The methodology described in this document may therefore need to be subject to update after the project has been completed as the resource and its response to power extraction become better understood (e.g. through knowledge gained from PerAWaT and the deployment of the first large-scale farms).

## 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.

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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 workpackages and, ultimately, 10 deliverables of which this report forms Deliverable 2 (D02) - which HRW, B&V and UoE have contributed to. The deliverables are outlined below.

D01 – Tidal resource characterisation
D02 – Continental Shelf Model (CSM) requirements specification document
D03 – Scenarios modelling
D04 – Cost of Energy Model and supporting documentation
D05 – Interface specification for detailed tidal current model 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 document describes the technical specifications, assumptions, requirements and exploitation of both the *coarse*- and *detailed*-resolution versions of the *Continental Shelf Model* (CCSM and DCSM respectively; CSM when either or both of the models are referred to). The technical specifications are primarily intended for model developers and are grouped in three categories: (a) the CSM inputs; (b) the CSM functional architecture; and (c) the CSM outputs. The description of the assumptions, requirements and exploitation of the CSM are intended to inform potential users.

The terminology is introduced below, with more emphasis and details in Sections 3 and 4.

## 2.1 CSM inputs

The CSM will be developed based on the TELEMAC system. As such it will rely on a number of inputs, split in this document in three distinct categories: (i) the CSM meshed domain, including spatial coverage, boundary locations, and resolution; (ii) the CSM static data inputs, including bathymetric maps, coastline, coordinate system; and (iii) the CSM dynamic data inputs, including the tidal forcing.

These inputs used together with the TELEMAC system will form a version of the CSM representing the existing conditions. This version will not include the implementation of future or proposed energy schemes, but will include existing energy schemes such as La Rance tidal power plant, based on known information and / or assumptions made on operating procedures. This configuration is hereafter referred to as “base case scenario”.

## 2.2 CSM functional architecture and associated user inputs

The application of the CSM to study the impact of tidal range and tidal current energy schemes requires that these schemes be represented and implemented within the TELEMAC source code, upon which the CSM is based. An energy scheme is represented in the model by a parameterised formulation, the parameters of which are provided by B&V and UoE. Different formulations represent different types of energy schemes or technologies; different parameters will represent variations in the setup, geographical location and extent of a given energy scheme or technology.

A parameterised formulation is defined by: (i) a logical algorithm or mathematical function; (ii) its interaction with the quantities considered and predicted by the TELEMAC system; and (iii) its user input parameters.

It should be noted that this document describes the parameterised formulation and associated user inputs in a generic manner; technology dependent input parameters, developed by B&V and UoE, have been provided and can be found in Appendix A and Appendix B of this report. For further information on the UK tidal resource characterisation and the methodology for predefining how the model/the user will select scenarios along with our predictions on initial scenarios, see D01 and D03.

## 2.3 CSM outputs

Once the scenarios have been selected by the model/the user, for every scenario analysed, a number of default outputs will be produced. These will principally be quantities predicted directly by the TELEMAC system such as time-varying maps of depth-averaged current velocities and water levels. The study of given tidal range and tidal current energy schemes, and their impact on the system, will require additional outputs from the model. Examples are time-varying maps of kinetic power density, maps of maximum and mean current velocity or tidal range, and similar outputs comparing the relative impact of scenarios with one another. For clarity in this document, direct outputs from the CSM will be referred to as model outputs; plots and maps will be referred to as graphic outputs; and outputs computed from model outputs will be referred to as processed outputs. By extension, graphic outputs include plots and maps of processed outputs as well as model outputs.

It should be noted, however, that restrictions on existing and third party Intellectual Property Rights will prevent any of the outputs from including datasets that can be used to infer or reverse engineer protected ownership, for instance bathymetric maps. These restrictions also apply to the arising Intellectual Property Rights for this project, which are vested with the ETI, for instance the node positions or the size and density of the triangular elements in the meshed domain of the CSM.

### 2.4 Principal assumptions

Modelling of the natural environment is based on a number of assumptions by definition. The assumptions anticipated at this stage for the development of the CSM and its application to the study of the impact of tidal range and tidal current energy schemes are highlighted throughout this document, in particular in Section 3.

It should be noted, however, that assumptions embedded within some of the chosen data inputs, such as assumptions made in producing bathymetric maps or in defining a parameterised formulation for a specific device and technology, are not included here. For these, references to separate documents and peered review publications are included where appropriate.

### 2.5 Principal requirements

The ETI requires that the CSM complies with a number of targeted operating performance criteria, in terms of the turn-around computing time to produce outputs. The CCSM and the DCSM will each have their own targeted operating performance assumptions.

In addition, a number of targeted validation performances are expected to be met by the CSM to ensure its soundness/authority against a standard recognised by the industry. In particular, the development of the CSM will follow the most stringent of recent guidance from either the *European Marine Energy Centre* (EMEC) on resource assessment, published in 2009 (EMEC, 2009) or the draft technical specification from IEC (IEC, 2011). These recommendations largely depend on the resource assessment phase for which the numerical model is developed. In the present case they include:

- A numerical model mesh cell growth rate of 10%;
- A numerical model with or without a vertical dimension (2D or 3D);
- Calibration and validation against the best available tidal height data, ideally from measured data;
- Comparison expressed in terms of harmonic constituents (amplitude and phase) for those constituents applied on the model driving boundary;
- Comparison against measured current data recommended at an early stage of model development.

It is noted that there are no clear performance criteria to be met in the IEC TC114 August 2011 draft technical specification. The EMEC guidance considers a 20% error in peak velocities acceptable at pre-feasibility stage. This criterion could be used to assess the model performance where current data are available (bearing in mind the fact that for sites with rapid spatial variation in currents there will often be a significant difference between a spot measurement and a c. 200m cell-averaged prediction).

### 2.6 CSM exploitation

It is anticipated at this stage that at least two options will be put in place for the exploitation of the CCSM and the DCSM.

Under the first option, the ETI, its members, the project participants and other third parties will be able to exploit the CSM based on a fee-for-services agreement, the terms and conditions of which have already been put in place.

Under the second option, the ETI and its members will be able to acquire the CSM including the complete model source code and the meshed domain for as long as they fulfil the terms of use of a number of third party Intellectual Property Rights from various sources upon which the CSM is based.

It should be noted that direct users of the CSM will have to be suitably experienced and knowledgeable in the use of similar advanced hydrodynamic solvers, if not of the TELEMAC system itself.

# 3 PROJECT DESIGN/METHODOLOGY

The objectives of the CSM are: (a) to study the interactions between selected scenarios (each representing the development of particular tidal energy extraction schemes) around the UK coasts; and (b) to study their potential impacts on European coasts. A separate report details the methodology for how the CSM/the user will select these scenarios where tidal energy extraction schemes include both tidal range (barrages and lagoons) and tidal current (generally free-flow turbine) energy schemes (See D03 – Scenarios modelling).

The following describes the technical specifications of both the CCSM and the DCSM necessary to achieve the CSM's objectives.

## 3.1 CSM for the base case scenario

As previously mentioned, the development of the CSM is based on a number of inputs and assumptions. This section details the specifications for the CSM inputs, including its geographical coverage, its boundary locations, the details of its resolution, its bathymetric maps, its coastline, its coordinate system and the tidal forcing and constituents.

The above inputs used together with the TELEMAC system will form the base case scenario application of the CSM, or the CSM representing the existing environment. This version will not include the implementation of future or proposed energy schemes, but will include existing energy schemes such as La Rance tidal power plant, based on known information and / or assumptions made on operating procedures.

### 3.1.1 Geographical coverage of the CSM

Figure 1 below highlights the locations of selected tidal range energy schemes (orange disks) and tidal current energy schemes (purple disks). It also shows three bathymetric contours (the edge of two colour bands) at 100 m, 200 m and 300 m depth, the latter being further highlighted in pink.

In order to include the energy scheme sites, the CSM should therefore, at the very least, extend to the north coast of France (i.e. include the English Channel), to the east coast of Ireland (i.e. include the North Channel and the Irish Sea), include part of the North Sea to the east of the coast of England and include the Orkney and Shetland Islands to the north of Scotland.

However, this coverage is insufficient. The impact of the selected energy schemes could reach across the seas as demonstrated in recent publications on the subject, particularly those reporting on the regional impact of tidal range schemes. For instance in the UK, the National Oceanography Centre studied the impact of tidal range energy schemes on the west coast of England, modelling 5 large tidal barrages (Burrows, 2009). It concluded that non-negligible changes in mean tidal range could be observed as far as the Malin Sea and the Celtic Sea. In Canada, the National Research Council Canadian Hydraulics Centre studied the impact of tidal lagoon and barrier operation within the Minas Basin region of the Bay of Fundy (Cornett, 2011). The study concluded that non-negligible changes in mean tidal range could be observed as far as Boston in the USA, across the Gulf of Maine, some 650 km away from the Minas Basin. While these results are specific to the particular configuration of the Bay of Fundy, they indicate that a rather small embayment with tidal barriers can affect very distant locations.

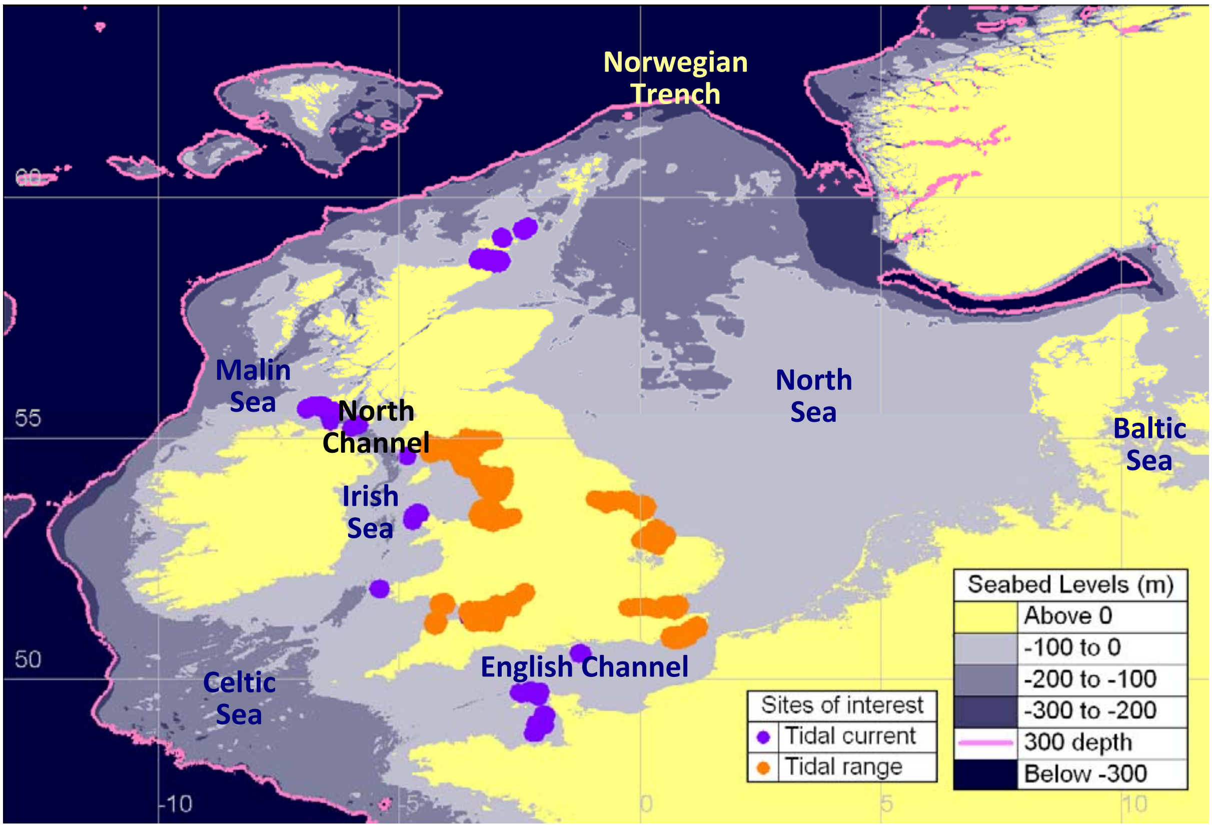


Figure 1 CSM model geographical coverage

The geographical coverage of the CSM will therefore be defined principally by the 300 m depth contour, along the Irish Shelf, Malin Shelf, Hebrides Shelf and West Shetland Shelf. It covers the Malin Sea, the Celtic Sea, the whole of the North Sea in addition to all the energy schemes' sites, the English Channel, the North Channel and the Irish Sea and the Orkney and Shetland Islands.

### 3.1.2 Limit of the CSM coverage

Model boundary contours are made of a series of lines or segments of different characteristics joined together to form a series of closed contours, the larger one being the outside boundary contour within which all the other boundaries lay. There are usually two types of segments:

- Solid boundary segments. These are defined by a no flow through condition (i.e. they highlight no exchange of water with the outside of the model) and usually represent coastlines or civil structures.
- Open boundary segments. These are defined by a flow through condition (i.e. they highlight an exchange of water with the outside of the model) and usually represent open waters, rivers and flows through civil structures.

The definition of these contours is dependent, first, on the resolution of the CSM and will be slightly different whether these are for the CCSM or the DCSM. Illustrations are provided below. Second, these are also dependant on the alignment of the contours with current streamlines and / or lines of equal tidal phase. Where possible, the open boundary segments will be either parallel to oceanic and tidal currents or parallel to lines of equal tidal phase.

#### *3.1.2.1 Outside boundary contour*

Having selected the geographical coverage of the CSM, the outside boundary contour will be made joining the following 6 segments in a clockwise direction, from the French coastline, south of Brittany:

- Open boundary Segment 1: To the south, the segment following the steepest slope down to the 300 m bathymetric contour;
- Open boundary Segment 2: To the southwest, west and northwest, the 300 m bathymetric contour along the northern European continental shelf;
- Open boundary Segment 3: To the north, the segment across the Norwegian Trench, along the steepest slopes going up to the coast of Norway;
- Solid boundary Segment 4: To the northeast, the coastlines of Norway and Sweden stopping in Gothenburg;
- Open boundary Segment 5: The link to (without including, rationale provided below) the Baltic Sea, along the steepest slopes joining with the north tip of the coastline of Denmark; and
- Solid boundary Segment 6: To the east, southeast and south, the coastlines of Denmark, Germany, The Netherlands, Belgium and France stopping south of Brittany.

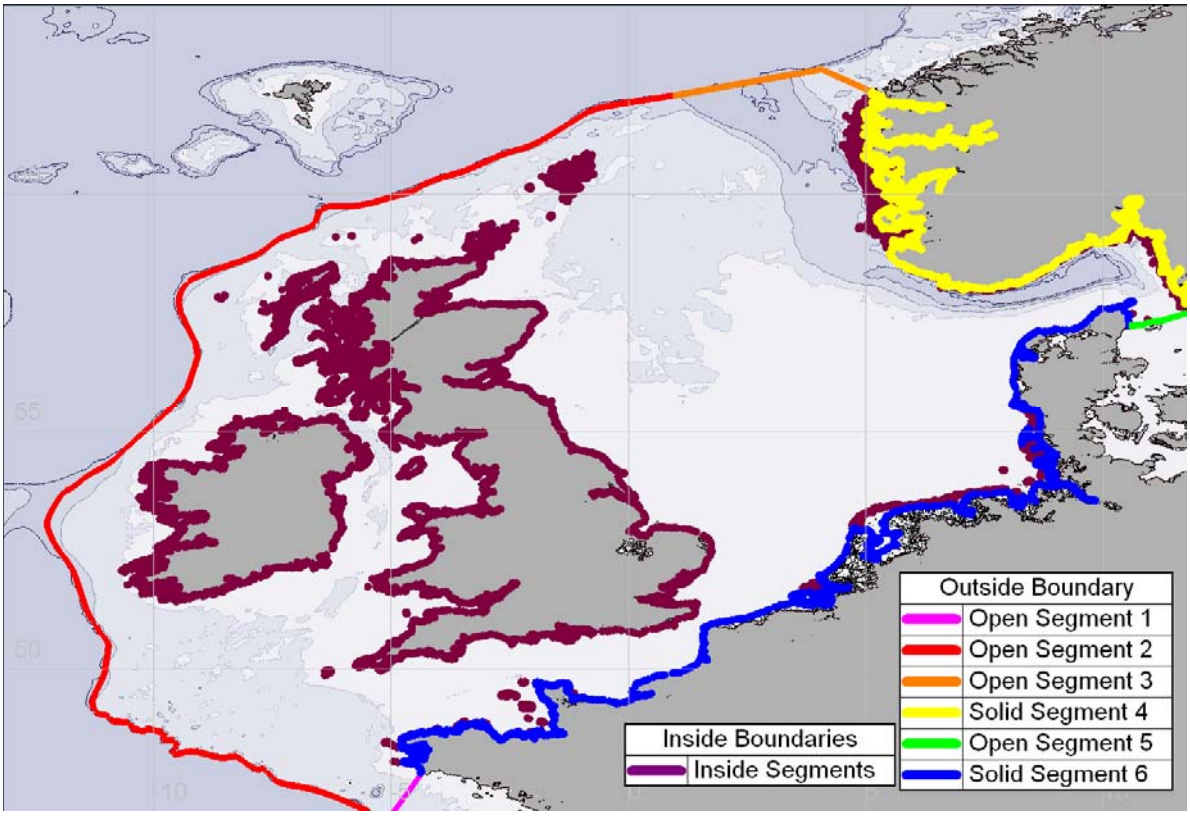


**Figure 2 Segmentation of the CSM outside boundary contour**

Figure 2 above shows the segmentation of the outside boundary contour and also highlights the inside boundary contours (see Section 3.1.2.2) made of more than 3,500 islands. The contours drawn are only for illustrative purposes.

It should be noted that Segment 4 and 6 will not include “minor” fiords, bays, inlets and estuaries, but rather smoothly cross over these, where “minor” is defined relative to the CSM resolution. The resolution threshold for what “minor” excludes, and illustrative examples, are detailed in the next Section 3.1.2.2. This is particularly the case for parts of the detached coast of Norway and The Netherlands. Since these water bodies would be too small for the chosen local resolution, the exchanged water flows are negligible compared to the tidal flows in the North Sea and of the English Channel.

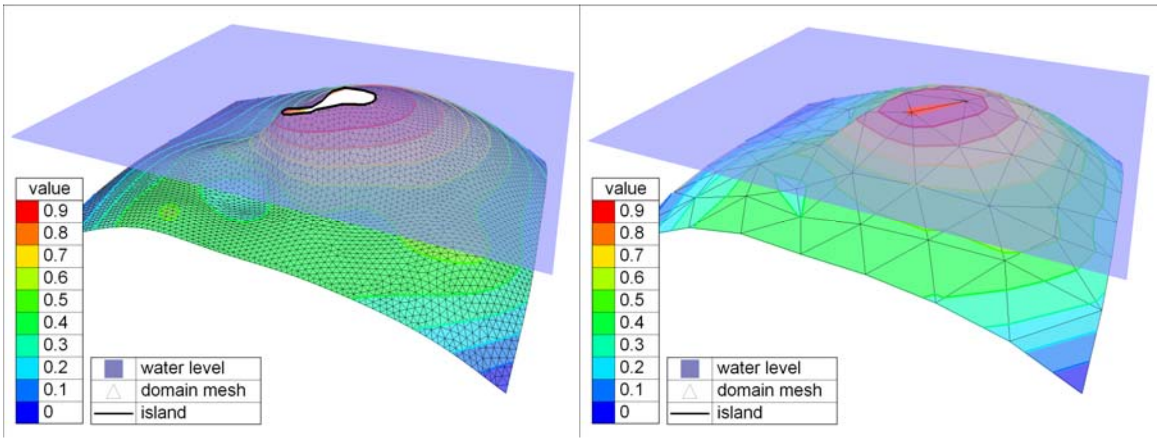
Moreover, the Baltic Sea will not be included in the model, but only represented through the open boundary Segment 5. Indeed, the tidal range and the maximum mean spring tidal current velocities, through Kattegat east of Denmark, across Segment 5 are virtually zero (Carlsson, 1997) with an annual mean discharge from the Baltic Sea around 2,000 $m^3/s$ This discharge will be imposed on Segment 5 but it is not expected to significantly affect the CSM.

### *3.1.2.2 Inside boundary contours*

The inside boundary contours will primarily be solid boundary segments, defining the coastlines of all “major” islands within the outside boundary contour (see Section 3.1.2.1), where “major” relates to the local resolution of the CSM. The resolution threshold is such that the perimeter of an island will be defined by a contour of at least 5 nodes (a pentagon of appropriate shape). In other terms, the perimeter should be at least 5 times the local resolution of the CSM. For instance:

- Lundy Island in the Bristol Channel has a perimeter of a little under 15 km. In this area, the resolution of the DCSM will be around 1 km, which makes the coastline of Lundy Island part of the inside boundary contours, i.e. the DCSM will explicitly represent the effects of the island blockage on the surrounding flows. However, it will not be part of the CCSM inside boundary contours since the local resolution in that case will be around 5 km in this area, i.e. the island will only be represented in the CCSM as a bump in the seabed, with bathymetric elevations averaged/interpolated over the CCSM resolution or areas of 5 km by 5 km in this case.

For clarity, the illustrations below show representations of an hypothetical island, in a detailed- (left image) or coarse- (right image) resolution model.



In these figures the colour contours show arbitrary elevations in the vicinity of the island. The mesh of triangles (see Section 3.2) defined by the model resolution is shown in grey and a see-through surface is shown in blue that represents the still water level. Particularly relevant to the image on the right, as the water level goes down with the tide, the model will introduce some dry cells at the tip of the (under water) island (marked as a thin red patch). The cells will become wet again when the water level goes up.

Islands excluded from the model because they are too small for the chosen local resolution are expected to have a negligible contribution to the blockage effect on the tidal flows at the scale of the continental shelf.

Similarly, “minor” passages between islands, or between islands and the mainland, and “minor” estuaries, inlets, channels and bays will not be part of the inside boundary contour, where “minor” is again defined relative to the local resolution of the CSM. The resolution threshold is set such that a passage will have to be defined with at least 3 nodes (v- or u-shaped passage), and therefore that an opening of less than 3 times the local resolution of the CSM will be excluded from the CSM. For instance:

- The Solent passage between the Isle of Wight and mainland England is about 1.3 km at its narrowest. In this area, the resolution of the DCSM will be around 200 m, which makes The Solent part of that CSM and the Isle of Wight separate from mainland England. However, since the resolution of the CCSM will be around 1 km in this area, it will not be part of that CSM and the Isle of Wight will therefore be attached to mainland England.

- Similarly, the Sound of Islay between the Isle of Islay and Isle of Jura is about 800 m at its narrowest. In this area, the resolution of the DCSM will be around 200 m, which makes the Sound of Islay part of that CSM. However, since the resolution of the CCSM will be around 1 km in this area, it will not be represented in that CSM and the two islands will be attached.

- In the Severn Estuary, the New Severn Crossing near Bristol is about 3.5 km long. In this area, the resolution of the CCSM will be around 1 km, which makes this location close to the upstream boundary of that CSM. However, since the resolution of the DCSM will be around 200 m in this area, the upstream boundary of that CSM will be near Westbury-on-Severn, some 40 km upstream of the M4 Bridge.

The respective resolutions of the CSMs are discussed in Section 3.1.3.

Again, since the excluded water bodies would be too small for the chosen local resolution, the exchanged water flows are negligible compared to the surrounding tidal flows at the scale of the continental shelf.

### 3.1.3 Resolution of the CSM

The resolution of a model is defined here as the distance between two prediction points, which can vary across the geographical coverage (see Section 3.2.3 where prediction points are also referenced as the vertices of the unstructured mesh). Therefore, in simplistic terms, the finer the resolution, the smaller the distance between prediction points, the higher the number of prediction points, the longer it takes to complete a scenario prediction.

Based on past modelling studies and on the estimation of the total area covered by the CSM (the area of the outside boundary contour minus the areas of the inside boundary contours, see Section 3.1.2), the following resolution criteria have been selected:

- DCSM: between c. 200 m at the locations of the selected tidal range and tidal current energy schemes, and c. 10,000 m towards the offshore boundary. The total number of prediction points for the DCSM should not exceed 5 million.

- CCSM: between c. 1 km at the locations of the selected tidal range and tidal current energy schemes, and c. 50 km towards the offshore boundary. The total number of prediction points for the CCSM should not exceed 50 thousand.

The initial aim of the modelling is to produce an accurate reflection of the tidal flows and therefore of the interactions between tidal energy extraction schemes within UK waters. Previous modelling experience related to various areas of interest for tidal currents, by all members of the project team, has shown that the resolution outlined above should allow a good representation of the tidal flows and large-scale arrays of interest. The model resolution has also been selected such that the model be technically robust yet accessible and useable, such that credible results are achieved with accessible run times. It should be emphasised that these criteria will be revised and the resolution of both models increased should the CSM produces predictions quicker than anticipated, at the time of development, to allow additional model resolution within accessible run times. In any case and on the basis of the above criteria, the CCSM should be practically able to complete its prediction on a standard desktop computer while the DCSM will require a high performance cluster of computers to remain practical.

### 3.1.4 Bathymetric cover for the CSM

Having defined the CSM meshed domain (geographical coverage, boundary contours and the variable resolutions), the static data inputs follow with the specification of the CSM bathymetric data source. The number of bathymetric charts, their coverage and their resolution details depend on the CSM meshed domain.

#### *3.1.4.1 Admiralty Charts*

Given the resolution of the DCSM, the bathymetry will be principally based on Level 1 and 2, completed by Level 3 to fill gaps, of the Electronic Navigation Charts (ENC, or digitized versions of the so-called Admiralty Charts) from the UK Hydrographic Office (UKHO). This dataset will be further completed along the French coast with the so-called S-57 charts from the French Service Hydrographique et Océanographique de la Marine (SHOM).

Figure 3 shows the extent of the various charts. In this figure the land above mean sea level is indicated in grey. The Wadden Sea, which is open to the North Sea, will be part of the CSM, contrary to what is illustrated in Figure 3.

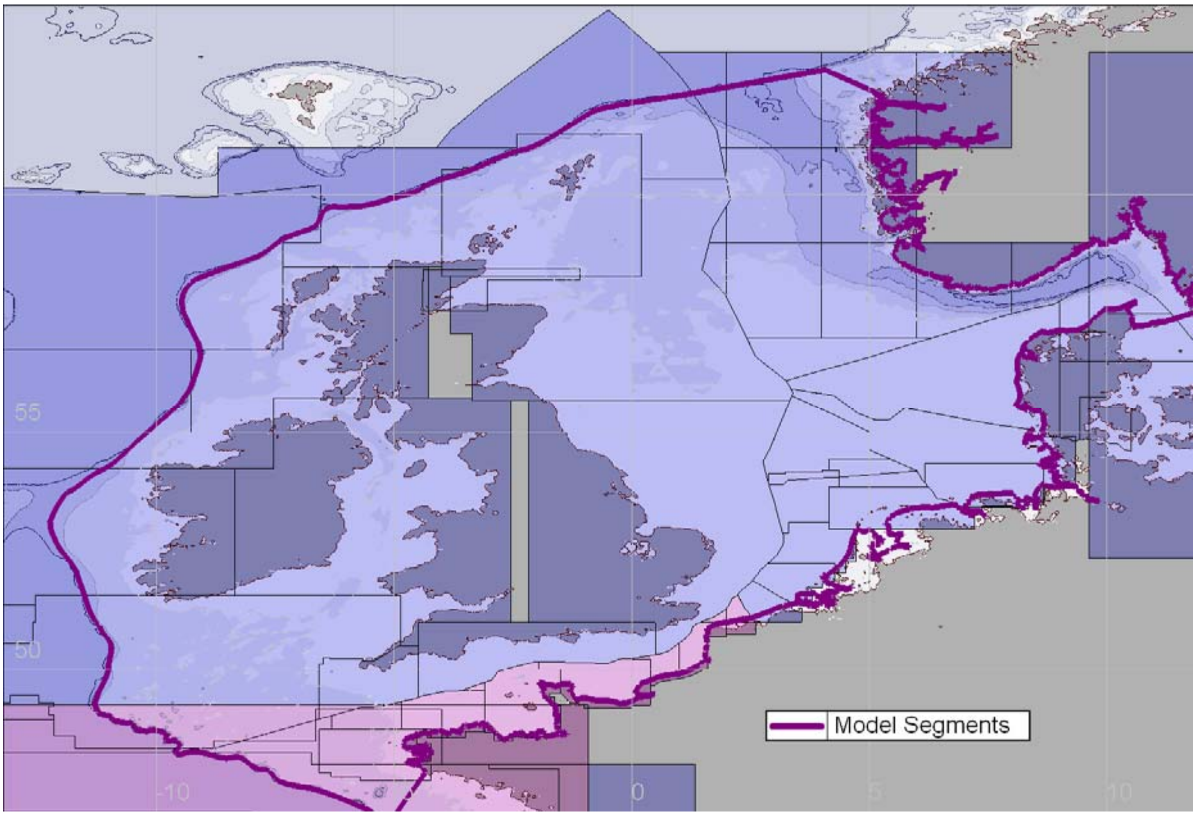


**Figure 3 Bathymetric coverage for the CSM**

It should be noted that SeaZone of HR Wallingford has already reached agreements with all necessary hydrographic institutions to be able to use and provide the data for this project.

#### *3.1.4.2 Underlying methodology for data extraction and interpolation*

Bathymetric data will be extracted and de-convoluted from the above-mentioned overlapping charts by SeaZone of HR Wallingford. The data will also include low water spring contours and high water spring contours, the later defining the CSM coastline, or the solid boundary parts of the outside and inside boundary contour (see Section 3.1.2). This will enable the CSM to predict if and when the area is wet or dry.

The extracted data will then be interpolated onto the meshed domain (a bathymetric value will be attributed to all prediction points) using the thin-plate-spline method (Harder, 1972).

Both soundings (points) and isobaths (contours) will be used to defined the model bathymetry.

The level of detail included in the charts is deemed sufficient for the interpolation on both versions of the CSM. The distance between Rathlin Island and mainland Ireland is about 4 km. The bathymetric details provided at Level 2 coverage are sufficient to define the 20 prediction points (or less as the mesh grows away from the coast) of the DCSM at this location.

### 3.1.5 Coastline of the CSM

As mentioned in Section 3.1.4.2, the low water spring and high water spring contours will be extracted from the electronic charts. These will be used to define the CSM intertidal areas in the absence of detailed bathymetry survey coverage. The coastline of the CSM, also referred to as solid segments in

Section 3.1.2, will be based on the high water spring contours, or the highest water level an average spring tide can reach.

This will enable the CSM to include predictions of the volumes of water leaving and entering estuaries and inlets on ebb and flood flows and for the entire period simulated.

### 3.1.6 Coordinate system and vertical datum reference

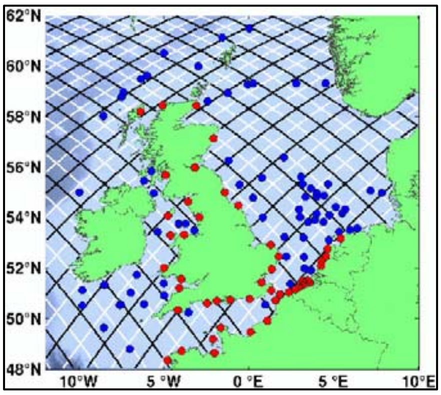
The coordinate system used in this study will be a spherical coordinate system (Latitude, Longitude), Ellipsoid WGS84. This choice is in agreement with marine maps published by The Crown Estate, even though at the UK latitude the North-South distances are displayed about 40% smaller than East West distances (see Figure 1 for instance). The vertical datum will be mean sea level. The directions will be quoted with respect to True North.

### 3.1.7 Tidal forcing at the CSM open boundary

The CSM will be driven by tidal forces imposed at its Segments 1, 2 and 3 (see Section 3.1.2). Tidal forces will be derived as spatially varying time histories of water levels covering at least a 15-day period of tidal cycles, spring to neap to spring, themselves reconstituted from tidal constituents derived from harmonic analyses of satellite remote sensing measurements.

#### *3.1.7.1 Satellite data and ocean tides*

The TPXO dataset is one of the most accurate global models of ocean tides (OSU, 2008). Its data are based on a best-fit of tide levels measured along remote sensing tracks from the TOPEX/POSEIDON satellite project in operation since 2002 to which a harmonic analysis is applied to produce complex amplitudes of earth-relative sea-surface elevation. The TPXO dataset provides eight primary harmonic constituents (M2, S2, N2, K2, K1, O1, P1, Q1), two long period harmonic constituents (Mf, Mm) and three non-linear harmonic constituents (M4, MS4, MN4), on a 1440x721, 1/4 degree global grid resolution. Each new version of the TPXO dataset increases the quality and the number of harmonic constituents, since it assimilates longer satellite time histories and a finer coverage of the earth surface. These constituents are by definition clean of atmospheric and surge variations, as these variations would not be part of the astronomical periods against which the tidal harmonics are being predicted.



Several refined versions of the global TPXO dataset exist, one of which covers the Northern European continental shelf, on a 660x420, 1/30 degree grid resolution, and includes the General Bathymetric Chart of the Oceans (GEBCO 1 degree) from the British Oceanographic Data Centre (GEBCO, 2008). More than just providing an interpolation of the harmonic constituents on a refined grid, this dataset has been validated against the available tide gauges as shown with blue and red filled circles in the illustration opposite (Egbert, 2010).

The 13 harmonic constituents available from the TPXO dataset define adequately tidal levels in the Atlantic Ocean. The constituents obtained at locations on or near Segments 1, 2 and 3 of the CSM (see Section 3.1.2) will be linearly interpolated before time histories of water levels are generated at all grid points along these segments.

As tidal flows, imposed on the open outside boundary contour (see Section 3.1.2), rise above the continental shelf and approach the coasts, the harmonics combine in a non-linear way and multiply (Doodson and Warburg, 1941; Vassie, 1986), which only a model is capable of predicting. The CSM could therefore predict within the selected geographical coverage a higher number of harmonic constituents, at specific sites of interest for tidal energy development.

#### *3.1.7.2 Underlying harmonic analysis methodology*

The freeware T-tide software will be used for all tidal harmonics analysis including the setup of tidal forcing at the boundary and the analysis of the tide gauges and model outputs against which the CSM will be validated.

T-tide is based on the original FORTRAN program developed by M.G.G. Foreman at the Institute of Ocean Sciences (Foreman, 2004). T-tide was developed further by S. Lentz and R. Beardsley from the Woods Hole Oceanographic Institution to include linear error estimation. It was then improved further by R. Pawlowicz (Pawlowicz, 2002) to use non-linear error estimation (to handle low signal to noise constituents more accurately) and work with complex (rather than real) mathematics for analysis of tidal currents. The T-tide package also applies nodal corrections to the harmonic amplitudes relative to centre time and computes the phase relative to Greenwich.

#### *3.1.7.3 Underlying average tide cycle selection methodology*

Time records will be generated along the CSM open boundary for a 20-year period based on the TPXO dataset, which is clean of atmospheric and surge events. Each of these records will be analysed to identify high and low and consequently the spring and neap cycles. The method described in Table V of the Admiralty Tide Tables (UKHO, 2009) will be used to calculate High Water Spring (HWS), Low Water Spring (LWS), High Water Neap (HWN) and Low Water Neap (LWN), i.e. the height of HWS will be computed as the “average of the heights of two successive high waters during the period when the range of the tide is greatest”, and the height of LWS will be computed as the “average height obtained by the two successive low waters during the same period”, and similarly for the neap tides.

Once all the high and low waters are determined for spring and neap cycles and for the 20-year period, the average values are computed. The originally generated time records are then scanned to find suitable representative periods when average spring and average neap conditions occurred within approximately 7 days of each other.

Ideally, one 15-day period will be selected from the 20-year time record to be representative of the average. However, because of the length of the open boundary (Segments 1 to 3), it is not guaranteed that the selected period would be the representative average for all latitudes concerned. If that was not the case, up to three 15-day period would be selected, each fitting better with the representative 20-year average at the following three locations: north of the Shetland Islands, east of Malin Sea and south east of Celtic Sea. Values of HWS, LWS, HWN and LWN for each 15-day period will be categorised against the others.

#### *3.1.7.4 Longer prediction periods for further harmonic analysis*

As part of the validation of the CSM, harmonic constituents will be extracted from the CSM outputs and compared to constituents at known sites. This process will be particularly relevant when comparing against observed data, which will include the effects of atmospheric and surge events, as the comparison of constituents or re-synthesised time histories will be clean of these external factors. It is noted that the IEC draft technical specification recommends that model and calibration data be compared on the basis of harmonic constituents for all constituents applied on the model driving boundary (13 in this case). As previously mentioned, the CSM will predict tidal levels within the geographical coverage with a higher number of harmonic constituents than that imposed at its open boundary, and therefore this is satisfactory. The rise of the tidal waters above the continental shelf combines these harmonics due to non-linear effects (Doodson and Warburg, 1941).

The number of harmonic constituents that can sensibly be extracted from a time record, and the reliability of those constituents, depend on its length. As a guide, five constituents can be obtained from a one-day record; 15 from 15 days; 26 from 29 days; 54 from 6 months and 60 from one year of data (Vassie, 1986). The actual number of constituents separable will depend on the level of background noise in the data. In this study, the CSM will be used to predict periods between 45 and 90 days in the context of the CSM validation against published and measured data. This will provide the 13 constituents imposed at the model driving boundary (for which a 15-day period is sufficient) but also additional non-linear constituents.

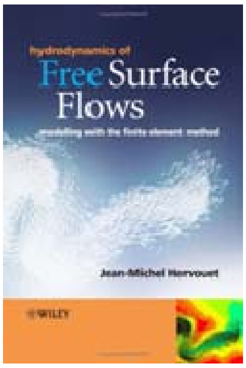
It is only envisaged at this stage to use the CSM for representative periods of 15 days (e.g. 20-year average), in the context of tidal range and tidal current energy scheme assessment. In this case, time histories only would be compared with and without the scheme in place, not tidal harmonic constituents.

## 3.2 Underlying CSM methodology

The open source, industry driven, TELEMAC system and more specifically its two dimensional module, will form the underlying methodology of both the CCSM and the DCSM.

### 3.2.1 Overview of the TELEMAC system

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. The TELEMAC system is currently being used by more than 1,000 organisations worldwide; it has been developed under a quality assurance system including the application of a standard set of validation tests.



The image opposite shows the cover of the latest book published on this solver (Hervouet J-M., 2007). This particular reference includes a complete description of the latest theoretical and numerical developments.

The TELEMAC system is open source software, enabling organisations to access and modify any part of its source code. The address of the official Internet website is: www.opentelemac.org. The website is managed, hosted and maintained by HR Wallingford. A number of documents can be downloaded (including manuals, tutorials, and theoretical notes) together with the entire source code and its documentation. Community driven tools are also in place including an active discussion forum.

### 3.2.2 Overview of the TELEMAC-2D module

The TELEMAC system is made of a number of modules, which can be used independently or be dynamically coupled to represent individual or combined effects. These are typically used to model physical processes such as two- and three-dimensional free surface flows, ground water flows, offshore to nearshore wave transformation, inshore wave agitation, water quality and silts, sands and geomorphologic processes.

The two-dimensional (2D) module, TELEMAC-2D, is typically used to study large scale hydraulic phenomena such as open waters tidal flows, estuarial and coastal flows, storm surges and tsunami propagation, floods in river systems and over urban areas, and dam break simulations. The effect of winds and atmospheric pressure variation can also be included in the models. Seabed friction can be specified either with a Chezy, Strickler / Manning, or a Nikuradse roughness length and can vary spatially over the model area. Viscosity can be set as a constant eddy viscosity or computed through a one- or two-equation turbulence model. Subcritical, trans-critical and supercritical, and wave absorbing boundaries are automatically dealt with.

### 3.2.3 Pertinent details of TELEMAC-2D

#### *3.2.3.1 Primary variables and interaction with energy scheme implementation*

TELEMAC-2D solves the 2D depth-averaged shallow water equations, also called the St Venant equations. These comprise three equations (one equation for the conservation of the volume of water and two equations representing the conservation of the water momentum) dependent on three environmental hydrodynamic variables (the water depth $h$ in meters and the depth-averaged current velocity components $u$ and $v$ in meters per second). These equations are as follows:

- continuity equation: $\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=Srce$

where $Srce$ is a variation of the volume of water within the water column (including rain, evaporation and other intakes and outlets such as found around hydraulic structures), and where $\partial/\partial t$, $\partial/\partial x$ and $\partial/\partial y$ are respectively the time and space component gradients; and

- x-momentum equation: $\rho h\frac{\partial u}{\partial t}+\rho hu\frac{\partial u}{\partial x}+\rho hv\frac{\partial u}{\partial y}=-\rho gh\frac{\partial(h+b)}{\partial x}+\frac{\partial}{\partial x}\left[h\nu_e\frac{\partial u}{\partial x}\right]+\frac{\partial}{\partial y}\left[h\nu_e\frac{\partial u}{\partial y}\right]+hF_x$
- y-momentum equation: $\rho h\frac{\partial v}{\partial t}+\rho hu\frac{\partial v}{\partial x}+\rho hv\frac{\partial v}{\partial y}=-\rho gh\frac{\partial(h+b)}{\partial x}+\frac{\partial}{\partial x}\left[h\nu_e\frac{\partial v}{\partial x}\right]+\frac{\partial}{\partial y}\left[h\nu_e\frac{\partial v}{\partial y}\right]+hF_y$

where $F_x$ and $F_y$ are source terms and body forces acting on the water momentum (including seabed friction, Coriolis, drag, and possible energy extraction devices), and where $g$ is the earth gravitational acceleration (in m/s$^2$), $\nu_e$ a diffusion coefficient (in m$^2$/s) including dispersion and turbulence, $\rho$ the water density and $b$ the seabed elevation.

Without detailing the theoretical background of these equations further, it is important to note that:

- Generic terms are already implemented in TELEMAC-2D to model the effect of both tidal range and tidal current energy devices (source terms in the continuity equation $Srce$ and source terms and body forces in the momentum equations $F_x$ and $F_y$ respectively); and
- Water depth and current velocity components are the primary variables of TELEMAC-2D, from which dynamic interactions and model post processing steps have to be defined.

#### *3.2.3.2 Boundary- and structure-fitted unstructured mesh*

The TELEMAC system was designed from the outset, 20 years ago, to use the mathematically advanced finite element formulation, which is ideally suited to very flexible unstructured meshes of triangular elements. This is superior to using orthogonal and/or curvilinear grids as there is more control over local resolution refinement particularly in cases such as detached coastlines, underwater features including high seabed gradients. In addition, currents that are tangential to coastal boundary conditions (slip or nonslip conditions) are correct by design. Open boundaries can be aligned to open water lines of equal tidal phase and streamlines and include radiation (Thompson boundary condition in the TELEMAC system).

Unstructured meshes are made of triangular elements of various shapes and sizes, allowing the detailed study, while saving on computation time with larger triangles. Figure 4 shows the unstructured mesh of triangles of an arbitrary model, coloured from purple to white according to triangle size. The density variations (along the green arrow) allow detailed capture and accurate modelling of small natural hydrodynamic features where the triangles are smaller, while expanding at a controlled growth to save on computing time where model results are of less interest.

The primary variables (water depth and the current velocity components, see Section 3.2.3.1) are defined at the nodes of the mesh, i.e. the vertices of triangles. Hence, a mesh with small triangles leads to a higher number of vertices to cover the domain, leads to a higher number of calculations, leads to longer computer time and resource requirements.

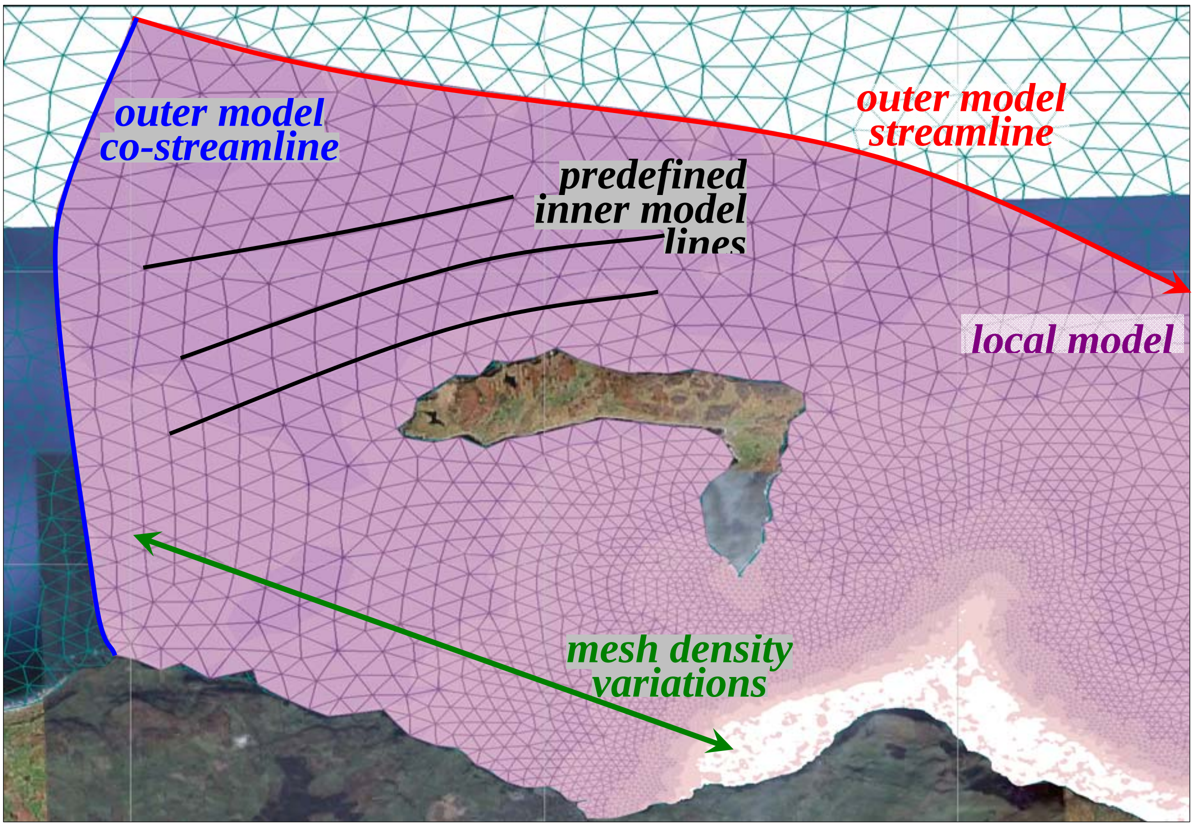


**Figure 4 Illustration of a boundary and structure fitted unstructured mesh**

Figure 4 also shows three more pertinent features of the unstructured meshes.

First, the outer model boundary can be fitted to run along known streamlines (shown in red). It is anticipated that the CSM outer boundary will run along such oceanic streamlines and follow the continental shelf west of Ireland.

Second, the outer model boundary can be fitted to run perpendicularly to streamlines or along steepest slopes of bathymetry maps as it joins up with the coastline (shown in blue). It is anticipated that the CSM outer boundary will run along such lines as it joins up with the coast of France, south of Brittany.

Third, the unstructured mesh of triangles can be fitted to include predefined inner model lines (shown in black). It is anticipated that the CSM will include such predefined lines to provide for potential positions of future tidal range barriers, helping these scenarios to be better represented in the CSM.

## 3.3 Typical representation of tidal range and tidal current energy schemes

A tidal range energy scheme is a lengthy narrow structure placed in the water to create a head difference on either side of the structure. It includes barrages and enclosed lagoons. Turbines are placed within the structure controlling the flows through it and in turn generating power. The number of turbines, their size and other characteristics, the length of the structure, and the head difference all come into play in the amount of power generated.

Conversely, a tidal current energy scheme covers an area of open water. Turbines are closely placed in farms to maximise the power extraction within the area of maximum resource. The tidal power is a direct function of the tidal current field. The number of turbines, their size and characteristics, the surface area of the farm and the spacing between the turbines, and the current velocity around and within the farm all contribute to the amount of power generated.

### 3.3.1 Tidal range parameterisation

As mentioned previously, a tidal range energy scheme is assumed to comprise a lengthy narrow structure or solid embankment with a number of openings (sluices or turbines) in it. When the structure is closed the behaviour of the water bodies on either side of the structure is independent. When the structure is operational, the discharge through the structure at all time can be computed as a function of the water level and current velocity on either side, and by extension the head and energy difference across the structure.

#### *3.3.1.1 Energy scheme interaction with continuity equation*

A generic equation will be used to represent all possible ranges of conventional turbines and openings, summarised as follows:

- $Q = D_1 + D_2\,\Delta h + D_3\,\Delta h^2 + D_4\,\Delta h^3 + D_5\,h\sqrt{\Delta h} + D_6\,\sqrt{\Delta h} + D_7\,\Delta u^2$

where $Q$ is the discharge in m$^3$/s, $\Delta h$ is the head difference in m, $h$ is the average water depth in m, $\Delta u^2$ relates to the energy difference and can be used to represent other energy losses and where $D_1$ to $D_7$ are constants defined by the technology type, the operational procedures, the turbine capacity, the size, submergence and types of the openings and other key turbine parameters (refer Appendix B).

The discharge $Q$ will be withdrawn upstream of the turbines by subtracting to the term $Srce$ in the continuity equation (see Section 3.2.3.1) the value of $Q$ (water sink). At the same time, the same discharge $Q$ will be reinserted downstream of the turbines by adding to the term $Srce$ in the same equation the value of $Q$. The head difference $\Delta h$ and the water depth $h$ will be calculated dynamically and constantly updated by the CSM from a difference and average of water depths upstream and downstream of the structure at all time. Thus, the power available will not remain uniform during the period of generation, but will vary with the head difference across and along the structure. It should be noted that while turbines follow a set of cubic equations, sluice gates, for instance, could be represented using other terms such as $h\sqrt{\Delta h}$ or $\sqrt{\Delta h}$ .

#### *3.3.1.2 Fitting with the unstructured mesh*

Tidal range energy schemes will be modelled at the scale and resolution of the versions of the CSM unstructured mesh. The principal lines defining the structure will be included in the model mesh as pre-defined inner-model lines (see Section 3.2.3.2). The stored water body will be represented dependent upon whether the surface area is small or large, relative to the local resolution of the CSM:

- In small impounded areas (smaller in surface area than c. 20 local elements), the triangular elements enclosed will be removed from the CSM mesh and a single volume-depth relationship will be used to represent the storage; and
- In larger impounded areas (bigger in surface area than c. 20 local elements), an impermeable barrier will be created along the predefined inner-model lines allowing the hydrodynamics of the enclosed waters to be modelled like any other area in the CSM.

The nodes of the mesh along the structure will further include a representation of one or more openings depending on the mesh resolution and the designed size and emplacement of the turbines. The amount of energy extracted at each node of the mesh will be related to the potential ‘packing density’ of turbines appropriate for the length along the structure represented by the node, for either the low or high resolution solution.

A set of rules will be defined (as described in Section 3.3.1.1) that control the flow exchanged through them. Sources and sinks either side of the structure line will be used for that purpose.

### 3.3.2 Tidal current parameterisation

As mentioned previously, a tidal current energy scheme is assumed to inhabit an area of open water with a number of turbines that in combination form a ‘farm’ of energy harvesting devices. When the turbines are not in operation mode (for instance, current velocity outside threshold of design operation) there remains a drag force through the area due to the presence of the turbines. When the turbines are in operation, the hydrodynamics around and within the farm of turbines can be computed at every time-step as a function of the energy extracted, other energy losses, and the drag and other forces, which are themselves a function of the local current velocity predicted by the CSM.

#### *3.3.2.1 Energy scheme interaction with momentum equation*

When tidal current devices are introduced in the hydrodynamic system, the system loses energy, whether the energy is extracted or whether drag forces are introduced. The various contributions for the loss of energy will be represented as additional body force terms, the sum of which will be $F_x$ and $F_y$ in the momentum equation presented in Section 3.2.3.1. These additional body force terms are a means of *parameterising* physical processes that occur at higher resolution than is used within the model. The parameterised terms replace small-scale physical processes (from the point of view of model resolution) with a continuous property applied across the area of the computational cell. Appendix A provides a detailed description of the parameterisation forms for modelling energy losses due to the introduction and operation of farms of TEC devices to be used in the CSM.

It is believed that this methodology, which effectively represents the tidal devices as ‘sinks’ of momentum, is adequate to reproduce the large scale flow patterns and the effects of power extraction on flow velocities throughout the model domain, except very close to the virtual tidal devices themselves.

#### *3.3.2.2 Fitting with the unstructured mesh*

As with the tidal range energy schemes, the tidal current devices will be modelled at the scale of the numerical model mesh. The intention is to refine the model to a resolution of approximately 200 m in areas identified of interest for tidal energy harnessing.

A set of polygons will be used to define the areas where the tidal devices are to be placed. Within each of these areas the force described in Section 3.3.2.1 will be applied to all nodes of the mesh to represent drag, energy extraction and other forces influencing the local flows. As with the tidal range energy scheme, the amount of energy loss at each node will be related to the potential ‘packing density’ of devices appropriate for the plan area represented by the node and the characteristics of the device representation selected for that particular node or farm representing efficient matching of technology with resource availability. The current velocities will be calculated dynamically and constantly updated by the CSM at all time-steps. Thus, the power available will not remain uniform during the period of generation, but will vary with the effect of the farm on its surrounding.

## 3.4 CSM for energy scheme scenarios

Both the CCSM and the DCSM will be developed to accept and interpret a set of user inputs, defining an energy scheme scenario. The CSM will make available a set of pre-selected scenarios, which will be developed during the project once the CSM is ready, see D03 – Scenarios modelling, but will also let the user define his/her own scenarios.

The definition of the parameterised formulation is purposefully generic (see formulations in Section 3.3.1.1 and 3.3.2.1) allowing the user to include the impact of energy scheme scenarios from other fields of renewable energy development.

Those users who have acquired the CSM will also have access to the CSM source code and be able to modify the formulations as they see fit.

### 3.4.1 Minimum user input to define an energy scheme scenario

Energy scheme scenarios will be defined by at least three types of user input data:

- First, a set of polylines and/or polygons defining the location and the extent of individual energy schemes. A polyline would be used to represent a structure (for instance a barrage). A polygon would be used to represent either a structure (for instance a lagoon) or an area of influence (for instance a tidal farm).

- Second, for each polyline/polygon, a set of device-driven parameters defining the representation of the technology. These parameters would be representative of either tidal range devices (parameters $D_1$ to $D_7$ in Section 3.3.1.1) or tidal current devices (parameters $K_2$ to $K_3$ in Section 3.3.2.1).

- Third, an operational threshold for the head difference $\Delta h$ or the velocity components $u$ and $v$ (or its magnitude) applicable to tidal range and tidal current energy schemes respectively. Turbines would only be operational when the head difference predicted by the CSM is within user defined threshold values. Similarly, a tidal farm would only run when the current velocity is predicted within the operational threshold values, leaving only the drag forces in other cases.

These types of user input data will be used to define scenarios during the course of this project and after, during the exploitation of the CSM. Users will be able to upload these inputs to either version (resolution) of the CSM before running the scenarios. Multiple scenarios will be possible through the same process. At the end of the project, a set of pre-selected scenarios D03 – Scenarios modelling will be made available for editing.

### 3.4.2 Additional user input

Users of the CSM will be given the option to upload additional input data in the form of modifications to the bathymetry at the site of interest, to include dredging activities for instance:

- Fourth, a set of polygons defining the location and the extent of bathymetric changes, together with a set of bathymetric points defining the new bathymetry within the polygons. The bathymetric points will have to be provided as x-y-z-values, in the same coordinate system as that used by the CSM (see Section 3.1.6). Within the polygons, the bathymetric values of the CSM will then be replaced by the user values interpolated on the CSM meshed domain.

### 3.4.3 Additional uses of the user inputs

As previously mentioned, the definition of each scenario, particularly its formulation and associated parameters, is generic. This will allow users to model the impact of similar energy scheme scenarios as well as other developments and reclamations, including from other fields of renewable energy development. For instance, should a thousand wind turbines be placed within an area of the North Sea, the user would be able to see the impact of the development on other scenarios by: (a) defining the lines delineating the wind farm, (b) estimating the parameters that represent the drag force (as a result of the presence of the piled structures), and (c) making sure that the forces always apply.

# 4 RESULTS, PRESENTATION OF CSM OUTPUTS

There will be two levels of graphic outputs produced by the CSM during the course of the project. The first level will include graphic outputs generated from the CSM primary variables to document mainly the validation of the versions of the CSM according to their respective resolutions. The second level will include graphic outputs from the first level but will expand to include those generated from secondary variables, to document mainly the analysis of the interactions between selected scenarios (each representing the development of particular tidal energy extraction schemes) around the UK coasts and of their potential impacts on European coasts. For consistency and comparative analysis, graphic outputs whether generated during the validation or the scenario analysis will share similar graphics and plotting formats.

It should be noted that spatially varying model output and processed outputs will be interpreted as contours in Shape File form (SHP) as published by the Economic and Social Research Institute and as Portable Network Graphic (PNG) picture form. Further, plots based on time histories will be extracted at specific locations of interest as comma separated value format (CSV) not necessarily related to the mesh node locations.

Finally, as mentioned in the introduction, it should be emphasised that restrictions on existing and third party Intellectual Property Rights will prevent any of the output from including datasets that can be used to infer or reverse engineer protected ownership, for instance bathymetric maps. These restrictions also apply to the arising Intellectual Property Rights for this project, which are vested with the ETI, for instance the node positions or the size and density of the triangular elements in the meshed domain of the CSM.

## 4.1 Primary and secondary variables

As defined previously (see Section 3.2.3.1), primary variables are those predicted by the CSM, i.e. the water depth and the current velocity. Secondary variables are those calculated based on existing CSM outputs.

Secondary variables will include:

- Temporal maximum and minimum water level and by extension maximum tidal range, directly processing the CSM outputs by calculating the temporal maximum and minimum of the predicted water level at each model node over the representative tidal period.

- Temporal maximum and mean current velocity magnitude, directly processing the CSM outputs by calculating the temporal maximum and average of the predicted current velocity magnitude at each model node over the representative tidal period.

- Temporal maximum and mean of the kinetic power density, processing the CSM outputs first to generate temporally-varying kinetic power density at each model node over the representative tidal period, and then by calculating the temporal maximum and average.

The secondary variable depth-averaged kinetic power density will be computed from primary variables at every mesh node as follows:

$$P = \frac{1}{2}\rho\sqrt{u^2+v^2}^{\,3}$$, where $u$ and $v$ are primary variables and $\rho$ is the water density

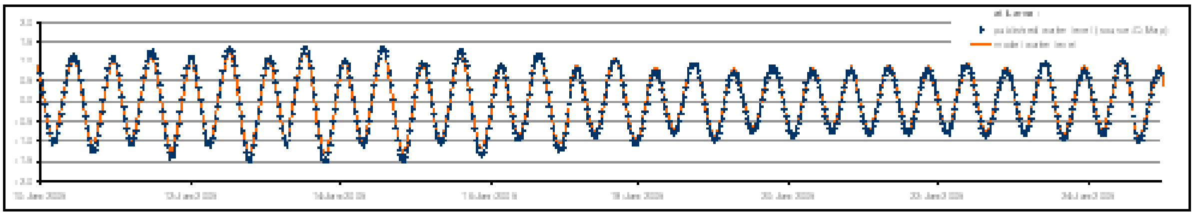
Kinetic power density provides a measure of the economic potential of tidal current developments before and after the implementation of a select set of energy schemes, whether these include tidal range or tidal current scenarios.

## 4.2 Types of graphic outputs

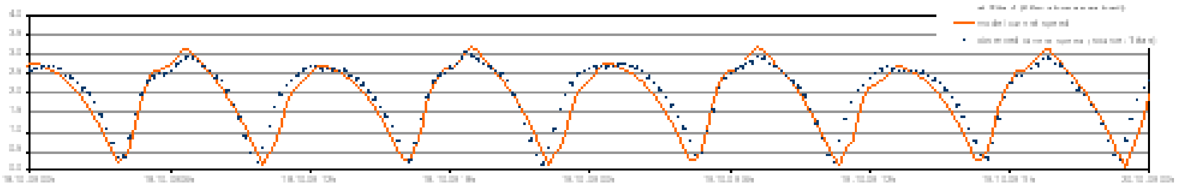
### 4.2.1 Time histories

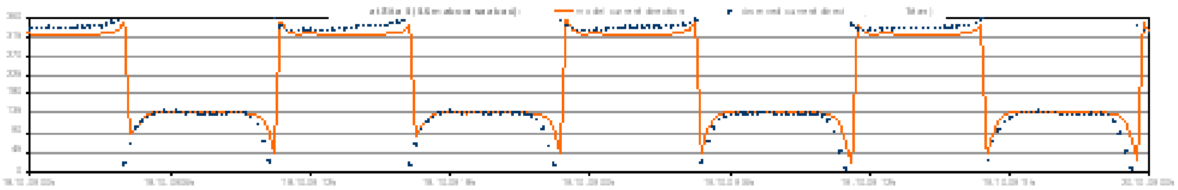
Comparison of tidal levels (and where possible current velocity magnitudes and directions) at specific sites over the representative tidal period is essential to the validation of the CSM. Time histories show the evolution of the variables with the spring-neap-spring tidal cycle as well as the evolution of the comparison over the entire time period. The horizontal axis is time. The vertical axis usually represents the magnitude of one of the primary variables.

The illustration below shows time histories of predicted water levels at a validation sites (orange line), compared to those observed for the same period (blue markers).

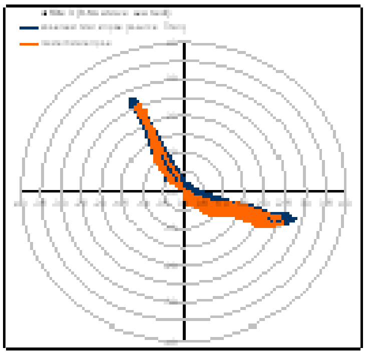


The illustration below shows time histories of current velocity magnitudes and directions. Here, the orange line represents 3D model predictions, and the dark blue markers the ADCP mooring data. For clarity, observations are only plotted every 15 min.





### 4.2.2 Tidal ellipses



Tidal ellipses are complementary to time histories of current velocity magnitudes and directions. A tidal ellipse is a representation of the direction and strength of the flow throughout one or more tidal cycles and gives a good indication of the major current axis. These ellipses can highlight, for instance, the relative performance potential of the ebb and flood flows for a bi-directional turbine.

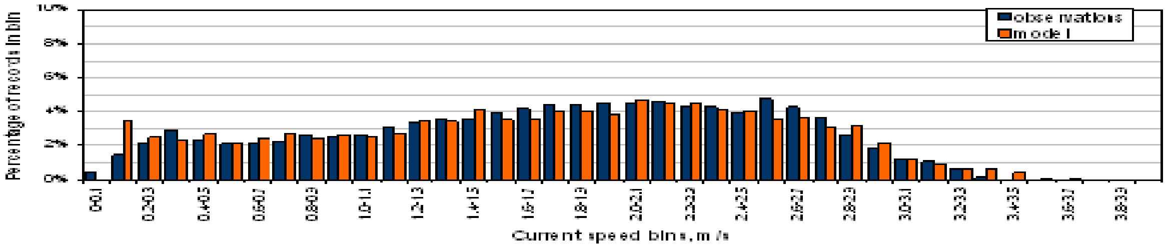
The rings on the ellipse represent the current speed. Each point represents a prediction time in the CSM. The current patterns during a spring tide and a neap tide can be differentiated from those over the whole of the representative tidal period.

The illustration above shows a tidal ellipse, at a specific site over the full the representative tidal period. The predicted current patterns are shown in orange, the observed current patterns in dark blue.

### 4.2.3 Distribution of current velocities and exceedance curves

Distributions of current velocities and exceedance curves are also complementary to time histories of current velocity. They can be used to highlight a percentage of occurrences, for instance, that the velocity is lower or higher than the operational threshold of a turbine.

Distribution curves are usually shown in the form of a bar plot where each bar represent the proportion of time the velocity magnitude fall within a unit range..



The illustration above shows the predicted distribution of current velocities at a specific site over the full representative tidal period in orange and the observed distribution is dark blue.

Exceedance curves, or cumulative probability distribution curves, are usually shown in the form of a single line plot where the curve can then be used to estimate the probability that a given velocity or kinetic energy threshold be exceeded.

### 4.2.4 Colour contour maps

Various colour contour maps will be produced whether at national or regional scale, whether for one of the primary or secondary variables (see Section 3.2.3.1). Colour contour maps show a number of lines or colour bands representing the spatial variations of a variable, where the lines or colour band represent one value or one range of values for that variable. For instance, Figure 1 shows colour bands of bathymetric values over the entire CSM geographical coverage.

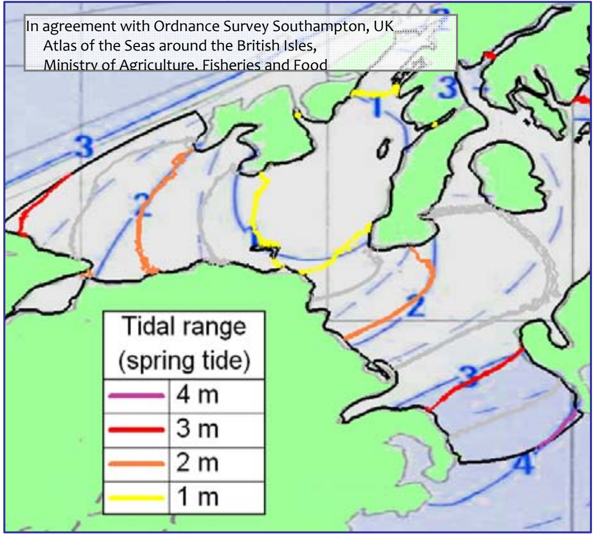
## 4.3 Graphic outputs for the CSM validation

Time history comparisons of the CSM outputs against observed data will depend on the type of data source and instrument.

At this stage, it is envisaged that tidal levels recorded as part of the UK tidal gauge network (UKTGN, 2011) and those made available through the Système d'Observation du Niveau des Eaux Littorales (SONEL) programme outside the UK will be used to calibrate and validate the CSM. Although data are available for more stations, it is anticipated that in the order of 20 stations could be used in this project to keep model calibration manageable. Time histories will be produced for the appropriate periods. Additional comparisons with satellite altimeter data may be presented, in particular in terms of spatial maps of tidal range / current speed, but these comparisons can only be regarded as secondary validation.

Time records of observed current velocity are harder to find and often proprietary. They would, however, provide a valuable contribution to the model verification and confidence in the CSM predictions for tidal currents. Efforts will therefore be made to identify suitable current velocity time records (in addition to what the ETI can provide) and use them to further validate the CSM. In this instance, time histories, tidal ellipses and distribution and exceedance curves will be produced. At the very least, a tidal ellipse will be made for available chart tidal diamonds.

Colour contour maps of observed data are virtually nonexistent but are presented as part of other model predictions or as the artistic interpretation of discrete sampled data such as contouring in atlases. The CSM outputs will be processed and compared against available atlases, in particular the Atlas of the Seas around the British Isles from the Ministry of Agriculture, Fisheries and Food (MAFF, 1981).


In agreement with Ordnance Survey Southampton, UK
Atlas of the Seas around the British Isles,
Ministry of Agriculture, Fisheries and Food

The illustration opposite shows in colour results of predicted tidal ranges for the North Channel, in comparison to the drawings of the above-mentioned atlas. It highlights the capability for TELEMAC-2D to predict the amphidromic point (absence of tidal range) between Islay and Kintyre Peninsula in Scotland.

Additionally, colour contour maps will compare spatial variations of maximum depth-averaged current speed and of cotidal lines, or lines along which high water occurs at the same time, and maximum tidal current velocity during mean spring tide (MAFF, 1981).

## 4.4 Graphic outputs for the scenario analysis

A number of additional plots and maps will be produced to help with the impact assessment of the scenarios relative to the base case scenario or to any other scenario. Comparisons will be made between similar individual plots and maps, where the individual plots or maps represent the implementation of different scenarios. In addition, plots and maps of the difference of two CSM outputs or processed outputs will also be produced.

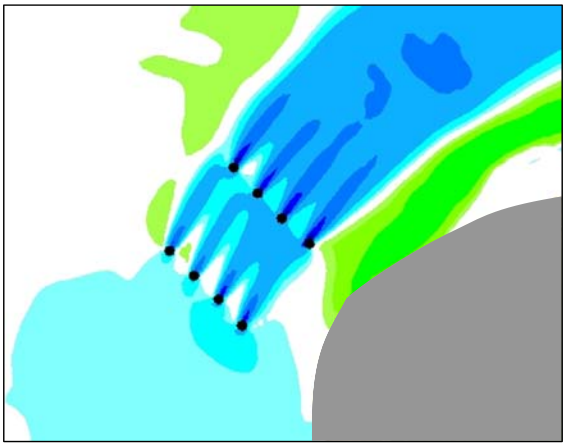
Time histories of predicted depth-averaged current speed and depth-averaged kinetic power density extracted at the tidal current sites will be produced for spring and neap conditions separately and together without and with the energy scheme. The spring and neap periods will be consistent (i.e. both start with an ebb or a flood cycle). In these figures the operational thresholds will be indicated for reference.

Colour contour maps will present the spatial variations of the mean and maximum tidal range, and the highest and lowest tidal levels.

Colour contour maps will present the spatial variations of predicted depth-averaged current speed for peak flood and peak ebb for both the neap and spring tides.

The illustration opposite shows a colour contour map of the impact of an energy scheme on the depth-averaged current speeds predicted by the model in the area of interest, computed as a difference in speed with and without the energy scheme in place.

This case was implemented with a significant level of detail around individual devices and shows the wake/shadow effect. In green, the flows have accelerated compared to the base-case scenario and in blue, the flows have slowed down.



While the CSM would not, given its proposed resolution, show the impact of individual turbines as is the case in this illustration, similar maps will show the total footprint of expected changes in current speed or tidal range due to the presence of the tidal current energy scheme.

Colour contour maps will present the proportion of time when the predicted current speed exceeds a given value threshold within the representative tidal period. This value threshold may vary depending on the technology used and local conditions. For every value in the threshold, the proportion of time will be computed at every mesh nodes by summing the time where the value is exceeding that value by reference to the length of the representative tidal period.

Cumulative probability distributions of predicted depth-averaged current speed and depth-averaged kinetic power density extracted at the tidal current sites will be produced for spring and neap conditions separately and together with and without the energy scheme present. Again, the spring and neap periods will be consistent (i.e. both start with an ebb or a flood cycle) and the operational thresholds will be indicated.

## 4.5 Graphic outputs and processed outputs for the cost of energy model

For tidal range energy schemes, a number of additional processed outputs will be generated specifically for use by the *Cost of Energy* (CoE) model and described in a separate report (D04 – Cost of Energy Model and supporting documentation). Full detail of the Cost of Energy input requirements from the CSM model are included in Appendix C. They will include, but may not be limited to, the following.

Time histories of predicted free surface elevation will be presented for both spring and neap conditions, both upstream or downstream of the structure of the tidal range energy scheme. They will inform the design and expected efficiency of the scheme.

Bathymetric profiles showing the spatial variations of the seabed along the structure will be re-sampled from the CSM to document the water depth at the toe of the structure. Similarly for tidal current energy schemes, an averaged bathymetric value of the seabed within the polygon representing the farm will be extracted from the CSM. These bathymetric values will depend on the resolution of the CSM.

Information about the energy scheme implemented will be available from the CSM to the CoE model, based on user inputs including its characteristics (number, size, type of turbines or sluice gates), its operational mode (for instance, thresholds, ebb only or flood and ebb operation). Total energy yield for the average 15-day period will also be computed by the CSM.

Finally, tables will also be produced that estimate the surface area covered by the water held behind a tidal range structure between MLWS and MHWS. These will be computed from the seabed elevation map developed for the CSM, particularly from the MLWS and MHWS contour lines and are therefore also depending on the resolution of the CSM. The values of MLWS and MHWS will be extracted separately, as will the total intertidal tidal area loss compared to base-case scenario and the average bed level of the embankment.

## 5 KEY FINDINGS

- The CSM will extend offshore slightly beyond the Northern European continental shelf and cover the coastlines of the United Kingdom, Ireland, the Channel Islands, France, Belgium, the Netherlands, Germany, Denmark, Sweden and Norway. It will include, amongst others, the Malin Sea, Irish Sea, Celtic Sea, English Channel and the North Sea.

- Admiralty Chart data will be processed and provided by SeaZone of HRW to develop the CSM model seabed map up to the highest astronomical tide level.

- The resolution of the CCSM will not be sufficient to represent the details of some of the narrowest inlets and channels. The purpose of the CCSM is primarily to provide preliminary impact assessment results for the entire Northern Europe continental shelf while remaining practical to use on a standard desktop computer. Although the resolution of the DCSM will provide more details it remains, similarly to the CCSM, a model of the entire Northern European continental shelf and should not be used in place of a refined local model when considering resources / impacts in specific areas.

- Only deep water tidal harmonic constituents will be considered at the offshore boundary of the CSM. The CSM will predict the shallow water and friction effects yielding non-linear tidal harmonic constituents at sites nearer the coasts.

- Generic parameterised formulations have been developed to represent tidal range and tidal current schemes at the scale and resolution of the CSM and cater for all types of current and future technology. Similar (but less detailed) parameterised formulations have been used in the past and implemented in the TELEMAC system for practical applications. The end-user of the model will need to supply his / her own input parameters based on the scenario tested. A selection of scenarios will be developed during the project to help the user set up specific cases after the project is completed.

- The development of the CSM will comply with the most recent draft technical specification from the IEC, a standard recognised by the marine renewable energy industry. In cases where the EMEC guidance is more stringent, it will generally be followed in place of the IEC draft technical specification.

## 6 CONCLUSIONS AND RECOMMENDATIONS

The ETI is proposing to develop a Continental Shelf Model 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, in collaboration with HR Wallingford and the University of

Edinburgh, is providing support with regard to the development of this model and subsequent use by the marine renewable energy industry.

This specification document provides the objectives and requirements for the Continental Shelf Model.

The Continental Shelf Model developed in this project will be versatile, and implementation of various energy schemes by the end-user will be made possible by the use of generic parameterisations of tidal range and tidal current energy schemes. It is noted that it will also be possible to implement other types of technologies, even wind turbines (modelled as drag force), should it be required to identify the likely impact of the civil works on the flow regime and its interaction with other schemes investigated in the Continental Shelf Model.

National / international guidelines will be followed to ensure adequate validation of the Continental Shelf Model. Some output will be generated specifically for the validation of the model. An example is the comparison of observed and predicted harmonic constituents (amplitude and phase) at representative locations throughout the model. It is expected that spatial maps showing the impact before / after scheme implementation, and cumulative probability distribution plots, will be most relevant when analysing the model results for various scenarios.

It is noted that the development of the tidal power industry is still at an early stage, particularly tidal current (although also technologies such as the Rolls-Royce tidal range turbine). The methodology described in this document may therefore need to be subject to update after the project has been completed as the resource and its response to power extraction become better understood (e.g. through knowledge gained from PerAWaT and the deployment of the first large-scale farms).

## 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.

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).

CCSM – Coarse Continental Shelf Model.

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.

DCSM – Detailed Continental Shelf Model.

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 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 (v2/2g), where v is velocity and g is gravitational acceleration. Head is often used meaning the total head difference (energy loss) 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.

MHWS – Mean High Water Springs
The height of Mean High Water Springs is the average, throughout a year, of the heights of two successive high waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is greatest.

MLWS – Mean Low Water Springs
The height of Mean Low Water Springs is the average, throughout a year, of the heights of two successive low waters during the same periods.

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 the 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.

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.

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# GUIDE TO APPENDICES

**Appendix A – Tidal Current Parameterisation**

**Appendix B – Tidal Range Parameterisation**

**Appendix C – Cost of Energy Model input requirements**

# APPENDIX A – TIDAL CURRENT PARAMETERISATION

## TIDAL CURRENT ENERGY DEVICE PARAMETERISATION

The introduction of a tidal current energy converter (TEC) device impacts the local tidal dynamics through a number of distinct physical interactions including:

1. The energy transferred from the fluid to the TEC device power capture element (e.g. rotating turbine element) during the operational phase acts as a retarding force on the fluid system (the force opposing the thrust acting on the TEC). This interaction will be referred to as the *energy harvesting* force.
2. Skin friction and pressure drag imparted by the fluid interaction with the TEC device (in particular the device support structure) acts as a further retarding force on the fluid system. This interaction will be referred to as the *device drag* force.
   The mixing downstream of the device between the free-stream region and the wake generated by the fluid-device interaction described in step 1 acts as a further retarding force acting on the fluid system. This interaction will be referred to as the *wake mixing* force.
3. The presence of the device reduces the cross-sectional area of the surrounding channel. This interaction will be referred to as the *area reduction* effect.

These processes occur at the device scale, and therefore will not be explicitly captured within the CSM model due to the resolution of the CSM grid. Hence, these physical interactions will instead be modelled using additional source terms and body forces in the momentum equations in a similar manner to the Coriolis and sea-bed friction described in Section 3.3.2. The difficulty in developing appropriate parameterisations is the lack of detailed measurement and observational data of full-scale TEC devices in the open-sea environment that can be used to inform and validate the parameterisation approach. The method adopted is to consider the impact that device presence and operation would have on the fundamental physics. The purpose of this appendix is therefore to describe the basis for the parameterisation terms to be included in the model.

### Parameterising the energy harvesting force

The energy harvesting force ($F_E$) has already been defined as the (equal and opposite) force opposing the thrust acting on a TEC device. The well-known equation describing thrust is

$$T = \frac{1}{2} C_T \rho A_d U^2$$

where $T$ (N) is the thrust, $C_T$ (non-dimensional) is the thrust coefficient, $\rho$ (kgm$^{-3}$) is the fluid density, $A_d$ (m$^2$) is the area of the capture element (e.g. the swept area for a horizontal-axis device), and $U$ (ms$^{-1}$) is the velocity acting on the device (assumed to be the depth-averaged velocity herein). The difficult with adopting this expression as the starting point for parameterising the energy harvesting force is that the value of $C_T$ varies with $U$. The relationship between these two terms has not been widely disclosed by existing tidal device developers and is difficult to infer. The limited full-scale device performance data that has been released in the public domain relates to the device power output (e.g. see figure A1). Fortunately, this provides an avenue to proceed, as the force acting on the device and power generated are related as

$$Power = Force \times Velocity$$

Hence, the energy harvesting force can be inferred through knowledge of the device power output, (device conversion efficiencies (detailed at the end of this section), and the local flow velocity. The CSM will provide the necessary velocity information, leaving a requirement for definition of the appropriate power generated by the device. If the power generated by a device can be directly related to the local velocity (via a power curve for instance if following the methodology adopted by the IEC Standards), then the energy harvesting force in a computational cell can be stated as:

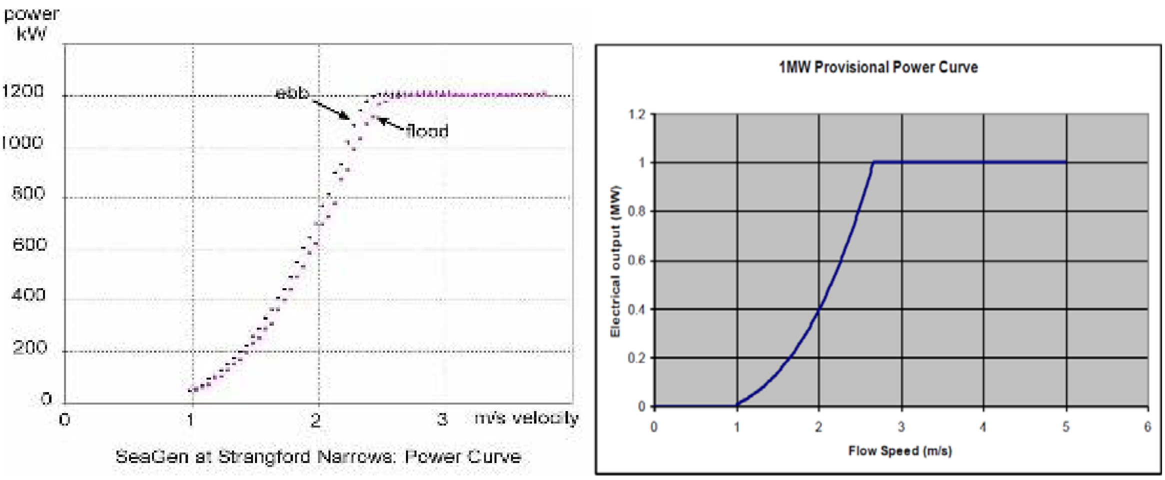

**Figure A1: Publicly available TEC device performance data derived from full-scale open-sea testing [1, 2].**

$$F_E = \frac{1}{E_f}\frac{nP}{\Delta x.\Delta y.h.\rho.U}$$

where $E_f$ is the water-to-wire efficiency, $\Delta x.\Delta y.h$ represents the volume of the computational cell that the device is located within, $n$ is the number of devices located within the cell, and $P$ (W) is the power harvested by the device. $F_E$ is appropriately expressed in units of ms$^{-2}$ in order to match the units of $F_x$, $F_y$ expressed in the momentum equations listed in Section 3.2.3.1.

Prescribing device power characteristics

Turbine device performance characteristics for public consumption are generally presented in the form of a power curve relating the power produced to the input flow velocity as depicted in the two tidal turbine power curves in figure A1. These two power curve figures represent the only representation of tidal device performance with a basis in full-scale open-sea testing available in the public domain. The two curves share common characteristics that are also generally observed in more readily available wind turbine device performance data representations:

- At low flow velocities there is no power generation, as the thrust imparted by the fluid on the device performance surface is not substantial enough to overcome the friction in the turbine system or it is not economically worthwhile to generate (the velocity condition at which the device begins operation is referred to as the *cut-in* velocity).
- At a prescribed power level the device reaches the maximum design performance of the power take-off system (referred to as the *rated power* that occurs at the *rated velocity*).
- Above rated velocity the power output is maintained at rated power (practically this can be achieved by various different design choices - pitching the turbine blades to alter the angle of attack is a common approach).
- The rated power of a particular device is a function of both the rated velocity of the device, and the area of the performance surface area of the device (the swept area in the case of a horizontal-axis device).
- In between the cut-in and rated velocities, the power generated increases with increasing input velocity.
- A typical turbine will be designed to optimise the efficiency of the device at and around the velocity conditions that maximise the average device power output across a tidal cycle.

Envisaging a future TEC device manufacturing industry that adopts a similar approach to the wind energy original equipment manufacturer (OEM) technology production model, it is likely that tidal turbines will be provided across a range of predefined rated velocities and device diameters rather than as bespoke solutions for each individual project. A project developer will therefore select from the available off-the-shelf products to identify the best fit to the site conditions for that particular development. In reality a variety of different device ratings and diameters may well be deployed across one site to produce an overall farm of devices that best utilises the local resource within the constraints applicable to that location. Hence, it is necessary to provide a common definition of a range of tidal turbine devices to be deployed within the CSM. Given the potential range of device performance across a variety of combinations of rated velocity and swept area of the turbine, the intention is to derive a formulation that provides a best fit with the two existing power curves in figure A1. Hence the instantaneous power harvested $P$, is derived dependent upon the instantaneous velocity $U$, cut-in velocity $U_c$, rated velocity magnitude $U_r$, and the device performance surface $A_d$:

```
If($U$.le. $U_c$)then
        $P = 0.0d0$
ElseIf($U$.gt.$U_c$.and.$U$.le.$U_r$)then
        $P = A_d*((-0.151U^5)+(1.25U^4)-(3.842U^3)+(6.44U^2)-(5U)+1.382984)$
ElseIf($U$.gt.$U_r$)then
        $P = A_d*((-0.151U_r^5)+(1.25U_r^4)-(3.842U_r^3)+(6.44U_r^2)-(5U_r)+1.382984)$
EndIf
```

This formulation was derived by interrogating the data provided in figure A1 to provide details of the variation of the power capture of the two listed devices, and then fitting a 5th order polynomial to best describe the variation with increasing velocity. The excellent agreement achieved is highlighted in the comparison in figure A2. Returning to the original definition of the thrust acting on the rotor surface presented in the first equation, the equivalent thrust that is implied by the power curves in figure A2 is presented diagrammatically in figure A3.

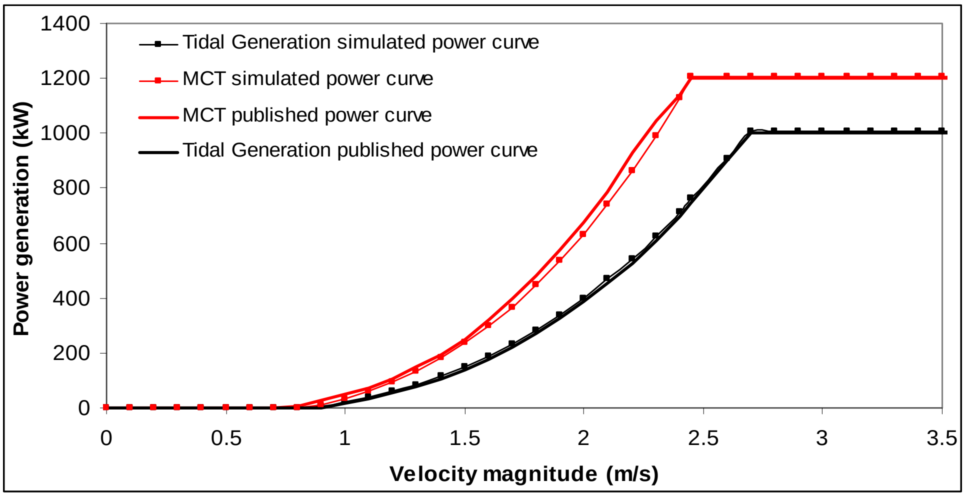

**Figure A2: Comparison of public domain device performance characteristics with power curves derived from the derived analytical expression (Performance surface of MCT device taken as 402 m$^2$ (2 x 16 m diameter), Tidal Generation device taken as 254 m$^2$ (18 m diameter)).**

The generic device properties are presented in figure A4 – the power output listed is per square metre of performance surface. Selection of the available device rated velocities and performance surface areas will be detailed further in WP2 and the associated D3 deliverable.

The final aspect of parameterising the energy harvesting force *acting on the fluid system* is to consider the efficiency of conversion from the fluid system through the device to electricity provided to the grid (the water-to-wire efficiency, E*f*). Two separate contributors to energy loss are

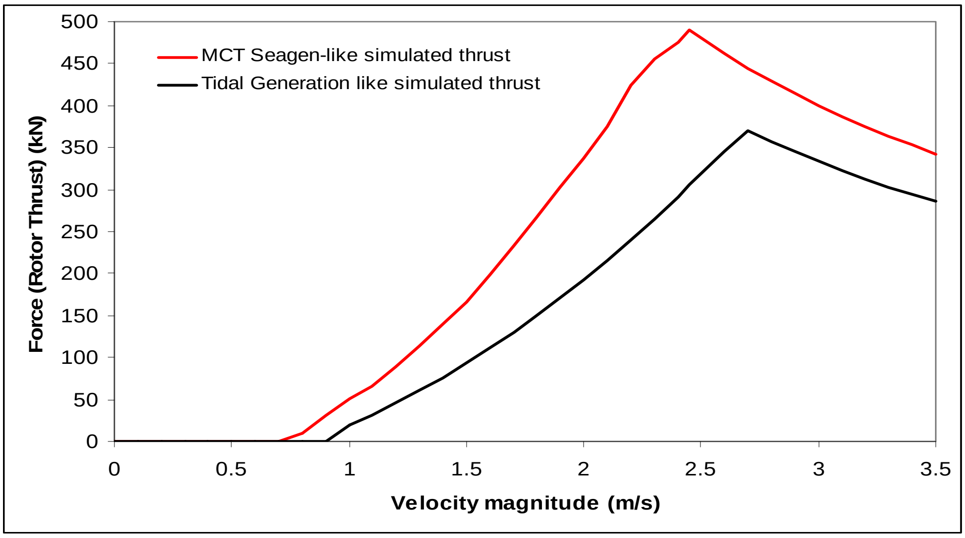

**Figure A3: Force acting on the device performance surface derived from the power curves in A2.**

considered, First, the hydrodynamic efficiency of the device performance surface (e.g. turbine blades), represented as $E_H$, and the mechanical conversion efficiency (e.g. accounting for losses due to the inefficiency of the power-take-off and grid conditioning systems), represented as $E_C$.

$$E_f = E_H E_C$$

Hence the overall device efficiency can be expressed by the user as desired for a particular simulation. Throughout the CSM scenario analysis, efficiencies of 85%, (hence a loss of 15%) will be assumed for both $E_H$ and $E_C$. Therefore a cumulative efficiency factor of 0.7225 will be applied to the energy harvesting force term throughout the CSM scenario analysis. This efficiency factor would be equivalent to the wind energy case where the Betz limit can be strictly applied to an assumption of overall device efficiency ($C_p$ [electrical] often quoted in the literature) of 0.42. These assumptions may be slightly conservative for certain technologies, and optimistic for others, but whether this ‘efficiency factor’ is 0.7225 or (for example) 0.80 will have limited impact on the overall CSM results given the other less understood parameters to be introduced below.

To future proof application of the model an additional representation of the energy harvesting force will be implemented based upon the assumption that the variation of the thrust acting on the TEC device of interest was known:

$$F_E = \frac{1}{E_f} \frac{nT}{\Delta x . \Delta y . h . \rho} \, .$$

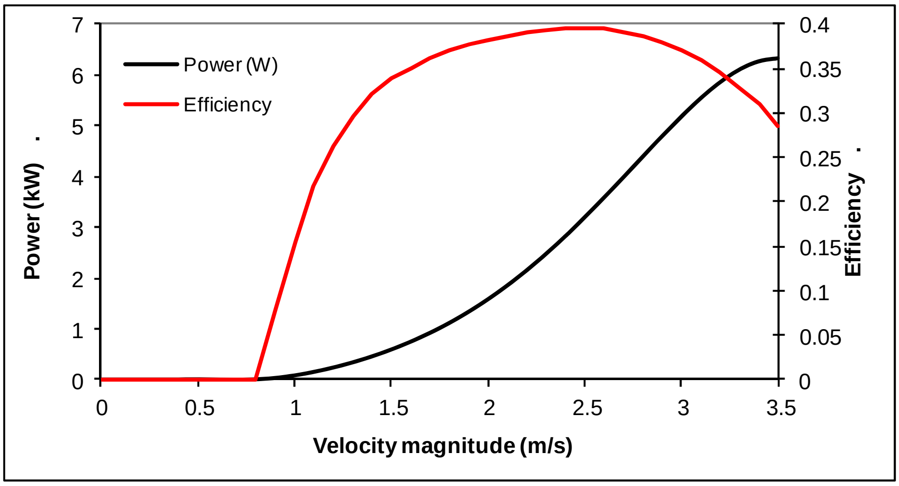

**Figure A4: Generic device characteristics (1 m$^2$, no rated velocity prescribed).**

## Parameterising the device drag force

The device drag force $F_D$ describes the influence of skin friction and pressure drag from the fluid-structure interaction. The TELEMAC model being applied in this project already contains an appropriate formulation for prescribing this parameter under certain simplifying assumptions. The primary assumption is that the majority of the drag force is contributed by the device support structure, and that the support structure elements can be simply described as having a projected dimension perpendicular to the flow direction (it will additionally be assumed that the support structure members are cylindrical). Accepting these assumptions, and the limitation of only enabling prescription of simple support structures (e.g. monopiles and jacket foundations), the existing well-proven drag formulation in the TELEMAC system is adopted:

$$F_D = \frac{n}{A}\frac{D}{2}C_D U^2 \times \left(\frac{\min(h,d)}{h}\right)$$

where: $n$ = the number of devices in the computational cell.
$D$ = the diameter of the support structure cylindrical elements.
$A$ = the surface area of the computational cell.
$C_D$ =non-dimensional drag coefficient.
The final term in brackets describes whether the structure is submerged or surface piercing ($d$ is the height of the vertical structure).

The only term that requires additional discussion is prescription of the non-dimensional drag coefficient. The ‘building blocks’ of the support structure have already been assumed to be cylindrical. Figure A4 details the variation of $C_D$ with Reynolds number. High-energy tidal flow regimes tend to have a Reynolds number in the region $10^6$, at which stage the boundary layer has become fully turbulent and hence $C_D$ values of 0.3 are quoted in standard engineering texts [3]. However the sensitivity of the parameterisation to the value of the drag coefficient is significant, as if the boundary layer remained laminar (even although the free stream flow is turbulent), the value of the drag coefficient would jump up to around 1.0 (see figure A5). Work presented in [4] demonstrated the importance of minimising the energy lost to the system due to the device drag force, particularly when an upper limit on flow disturbance (e.g. reduction in peak velocity) is imposed for environmental protection reasons. Ensuring that the support structure does in fact induce a turbulent boundary layer will therefore become an important design consideration as the sector moves towards maturity (e.g. an appropriate level of surface roughness can ‘trip’ the boundary layer from laminar to turbulent). Additionally, marine structures are also susceptible to marine growth, and this can significantly increase the drag coefficient. Finally it is instructive to observe images of the wake around the MCT Seagen device where it is obvious that flow separation occurs on the upstream face of the monopile at the free surface, indicative of a laminar boundary layer (even although the Reynolds number would be expected to be above $10^6$). This may well be related to the additional structural elements attached to the monopile that will alter the fluid-structure interaction.

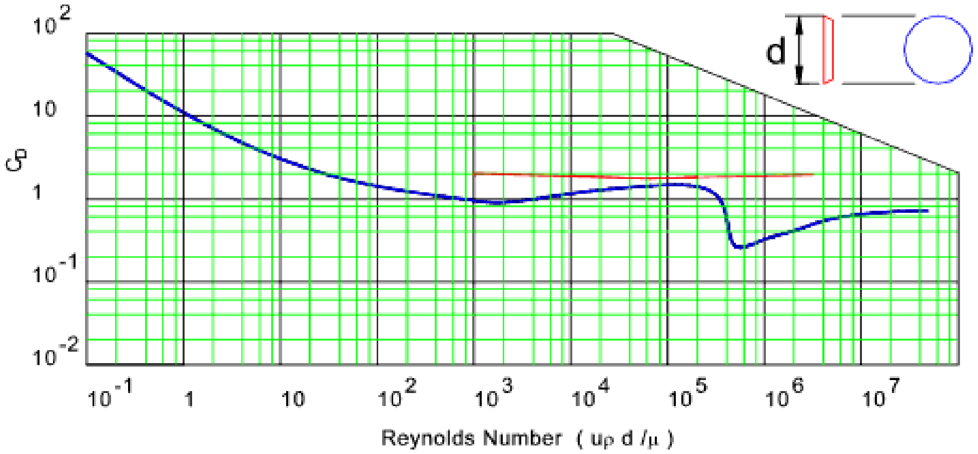

**Figure A5: Variation of drag coefficient with Reynolds number for a cylindrical pile (source [5]).**

For the purposes of this analysis, a $C_D$ value of 0.3 will be assumed, as when devices reach mass production, there will be a strong incentive to minimise drag on the support structure – however it must be highlighted that this could be considered an optimistic assumption. Evaluating the equivalent power generation that this equates to as presented in figure A6 indicates that losses due to support structure drag accounts for 15-30% of the power generated at rated velocity, and significantly more above rated velocity when considering highly simplified representations of existing full-scale device support structures. If the turbulent boundary layer, high Reynolds number conditions previously detailed as required to ensure a low drag coefficient were not achieved and the drag coefficient reverted to the range 1.0-1.2, then a similar amount of retarding force would be imparted from the fluid system in terms of overcoming support structure drag as was directly contributing to power generation. In these circumstances, investigation of support structure elements with more streamlined or slender shapes orientated in the principal current direction would definitely be of economic benefit to a project even though the machining of more complex support structure shapes would itself come at a price (e.g. a more streamlined ellipse with the same frontal area as the circular pile considered thus far would reduce the value of $C_D$ to 0.2 with a 2:1 streamwise length-width ratio and 0.1 with a 8:1 ratio). The next generation Seagen 'U' technology proposals [6] already present an example of a device manufacturer incorporating support structure elements that are streamlined in the over-arching device design in order to reduce the device drag force.

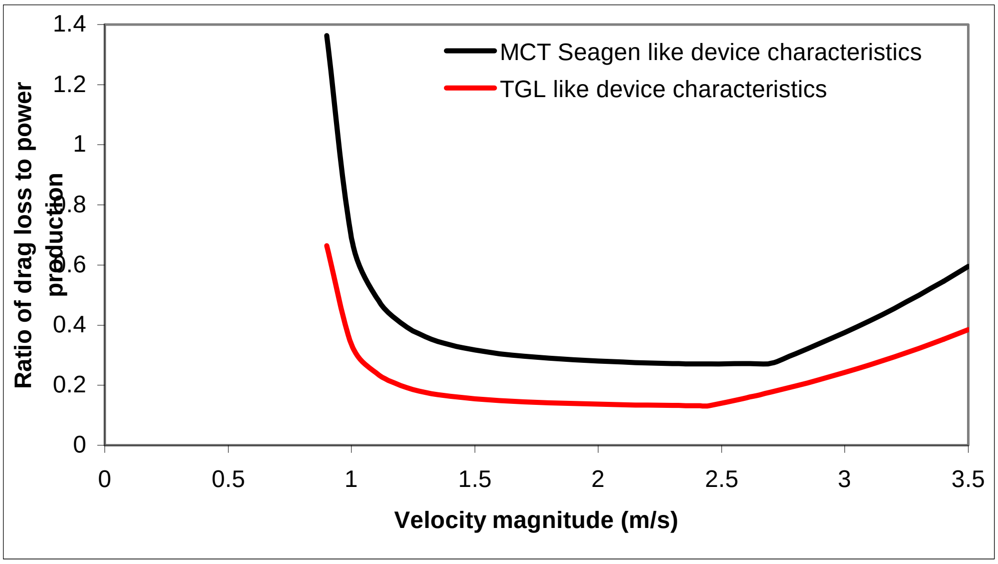

**Figure A6: Rough estimation of ratio of drag loss (W) to power production (W) for two simplified tidal device types (one submerged, one surface piercing).**

## Parameterising the wake mixing force

Parameterisation of the wake mixing force has yet to be presented in the existing tidal energy literature in a form that would be appropriate for inclusion in a tidal hydrodynamic model. While there has been some progress from an analytical perspective in understanding the 1-dimensional response using actuator disk theory [e.g. 7], this is difficult to translate to hydrodynamic application. What [7] does demonstrate is that if the actuator disk is working at optimal conditions the energy loss in the wake mixing process is equivalent to half of the power generated by the device (under certain simplified conditions). However, an actuator disk is also a simplification of the underlying physics in the first place!

Turning instead to the related field of wind energy, it is apparent that although significantly more mature as both an industry and field of scientific research, the energy lost due to wake mixing force has not been appropriately derived or parameterised. Observational studies of full-scale arrays of device operation do provide some relevant insight, but no overarching theory is provided – the existing engineering interest appears to have been in defining the flow reduction in the wake rather than understanding how much of the energy loss occurring in the device wake can be specifically ascribed to wake mixing. Knowledge transfer that can be of benefit is that the turbulence intensity is significantly increased in the wake region, and the ‘recharge’ of the reduced flow region in the wake is sensitive to the overall amount of turbulent intensity (so wake lengths tend to be longer offshore than onshore as the background turbulence intensity on land is higher due to the non-uniformity of the boundary (terrain) and presence of various scales of roughness element (e.g. trees, buildings, etc.)). The background turbulence intensity in areas of interest for harvesting tidal current energy are likely to be more like onshore than offshore experience as the variability of the seabed and relative roughness is more similar to the onshore situation in coastal seas. The importance of turbulence intensity in wake mixing/recovery highlights one of the limitations of the majority of existing laboratory based analyses of TEC device interactions – that the background turbulence intensity in laboratory simulations is generally significantly below that observed in the field.

Nonetheless, the question remains unanswered as how best to parameterise the wake mixing force. Assessing from a physical interaction perspective, the energy loss in the wake is associated with the transfer of energy from the free-stream into the wake, hence it is the gradient between the two flow regions that drives the recovery of the wake, but the process is inefficient – the system energy loss is in the form of heat generation when mixing takes place. In a hydrodynamic modelling context, these mixing processes will be sub-grid scale. What is therefore proposed for this project is an assumption that the variation of the wake mixing force/losses has a direct relationship with the variation of the thrust acting on the device capture element. This is deemed logical, as the velocity reduction in the wake will be related to the amount of energy being harvested. It is also considered representative that losses due to wake mixing above the rated velocity of a device will remain constant, as the increase in flow velocity in the free-stream will be matched by the increase in flow velocity in the wake (to the first order). The ETI-TRM Deliverable D01 [8] proposed that a median value for the wake mixing force would be 10% of the energy harvesting force in line with sensitivities adopted in [9]. It is acknowledged that this is an engineering solution as opposed to an exact scientific representation. Hence, when implemented in the TELEMAC code, the $F_M$ term will be configured to allow the user to input the mixing ‘efficiency’ ($E_M$). If $E_M$ is set by the user to equal 0, this would be equivalent to removing the wake mixing force parameterisation from that particular simulation. The wake mixing force parameterisation is therefore represented as:

$$F_M = E_M F_E = \frac{E_M}{E_f} \frac{nP}{\Delta x . \Delta y . h . \rho . U}$$

## Parameterising the area reduction effect

The final physical interaction with the existing tidal hydrodynamic system induced by the introduction of TEC devices is the reduction in cross-sectional area. TELEMAC already has a parameterisation methodology for dealing with obstacles smaller than the size of the mesh that is termed 'porosity' [10]. Hence this could be easily implemented. However, given that the plan area of a device (order 5-20 $m^2$) is so insignificant in comparison with the remaining plan fluid area (10000 $m^2$ assuming the basic device spacing recommended in [8] with an assumed turbine diameter of 20 m), the impact of imposing the resultant porosity within the model is negligible. Hence it is proposed that area reduction is not considered further.

## Conclusion

This appendix has presented a means of parameterising the physical impacts on tidal physics arising from the addition and operation of TEC devices in the CSM domain. The parameterisations are presented in the form of additional body forces to be applied as part of the CSM momentum equations. Summarising these additional body force terms in the x- and y- directions,

$$F_x = F_{Dx} + F_{Ex} + F_{Mx}$$
$$F_y = F_{Dy} + F_{Ey} + F_{My}$$

The three components of the additional overall body force term have been prescribed as a function of:

- The CSM primary variables (water depth $h$ in metres and current velocity $u$ and $v$ in m/s), which the CSM predicts (at all simulated times).
- The properties of the TEC device(s) to be deployed.
- Appropriately justified empirical coefficients.

As technology developers and the research community gain additional experience and better understanding of the properties of TEC devices and their operation, it would be a very simple operation to alter the empirical factors adopted in each of the new body force terms. For instance, the polynomial representation of the variation of power generated by a device used in prescription of $F_E$ could be selected to be representative of any power curve that a device manufacturer releases in the future. Similarly, $F_D$ could evolve to represent the device drag force as explicitly measured and specified by the technology provider, or if the resolution of the CSM was significantly increased, the device support structure could be explicitly represented as an island element (land – hence no flow) representative of complete blockage (assuming the support structure was surface piercing). The project team believes this provides the most appropriate and flexible means of incorporating TEC devices in the CSM environment.

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# APPENDIX B – TIDAL RANGE PARAMETERISATION

## TIDAL RANGE ENERGY DEVICE PARAMETERISATION

### Notation

$A$ = cross section area
$A_{1sluice}$ = sluice throat area
$A_{0sluice}$ = sluice exit area
$A_{1turbine}$ = turbine throat area
$A_{0turbine}$ = turbine exit area
$A_t$ = Turbine swept area for Rolls-Royce turbines
$A_{t9m}$ = Turbine swept area for 9m dia. Rolls-Royce turbines
$A_{t14m}$ = 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
$D$ = turbine runner 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
$g$ = acceleration due to gravity
$H$ = loss of total head across barrage structure
$H_{min}$ = minimum operating head
$H_{int}$ = intermediate head
$H_{rated}$ = rated head
$H_{P,min}$ = minimum pumping head
$H_{P,max}$ = maximum pumping head
$h$ = water level
$J_1,J_2,J_3,J_4$ = pumping discharge/head characteristics
$K_1,K_2,K_3,K_4$ = pumping power/head characteristics
$k$ = 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
$N_{9m}$ = number of 9m dia. Rolls-Royce turbines
$N_{14m}$ = number of 14m dia. Rolls-Royce turbines
$n$ = rotational speed of turbine
$n_{11}$ = unit speed of turbine
$P$ = power
$P_{max}$ = turbine power at rated head / generator capacity including turbine and shaft (gearbox) losses
$Q$ = discharge
$Q_{11}$ = specific discharge of turbine
$R_1,R_2,R_3,R_4$ = 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
$CW_{sluice}$ = width of sluice caisson
$CW_{turbine}$ = width of caisson
$t$ = time since previous high or low water sea level
$T_{start}$ = turbine starting time
$U_1,U_2,U_3,U_4$ = 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
$W_1,W_2,W_3,W_4$ = pumping discharge/head characteristics for 9m dia. Rolls-Royce turbines
$X_1,X_2,X_3,X_4$ = pumping power/head characteristics for 9m dia. Rolls-Royce turbines
$Y_1,Y_2,Y_3,Y_4$ = pumping discharge/head characteristics for 14m dia. Rolls-Royce turbines
$Z_1,Z_2,Z_3,Z_4$ = pumping power/head characteristics for 14m dia. Rolls-Royce turbines

$\alpha_{ebb}$ = sluice discharge coefficient on ebb tide
$\alpha_{flood}$ = sluice discharge coefficient on flood tide
$\beta_{ebb}$ = free-running turbine discharge coefficient on ebb tide
$\beta_{flood}$ = free-running turbine discharge coefficient on flood tide
$\eta$ = turbine efficiency
$\rho$ = density

Subscripts
1 = upstream of barrage
0 = at barrage
2 = downstream of barrage
x = value summed over total ‘flow’ cross section

### Headloss across the barrage

The headloss across the barrage (H) is calculated using the method described in a paper on *One-dimensional modelling of tidal power schemes* by Keiller and Thompson (1981). The schematic diagram in Figure B1 is reproduced directly from the Keiller and Thompson paper (1981).

The water level difference across the barrage is given by the following equation:

$$h_1 - h_2 = H - \frac{Q_x^2}{2gA_{1x}^2} + \frac{Q_0^2}{2gA_2^2}\left[\left(\frac{A_2}{A_0}\right)^2 - \frac{2A_2}{A_0} + 2\right]$$

where H is the loss of energy (total head) within the barrage. Note that $Q_x/A_{1x}$ is the approach velocity to the barrage and that $A_2$ is the sluice/turbine caisson width multiplied by water depth, downstream of the barrage.

The headloss term (H) in the equation above allows the energy loss as water passes through the turbine/sluice caissons to be captured in the modelling. Discharge through the turbines/sluices is defined by equations that take account of the turbine efficiency losses, mechanical and electrical generator losses, contraction/inlet losses and the expansion/exit losses. The models calculate the discharge and electrical power output from the headloss across the barrage (H), which in turn is calculated using the water levels from the model upstream ($h_1$) and downstream ($h_2$) of the impoundment line. Effectively this means that the wake mixing area where water expands from the turbine/sluice exit ($A_0$) to turbine/sluice caisson width and full depth ($A_2$) is represented by the headloss equation.

The detailed application of these equations depends on the type of model. In the 0-d model, the upstream and downstream water levels are the basin and sea levels respectively. In the 2-d model, upstream and downstream water levels are the levels in grid cells either side of the barrage. This initial wake mixing where flows expand from the draft tube into the full cross section of the local grid cell is a sub-grid process: Any 2-d model assumes uniform flow and depth within each grid cell so is not able to represent the three-dimensional effects within this expansion zone (a 3-d CFD model would be required to do this). The implicit assumption is that the wake is uniform by the time it enters the 2-d model. The 2-d model then represents the expansion of the flow from the turbine/sluice caissons to the full impoundment line width.

This approach to the evaluation of head across the turbine was formulated in 1981 (Keiller & Thompson, 1981) and applied to the Severn Barrage Commission studies at that time and in many later studies including the DECC (2010) studies of the Severn. This formulation of the barrage equation was considered within the Joule, 2009 studies (Appendix A.2.2) but not included in their model formulation (Appendix A.2.1) as the difference between the two equations was considered small.

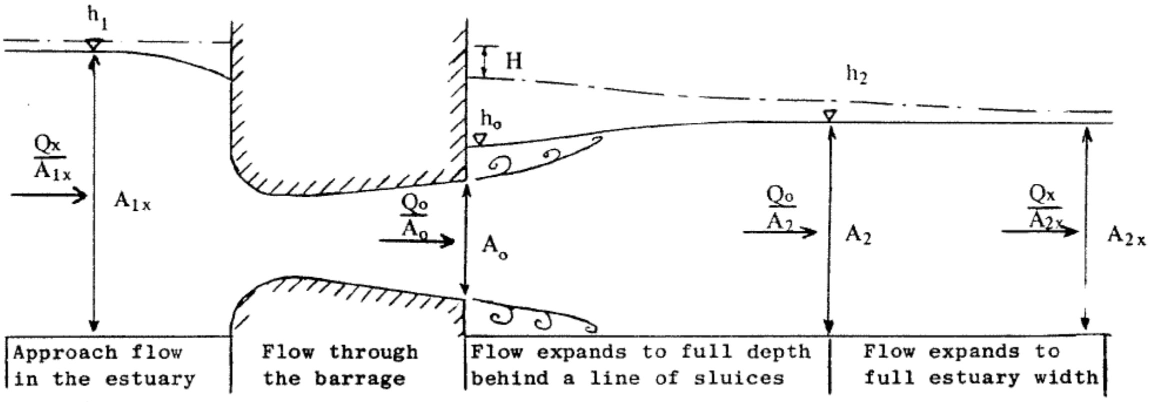


**Figure B1 Schematic diagram of discharge through sluices and turbines**

### Orifice sluice equations for discharge

The discharge through orifice sluices is calculated from:

$$Q_0 = A_{1sluice}\alpha\sqrt{2gH}$$

In previous studies of ebb-only schemes, sluices are usually closed throughout the ebb tide ($\alpha_{ebb} = 0$) to retain water within the basin and maximise high tide levels. In this study, sluices have been opened following ebb generation to maximise tidal range within the basin.

### Turbine equations for discharge and power (conventional turbines)

Free-running turbines

The discharge through the free-running (non-generating) turbines is calculated with an equation of the same form as for sluices.

When $H < H_{min}$:

$$Q_0 = A_{1turbine}\beta\sqrt{2gH}$$
$$P = 0$$

So setting $\beta = 0$ prevents the turbines from free-running. As with sluices, for ebb-only schemes, $\beta_{ebb}$ is usually zero to hold water within the basin after generation ends. In this study turbines are allowed to free-wheel after ebb generation to maximise tidal range within the basin.

Turbines generating

*Turbine hill chart*

A turbine hill chart relates unit speed ($n_{11}$), specific discharge ($Q_{11}$) and efficiency ($\eta$) during generation, where:

$$Q_{11} = \frac{Q}{D^2 H^{0.5}}$$

$$n_{11} = \frac{nD}{H^{0.5}}$$

The following sections explain how the turbine performance during generation has been parameterised.

*Selection of turbine diameter, rotational speed and rated capacity.*

Defining turbine diameter and rotational speed gives the head, discharge and power at any point on the hill chart as:

$$H = \left[\frac{nD}{n_{11}}\right]^2$$

$$Q = Q_{11} D^2 H^{0.5}$$

$$P = \rho g Q H \eta$$

where H = head across the turbine (m), n = rotational speed (rpm), D = turbine runner diameter (m), Q = discharge ($m^3/s$), P = power (W), ρ = density of water ($kg/m^3$), g = acceleration due to gravity ($m/s^2$) and η = efficiency (%).

*Route through the hill chart*

The route taken through the hill chart defines the specific discharge at each unit speed during normal operation of the turbine. This has been defined in two stages:

1. Starting from the highest unit speed, following the maximum output line through the hill chart until the generator capacity is reached.
2. Above the rated head, the specific discharge is reduced to maintain the power output at the rated power output.

This gives a table of values of $Q_{11}$, $n_{11}$, H, Q and P.

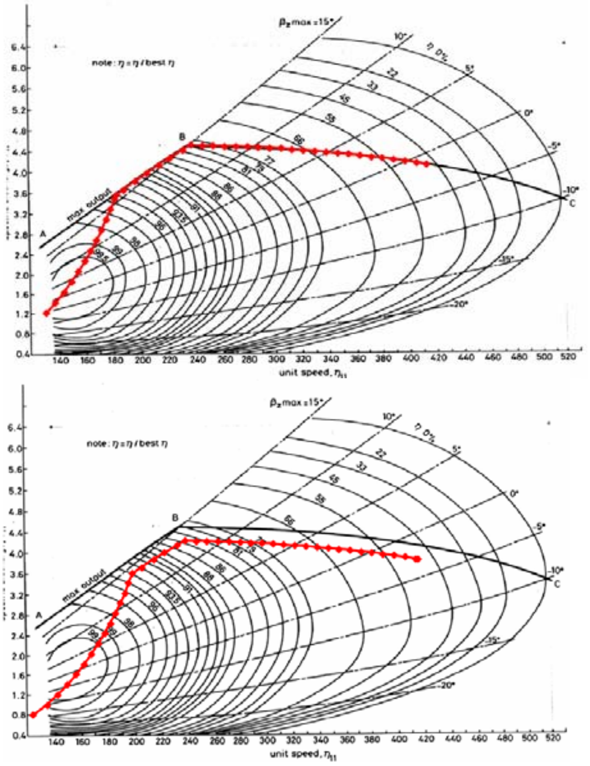
In this study the hill chart given in Baker (1991) has been used with the following modifications:

- For ebb-only operation, taking the maximum output line through the hill chart up to rated head.
- For dual operation, taking 95% of the maximum output line through the hill chart up to rated head. This is a simplification that approximates taking:
  - 100% of maximum output for ebb generation;
  - 90% of maximum output for flood generation (to account for less effective performance for flood generation); and
  - assuming that half the turbines face into the impoundment and half face out of the impoundment.
- The maximum turbine efficiency has been defined based on knowledge of turbine characteristics from previous studies including the Severn Estuary Tidal Power Feasibility Study (2010). It includes an allowance for:
  - the maximum turbine efficiency for hill charts of the type shown by Baker;
  - a step-up increase for majoration based on the turbine diameter; and
  - improvements in turbine design since the 1970s (on which the Baker characteristic is based).
- To generate power in both directions requires some modification to the turbine design, which reduces the efficiency of generation. For dual operation, maximum turbine efficiency has been reduced by 2.5%. This is equivalent to a 4% efficiency reduction for

flood generation and 1% efficiency reduction for ebb generation, taken as an average in both directions.

- The minimum turbine efficiency for generation is 45%. This defines a cutoff head below which no power generation will take place. Operating the turbines at lower efficiency will provide relatively little power but would damage the turbine and the greater turbulence would cause greater damage to fish.
- The generator efficiency is assumed to be 97.5%, so that the maximum turbine power $P_T = 1.026P_G$, where $P_G$ is the generator capacity.

Two examples of this methodology are shown in Figure B2, with the selected route overlain on the hill chart given in Baker (1991).



a) ebb-only generation b) dual (ebb-flood) generation

**Figure B2 Examples of route taken through hill chart**

*Deriving polynomial equations*

The turbine performance is represented in the hydrodynamic model using cubic polynomial equations. These equations are derived by first plotting discharge and power against head as a scatter plot. Four cubic polynomial trendlines are then fitted to the data points for:

- discharge between minimum and intermediate head
- discharge between intermediate and rated head
- discharge above rated head
- power below rated head

Note that the power above rated head remains constant at the generator capacity so a polynomial is not required.

The discharge and power cubic polynomial equations are as follows:

$H_{min} < H < H_{int}$

$$Q_0 = B_1 + B_2H + B_3H^2 + B_4H^3$$

$$P = F_1 + F_2H + F_3H^2 + F_4H^3$$

$H_{int} < H < H_{rated}$

$$Q_0 = C_1 + C_2H + C_3H^2 + C_4H^3$$
$$P = F_1 + F_2H + F_3H^2 + F_4H^3$$

$H_{rated} < H$

$$Q_0 = E_1 + E_2H + E_3H^2 + E_4H^3$$
$$P = P_{max}$$

Figure B3 shows an example of the cubic polynomial trendlines used to represent the data points relating head, discharge and power.

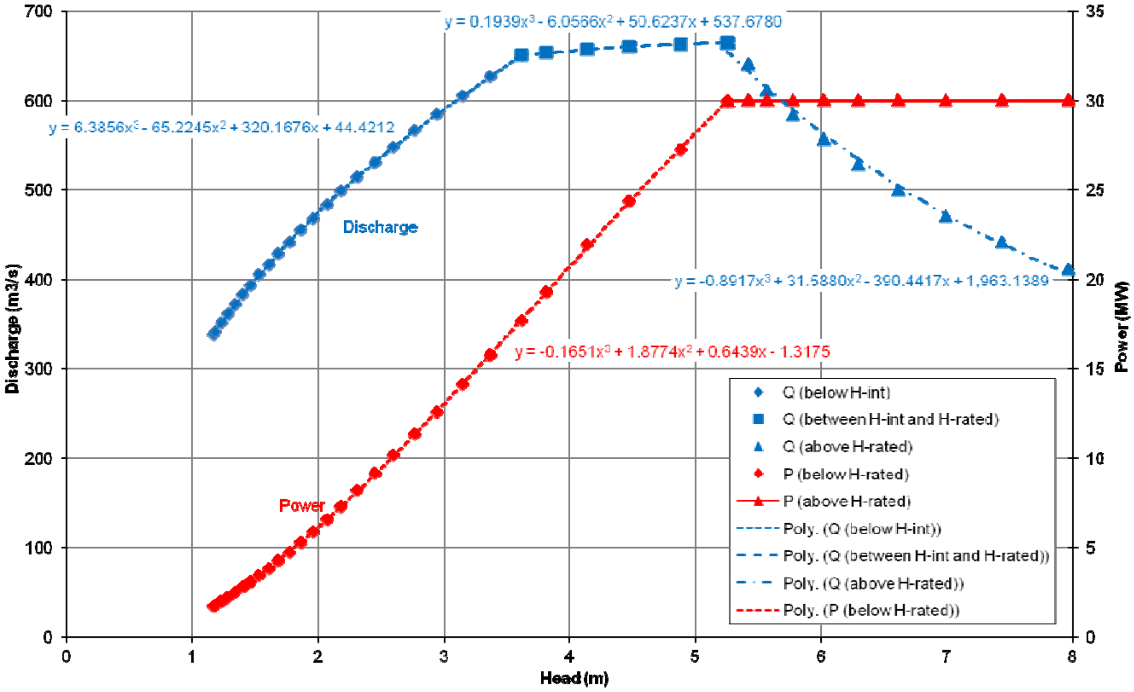


Figure B3 Example of deriving polynomial equations

Starting heads for generation

The head difference at which the turbines open for power generation is defined as a table of 12 data pairs relating high/low water level to starting head. The preceding high water level (for ebb generation) and low water level (for flood generation) is assessed from sea levels outside of the basin. Linear interpolation is used between the data points given.

| HW/LW | $H_{start}$ |
|---|---|
| $L_1$ | $H_1$ |
| $L_2$ | $H_2$ |
| $L_3$ | $H_3$ |
| $L_4$ | $H_4$ |
| $L_5$ | $H_5$ |
| $L_6$ | $H_6$ |
| $L_7$ | $H_7$ |
| $L_8$ | $H_8$ |

| | |
|---|---|
| $L_9$ | $H_9$ |
| $L_{10}$ | $H_{10}$ |
| $L_{11}$ | $H_{11}$ |
| $L_{12}$ | $H_{12}$ |

Starting time for generation

As a backup to ensure that there is generation on every tide, a starting time for generation has also been defined. Generation starts if $H > H_{min}$ and $t > T_{start}$, where t is the time since the last high water or low water sea level outside of the basin.

For all cases a maximum delay ($T_{start}$) of 5 hours has been used.

Ramp time

The 0-d modelling has assumed that all turbines will be switched on and off instantaneously. This cannot be done in practice because the hydraulic surge that would result when turbines start or stop would be large and likely to destabilise the hydrodynamic model. In addition, particularly for the larger tidal range schemes, the large increase or decrease in power delivered to the electricity grid would also cause major problems. These difficulties are overcome by including a ramp time that switches all the turbines and sluices on or off over a defined period. In the majority of cases this ramp time is set at 15 minutes but this period could be lengthened if it causes hydraulic or electrical problems.

Pumping

If the turbines are used to help refill and/or empty the basin by pumping it is necessary to define:

- the minimum/starting head for pumping ($H_{p,min}$);
- the maximum/finishing head for pumping ($H_{p,max}$);
- the relationship between head and discharge; and
- the relationship between head and power.

The head, discharge and power relationships are defined using cubic polynomial equations derived from a turbine pumping hill chart in the same way as described in Section on Turbines generating such that:

For $H_{p,min} < H < H_{p,max}$:

$$Q_0 = -(J_1 + J_2 H + J_3 H^2 + J_4 H^3)$$
$$P = -(K_1 + K_2 H + K_3 H^2 + K_4 H^3)$$

Pumping has not been included in the selections made for scenario development in this study.

**Turbine equations for discharge and power (Rolls-Royce turbines)**

Headloss across the barrage

The discharge and power equations for Rolls-Royce turbines have not been defined in the same way as for conventional turbines. The information provided by Rolls-Royce relates discharge and power to water level difference across the barrage ($h_1 – h_2$) rather than the loss of total head across the barrage (H). The 2-d model uses the water levels from the model grid upstream ($h_1$) and downstream ($h_2$) of the impoundment line to calculate discharge and power. It is assumed that Rolls-Royce have fully allowed for the energy losses related to turbine efficiency, contraction/inlet losses and the expansion/exit losses in their equations relating flow, power and water level difference at the barrage. As with conventional turbines, the wake mixing zone as flow expands from the turbine exit to caisson width is not represented by the 2-d model since it should already be represented by the discharge equation.

Free-running turbines

The equation for discharge with free-running Rolls-Royce turbines is slightly different to that for conventional turbines as it uses the water level difference across the barrage ($h_1 - h_2$) rather than the loss of total head across the barrage (H).

For $H < H_{min}$:

$$Q_0 = A_t\sqrt{2gk(h_1 - h_2)}$$
$$P = 0$$

The turbine area ($A_t$) is the rotor area minus both the hub area (taking the hub diameter as 30% of the rotor diameter) and the blade area (assumed to be 10% of the remaining area) so that:

$$A_t = \frac{819\pi}{4000}D^2$$

Turbines generating

The relationship between water level difference across the barrage, discharge and power is represented using cubic polynomial equations. Rolls-Royce provided the turbine performance table used for the SETS study relating water level difference, turbine discharge and turbine power. The turbine power was converted to generator output by applying 96% gearbox efficiency and 98% electrical efficiency. The cubic polynomial equations were derived by fitting trendlines to the data and are in the following form.

For $H_{min} < H$ and 9m diameter turbines:

$$Q_0 = R_1 + R_2(h_1 - h_2) + R_3(h_1 - h_2)^2 + R_4(h_1 - h_2)^3$$
$$P = S_1 + S_2(h_1 - h_2) + S_3(h_1 - h_2)^2 + S_4(h_1 - h_2)^3$$

For $H_{min} < H$ and 14m diameter turbines:

$$Q_0 = U_1 + U_2(h_1 - h_2) + U_3(h_1 - h_2)^2 + U_4(h_1 - h_2)^3$$
$$P = V_1 + V_2(h_1 - h_2) + V_3(h_1 - h_2)^2 + V_4(h_1 - h_2)^3$$

Starting heads and starting time for generation

The starting heads and times for generation are defined in the same ways as for conventional turbines (see Sections on Conventional Turbines Starting heads for generation and Conventional Turbines Starting time for generation).

Ramp time

The ramp times are defined in the same way as for conventional turbines (see section on Conventional Turbines Ramp time).

Pumping

If pumping is used, it is defined in the same way as for conventional turbines (Section on Conventional Turbines Pumping, except that the discharge and power is calculated from water level difference ($h_1 - h_2$) rather than the loss of total head across the barrage (H) so that the equations become:

For $H_{p,min} < H < H_{p,max}$ and 9m diameter turbines:

$$Q_0 = W_1 + W_2(h_1 - h_2) + W_3(h_1 - h_2)^2 + W_4(h_1 - h_2)^3$$

$$P = X_1 + X_2(h_1 - h_2) + X_3(h_1 - h_2)^2 + X_4(h_1 - h_2)^3$$

For $H_{p,min} < H < H_{p,max}$ and 14m diameter turbines

$$Q_0 = Y_1 + Y_2(h_1 - h_2) + Y_3(h_1 - h_2)^2 + Y_4(h_1 - h_2)^3$$
$$P = Z_1 + Z_2(h_1 - h_2) + Z_3(h_1 - h_2)^2 + Z_4(h_1 - h_2)^3$$

Pumping has not been included in the selections made for scenario development in this study.

## Results

### General

This section gives the adopted parameters for the schemes selected for scenario development in the *Tidal Range Resource Characterisation* (D1) report (B&V, 2011).

The following abbreviations have been used for the selected sites:

SF = Solway Firth
MB = Morecambe Bay
ME = Mersey
DE = Dee
SO = Severn Outer
SCW = Severn Cardiff-Weston
TH = Thames
WA = The Wash
HU = Humber
WB = Wigtown Bay
KB = Kirkcudbright Bay
CU = Cumbria
DW = Dee-Wirral
OX = Oxwich
AB = West Aberthaw
RH = Rhoose
BB = Bridgwater Bay
MO = Morte Bay
RB = Rye Bay
DY = Dymchurch

The following section presents the parameterisation required for each site selected in D1 – Tidal Range Characterisation for each turbine option, the Conventional turbine input parameters are provided initially, followed by the Rolls-Royce turbines input parameters.

## Conventional turbines input parameters

| Site | SF | MB | ME | DE | SO | SCW |
|---:|---:|---:|---:|---:|---:|---:|
| Mode | Ebb | Ebb | Ebb | Ebb | Ebb | Ebb |
| $N_{sluice}$ | 226 | 140 | 18 | 40 | 320 | 166 |
| $A_{1sluice}$ | 144 | 144 | 144 | 96 | 144 | 144 |
| $A_{0sluice}$ | 263 | 263 | 263 | 175 | 263 | 263 |
| $CW_{sluice}$ | 20 | 20 | 20 | 20 | 20 | 20 |
| $\alpha_{ebb}$ | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| $\alpha_{flood}$ | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| $N_{turbine}$ | 200 | 120 | 28 | 40 | 370 | 216 |
| D | 9.0 | 9.0 | 8.0 | 8.0 | 9.0 | 9.0 |
| $A_{0turbine}$ | 228.2 | 228.2 | 180.3 | 180.3 | 228.2 | 228.2 |
| $CW_{turbine}$ | 20.5 | 20.5 | 18.2 | 18.2 | 20.5 | 20.5 |
| $\beta_{ebb}$ | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 |
| $\beta_{flood}$ | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 |
| $H_{rated}$ | 5.25 | 3.30 | 5.17 | 4.61 | 6.33 | 6.33 |
| $P_{max}$ | 29 | 16 | 25 | 21 | 40 | 40 |
| $H_{min}$ | 0.87 | 1.16 | 1.24 | 1.11 | 1.18 | 1.18 |
| $H_{int}$ | 2.67 | 3.30 | 3.80 | 3.40 | 3.62 | 3.62 |
| $B_1$ | 43.6239 | 46.5436 | 41.1125 | 38.8681 | 50.7255 | 50.7255 |
| $B_2$ | 385.8748 | 340.6646 | 255.6151 | 270.3756 | 331.8523 | 331.8523 |
| $B_3$ | -104.5957 | -71.2789 | -48.7017 | -57.6252 | -66.5287 | -66.5287 |
| $B_4$ | 13.6946 | 7.2093 | 4.4820 | 5.9344 | 6.4423 | 6.4423 |
| $C_1$ | 379.2518 | 46.5436 | 648.0724 | 621.4419 | 505.3604 | 505.3604 |
| $C_2$ | 155.9430 | 340.6646 | -88.4072 | -100.3078 | 93.0557 | 93.0557 |
| $C_3$ | -36.9326 | -71.2789 | 24.6503 | 30.9226 | -14.9324 | -14.9324 |
| $C_4$ | 2.9571 | 7.2093 | -2.0573 | -2.8736 | 0.8079 | 0.8079 |
| $E_1$ | 2101.2813 | 5008.0054 | 2380.8104 | 2274.3997 | 2587.5340 | 2587.5340 |
| $E_2$ | -489.8305 | -2619.0392 | -624.2522 | -673.3050 | -519.2081 | -519.2081 |
| $E_3$ | 47.7244 | 497.4662 | 64.6386 | 78.5465 | 42.8784 | 42.8784 |
| $E_4$ | -1.6628 | -32.0144 | -2.3313 | -3.1886 | -1.2580 | -1.2580 |
| $F_1$ | -1.5566 | -0.8875 | -0.9368 | -0.7907 | -1.5402 | -1.5402 |
| $F_2$ | 1.7465 | 0.1434 | 0.3299 | 0.3104 | 0.9600 | 0.9600 |
| $F_3$ | 1.6552 | 2.1201 | 1.5355 | 1.6249 | 1.7887 | 1.7887 |
| $F_4$ | -0.1683 | -0.1844 | -0.1219 | -0.1444 | -0.1437 | -0.1437 |

| Site | SF | MB | ME | DE | SO | SCW |
|---|---|---|---|---|---|---|
| Mode | Ebb | Ebb | Ebb | Ebb | Ebb | Ebb |
| Tstart | 5 | 5 | 5 | 5 | 5 | 5 |
| L1 | -5.48 | -6.14 | -6.46 | -5.95 | -6.95 | -7.90 |
| L2 | -4.38 | -4.91 | -5.17 | -4.76 | -5.56 | -6.32 |
| L3 | -3.29 | -3.68 | -3.88 | -3.57 | -4.17 | -4.74 |
| L4 | -2.74 | -3.07 | -3.23 | -2.98 | -3.48 | -3.95 |
| L5 | -2.19 | -2.46 | -2.58 | -2.38 | -2.78 | -3.16 |
| L6 | -1.10 | -1.23 | -1.29 | -1.19 | -1.39 | -1.58 |
| L7 | 1.10 | 1.23 | 1.29 | 1.19 | 1.39 | 1.58 |
| L8 | 2.19 | 2.46 | 2.58 | 2.38 | 2.78 | 3.16 |
| L9 | 2.74 | 3.07 | 3.23 | 2.98 | 3.48 | 3.95 |
| L10 | 3.29 | 3.68 | 3.88 | 3.57 | 4.17 | 4.74 |
| L11 | 4.38 | 4.91 | 5.17 | 4.76 | 5.56 | 6.32 |
| L12 | 5.48 | 6.14 | 6.46 | 5.95 | 6.95 | 7.90 |
| H1 | 3.25 | 2.50 | 2.00 | 2.00 | 2.00 | 4.00 |
| H2 | 3.25 | 2.50 | 3.25 | 2.75 | 4.75 | 5.50 |
| H3 | 3.50 | 3.00 | 4.75 | 4.50 | 5.25 | 5.50 |
| H4 | 3.50 | 3.25 | 4.50 | 4.50 | 4.75 | 5.75 |
| H5 | 3.00 | 3.00 | 3.75 | 3.75 | 4.25 | 5.25 |
| H6 | 2.75 | 2.50 | 2.00 | 2.00 | 2.00 | 3.75 |
| H7 | 2.75 | 2.50 | 2.00 | 2.00 | 2.00 | 3.75 |
| H8 | 3.00 | 3.00 | 3.75 | 3.75 | 4.25 | 5.25 |
| H9 | 3.50 | 3.25 | 4.50 | 4.50 | 4.75 | 5.75 |
| H10 | 3.50 | 3.00 | 4.75 | 4.50 | 5.25 | 5.50 |
| H11 | 3.25 | 2.50 | 3.25 | 2.75 | 4.75 | 5.50 |
| H12 | 3.25 | 2.50 | 2.00 | 2.00 | 2.00 | 4.00 |

| Site | TH | WA | HU | SF | ME | DE |
|---:|---:|---:|---:|---:|---:|---:|
| Mode | Ebb | Ebb | Ebb | Dual | Dual | Dual |
| $N_{sluice}$ | 32 | 140 | 80 | 0 | 0 | 0 |
| $A_{1sluice}$ | 144 | 144 | 144 | - | - | - |
| $A_{0sluice}$ | 263 | 263 | 263 | - | - | - |
| $CW_{sluice}$ | 20 | 20 | 20 | - | - | - |
| $\alpha_{ebb}$ | 1.6 | 1.6 | 1.6 | - | - | - |
| $\alpha_{flood}$ | 1.6 | 1.6 | 1.6 | - | - | - |
| $N_{turbine}$ | 32 | 120 | 60 | 1100 | 25 | 60 |
| D | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 |
| $A_{0turbine}$ | 228.2 | 228.2 | 228.2 | 228.2 | 228.2 | 228.2 |
| $CW_{turbine}$ | 20.5 | 20.5 | 20.5 | 20.5 | 20.5 | 20.5 |
| $\beta_{ebb}$ | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 |
| $\beta_{flood}$ | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 |
| $H_{rated}$ | 3.82 | 4.19 | 3.82 | 3.65 | 3.65 | 3.65 |
| $P_{max}$ | 20 | 23 | 20 | 18 | 18 | 18 |
| $H_{min}$ | 0.89 | 0.98 | 0.89 | 1.17 | 1.17 | 1.17 |
| $H_{int}$ | 2.74 | 2.99 | 2.74 | 3.62 | 3.62 | 3.62 |
| $B_1$ | 44.1312 | 46.1602 | 44.1312 | 50.3361 | 50.3361 | 50.3361 |
| $B_2$ | 381.4394 | 364.6729 | 381.4394 | 310.7393 | 310.7393 | 310.7393 |
| $B_3$ | -101.0303 | -88.2846 | -101.0303 | -60.5084 | -60.5084 | -60.5084 |
| $B_4$ | 12.9254 | 10.3237 | 12.9254 | 5.6435 | 5.6435 | 5.6435 |
| $C_1$ | 590.5510 | 603.5602 | 590.5510 | 50.3361 | 50.3361 | 50.3361 |
| $C_2$ | -31.6277 | -17.9626 | -31.6277 | 310.7393 | 310.7393 | 310.7393 |
| $C_3$ | 19.4214 | 13.4426 | 19.4214 | -60.5084 | -60.5084 | -60.5084 |
| $C_4$ | -2.6101 | -1.7487 | -2.6101 | 5.6435 | 5.6435 | 5.6435 |
| $E_1$ | 2136.8583 | 2228.7204 | 2136.8583 | 3728.5906 | 3728.5906 | 3728.5906 |
| $E_2$ | -672.9769 | -638.2876 | -672.9769 | -1584.5345 | -1584.5345 | -1584.5345 |
| $E_3$ | 85.0025 | 73.3762 | 85.0025 | 250.8029 | 250.8029 | 250.8029 |
| $E_4$ | -3.7482 | -2.9458 | -3.7482 | -13.5105 | -13.5105 | -13.5105 |
| $F_1$ | -0.7392 | -0.8503 | -0.7392 | -0.8723 | -0.8723 | -0.8723 |
| $F_2$ | 0.3830 | 0.4078 | 0.3830 | -0.0514 | -0.0514 | -0.0514 |
| $F_3$ | 2.2754 | 2.1718 | 2.2754 | 2.2162 | 2.2162 | 2.2162 |
| $F_4$ | -0.2502 | -0.2181 | -0.2502 | -0.2167 | -0.2167 | -0.2167 |

| Site | TH | WA | HU | SF | ME | DE |
|---|---|---|---|---|---|---|
| Mode | Ebb | Ebb | Ebb | Dual | Dual | Dual |
| Tstart | 5 | 5 | 5 | 5 | 5 | 5 |
| L1 | -4.20 | -4.46 | -4.10 | -5.48 | -6.46 | -5.95 |
| L2 | -3.36 | -3.57 | -3.28 | -4.38 | -5.17 | -4.76 |
| L3 | -2.52 | -2.68 | -2.46 | -3.29 | -3.88 | -3.57 |
| L4 | -2.10 | -2.23 | -2.05 | -2.74 | -3.23 | -2.98 |
| L5 | -1.68 | -1.78 | -1.64 | -2.19 | -2.58 | -2.38 |
| L6 | -0.84 | -0.89 | -0.82 | -1.10 | -1.29 | -1.19 |
| L7 | 0.84 | 0.89 | 0.82 | 1.10 | 1.29 | 1.19 |
| L8 | 1.68 | 1.78 | 1.64 | 2.19 | 2.58 | 2.38 |
| L9 | 2.10 | 2.23 | 2.05 | 2.74 | 3.23 | 2.98 |
| L10 | 2.52 | 2.68 | 2.46 | 3.29 | 3.88 | 3.57 |
| L11 | 3.36 | 3.57 | 3.28 | 4.38 | 5.17 | 4.76 |
| L12 | 4.20 | 4.46 | 4.10 | 5.48 | 6.46 | 5.95 |
| H1 | 1.50 | 1.75 | 1.50 | 5.25 | 1.17 | 1.17 |
| H2 | 1.50 | 2.50 | 2.00 | 5.50 | 1.17 | 4.50 |
| H3 | 2.50 | 3.50 | 3.50 | 5.25 | 1.17 | 4.50 |
| H4 | 3.00 | 3.00 | 2.50 | 5.00 | 1.50 | 4.75 |
| H5 | 2.00 | 2.50 | 2.25 | 4.75 | 1.50 | 4.50 |
| H6 | 1.50 | 1.75 | 1.50 | 3.50 | 1.50 | 1.17 |
| H7 | 1.50 | 1.75 | 1.50 | 3.50 | 1.50 | 1.17 |
| H8 | 2.00 | 2.50 | 2.25 | 4.75 | 1.50 | 4.50 |
| H9 | 3.00 | 3.00 | 2.50 | 5.00 | 1.50 | 4.75 |
| H10 | 2.50 | 3.50 | 3.50 | 5.25 | 1.17 | 4.50 |
| H11 | 1.50 | 2.50 | 2.00 | 5.50 | 1.17 | 4.50 |
| H12 | 1.50 | 1.75 | 1.50 | 5.25 | 1.17 | 1.17 |

| Site | SO | WA | WB | KB | CU | DW |
|---|---|---|---|---|---|---|
| Mode | Dual | Dual | Dual | Dual | Dual | Dual |
| $N_{sluice}$ | 0 | 0 | 0 | 0 | 0 | 0 |
| $A_{1sluice}$ | - | - | - | - | - | - |
| $A_{0sluice}$ | - | - | - | - | - | - |
| $CW_{sluice}$ | - | - | - | - | - | - |
| $\alpha_{ebb}$ | - | - | - | - | - | - |
| $\alpha_{flood}$ | - | - | - | - | - | - |
| $N_{turbine}$ | 875 | 350 | 160 | 14 | 70 | 250 |
| D | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 |
| $A_{0turbine}$ | 228.2 | 228.2 | 228.2 | 228.2 | 228.2 | 228.2 |
| $CW_{turbine}$ | 20.5 | 20.5 | 20.5 | 20.5 | 20.5 | 20.5 |
| $\beta_{ebb}$ | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 |
| $\beta_{flood}$ | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 |
| $H_{rated}$ | 3.65 | 3.13 | 3.13 | 3.65 | 3.65 | 3.65 |
| $P_{max}$ | 18 | 14 | 14 | 18 | 18 | 18 |
| $H_{min}$ | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 |
| $H_{int}$ | 3.62 | 3.62 | 3.62 | 3.62 | 3.62 | 3.62 |
| $B_1$ | 50.3361 | 32.6340 | 32.6340 | 50.3361 | 50.3361 | 50.3361 |
| $B_2$ | 310.7393 | 339.5230 | 339.5230 | 310.7393 | 310.7393 | 310.7393 |
| $B_3$ | -60.5084 | -75.2708 | -75.2708 | -60.5084 | -60.5084 | -60.5084 |
| $B_4$ | 5.6435 | 8.0371 | 8.0371 | 5.6435 | 5.6435 | 5.6435 |
| $C_1$ | 50.3361 | 32.6340 | 32.6340 | 50.3361 | 50.3361 | 50.3361 |
| $C_2$ | 310.7393 | 339.5230 | 339.5230 | 310.7393 | 310.7393 | 310.7393 |
| $C_3$ | -60.5084 | -75.2708 | -75.2708 | -60.5084 | -60.5084 | -60.5084 |
| $C_4$ | 5.6435 | 8.0371 | 8.0371 | 5.6435 | 5.6435 | 5.6435 |
| $E_1$ | 3728.5906 | 2272.6748 | 2272.6748 | 3728.5906 | 3728.5906 | 3728.5906 |
| $E_2$ | -1584.5345 | -891.7772 | -891.7772 | -1584.5345 | -1584.5345 | -1584.5345 |
| $E_3$ | 250.8029 | 133.2140 | 133.2140 | 250.8029 | 250.8029 | 250.8029 |
| $E_4$ | -13.5105 | -6.7645 | -6.7645 | -13.5105 | -13.5105 | -13.5105 |
| $F_1$ | -0.8723 | -0.2209 | -0.2209 | -0.8723 | -0.8723 | -0.8723 |
| $F_2$ | -0.0514 | -1.1078 | -1.1078 | -0.0514 | -0.0514 | -0.0514 |
| $F_3$ | 2.2162 | 2.7564 | 2.7564 | 2.2162 | 2.2162 | 2.2162 |
| $F_4$ | -0.2167 | -0.3040 | -0.3040 | -0.2167 | -0.2167 | -0.2167 |

| Site | SO | WA | WB | KB | CU | DW |
|---|---|---|---|---|---|---|
| Mode | Dual | Dual | Dual | Dual | Dual | Dual |
| Tstart | 5 | 5 | 5 | 5 | 5 | 5 |
| L1 | -6.95 | -4.46 | -4.75 | -5.10 | -5.45 | -5.95 |
| L2 | -5.56 | -3.57 | -3.80 | -4.08 | -4.36 | -4.76 |
| L3 | -4.17 | -2.68 | -2.85 | -3.06 | -3.27 | -3.57 |
| L4 | -3.48 | -2.23 | -2.38 | -2.55 | -2.73 | -2.98 |
| L5 | -2.78 | -1.78 | -1.90 | -2.04 | -2.18 | -2.38 |
| L6 | -1.39 | -0.89 | -0.95 | -1.02 | -1.09 | -1.19 |
| L7 | 1.39 | 0.89 | 0.95 | 1.02 | 1.09 | 1.19 |
| L8 | 2.78 | 1.78 | 1.90 | 2.04 | 2.18 | 2.38 |
| L9 | 3.48 | 2.23 | 2.38 | 2.55 | 2.73 | 2.98 |
| L10 | 4.17 | 2.68 | 2.85 | 3.06 | 3.27 | 3.57 |
| L11 | 5.56 | 3.57 | 3.80 | 4.08 | 4.36 | 4.76 |
| L12 | 6.95 | 4.46 | 4.75 | 5.10 | 5.45 | 5.95 |
| H1 | 1.17 | 3.25 | 4.25 | 5.25 | 4.50 | 4.50 |
| H2 | 2.75 | 3.50 | 4.25 | 5.25 | 4.75 | 4.75 |
| H3 | 3.25 | 3.25 | 4.25 | 4.75 | 4.75 | 5.00 |
| H4 | 3.50 | 3.25 | 4.00 | 4.25 | 4.25 | 4.50 |
| H5 | 3.50 | 2.75 | 4.00 | 3.75 | 4.25 | 4.50 |
| H6 | 3.00 | 2.75 | 3.75 | 2.75 | 4.25 | 4.50 |
| H7 | 3.00 | 2.75 | 3.75 | 2.75 | 4.25 | 4.50 |
| H8 | 3.50 | 2.75 | 4.00 | 3.75 | 4.25 | 4.50 |
| H9 | 3.50 | 3.25 | 4.00 | 4.25 | 4.25 | 4.50 |
| H10 | 3.25 | 3.25 | 4.25 | 4.75 | 4.75 | 5.00 |
| H11 | 2.75 | 3.50 | 4.25 | 5.25 | 4.75 | 4.75 |
| H12 | 1.17 | 3.25 | 4.25 | 5.25 | 4.50 | 4.50 |

| Site | OX | AB | RH | BB | MO | RB / DY |
|---:|---:|---:|---:|---:|---:|---:|
| Mode | Dual | Dual | Dual | Dual | Dual | Dual |
| $N_{sluice}$ | 0 | 0 | 0 | 0 | 0 | 0 |
| $A_{1sluice}$ | - | - | - | - | - | - |
| $A_{0sluice}$ | - | - | - | - | - | - |
| $CW_{sluice}$ | - | - | - | - | - | - |
| $\alpha_{ebb}$ | - | - | - | - | - | - |
| $\alpha_{flood}$ | - | - | - | - | - | - |
| $N_{turbine}$ | 16 | 45 | 40 | 120 | 14 | 110 |
| D | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 |
| $A_{0turbine}$ | 228.2 | 228.2 | 228.2 | 228.2 | 228.2 | 228.2 |
| $CW_{turbine}$ | 20.5 | 20.5 | 20.5 | 20.5 | 20.5 | 20.5 |
| $\beta_{ebb}$ | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 |
| $\beta_{flood}$ | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 |
| $H_{rated}$ | 4.15 | 4.84 | 4.84 | 5.25 | 3.65 | 3.65 |
| $P_{max}$ | 22 | 27 | 27 | 30 | 18 | 18 |
| $H_{min}$ | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 | 1.17 |
| $H_{int}$ | 3.62 | 3.62 | 3.62 | 3.62 | 3.62 | 3.62 |
| $B_1$ | 44.4212 | 44.4212 | 44.4212 | 44.4212 | 50.3361 | 50.3361 |
| $B_2$ | 320.1676 | 320.1676 | 320.1676 | 320.1676 | 310.7393 | 310.7393 |
| $B_3$ | -65.2245 | -65.2245 | -65.2245 | -65.2245 | -60.5084 | -60.5084 |
| $B_4$ | 6.3856 | 6.3856 | 6.3856 | 6.3856 | 5.6435 | 5.6435 |
| $C_1$ | 1240.6930 | 795.4994 | 795.4994 | 537.6780 | 50.3361 | 50.3361 |
| $C_2$ | -482.0776 | -135.6645 | -135.6645 | 50.6237 | 310.7393 | 310.7393 |
| $C_3$ | 128.2655 | 38.5536 | 38.5536 | -6.0566 | -60.5084 | -60.5084 |
| $C_4$ | -11.0787 | -3.3466 | -3.3466 | 0.1939 | 5.6435 | 5.6435 |
| $E_1$ | 2976.3724 | 2014.4589 | 2014.4589 | 1963.1389 | 3728.5906 | 3728.5906 |
| $E_2$ | -1008.0453 | -445.5479 | -445.5479 | -390.4417 | -1584.5345 | -1584.5345 |
| $E_3$ | 132.6627 | 39.6954 | 39.6954 | 31.5880 | 250.8029 | 250.8029 |
| $E_4$ | -6.0453 | -1.2293 | -1.2293 | -0.8917 | -13.5105 | -13.5105 |
| $F_1$ | -1.6279 | -1.1970 | -1.1970 | -1.3175 | -0.8723 | -0.8723 |
| $F_2$ | 1.1035 | 0.4794 | 0.4794 | 0.6439 | -0.0514 | -0.0514 |
| $F_3$ | 1.6682 | 1.9448 | 1.9448 | 1.8774 | 2.2162 | 2.2162 |
| $F_4$ | -0.1357 | -0.1735 | -0.1735 | -0.1651 | -0.2167 | -0.2167 |

| Site | OX | AB | RH | BB | MO | RB / DY |
|---:|---:|---:|---:|---:|---:|---:|
| Mode | Dual | Dual | Dual | Dual | Dual | Dual |
| Tstart | 5 | 5 | 5 | 5 | 5 | 5 |
| L1 | -6.10 | -7.45 | -7.45 | -8.25 | -5.45 | -5.15 |
| L2 | -4.88 | -5.96 | -5.96 | -6.60 | -4.36 | -4.12 |
| L3 | -3.66 | -4.47 | -4.47 | -4.95 | -3.27 | -3.09 |
| L4 | -3.05 | -3.73 | -3.73 | -4.13 | -2.73 | -2.58 |
| L5 | -2.44 | -2.98 | -2.98 | -3.30 | -2.18 | -2.06 |
| L6 | -1.22 | -1.49 | -1.49 | -1.65 | -1.09 | -1.03 |
| L7 | 1.22 | 1.49 | 1.49 | 1.65 | 1.09 | 1.03 |
| L8 | 2.44 | 2.98 | 2.98 | 3.30 | 2.18 | 2.06 |
| L9 | 3.05 | 3.73 | 3.73 | 4.13 | 2.73 | 2.58 |
| L10 | 3.66 | 4.47 | 4.47 | 4.95 | 3.27 | 3.09 |
| L11 | 4.88 | 5.96 | 5.96 | 6.60 | 4.36 | 4.12 |
| L12 | 6.10 | 7.45 | 7.45 | 8.25 | 5.45 | 5.15 |
| H1 | 5.50 | 6.75 | 7.00 | 7.50 | 5.00 | 5.25 |
| H2 | 5.50 | 6.75 | 7.25 | 7.75 | 5.00 | 5.25 |
| H3 | 5.25 | 6.75 | 7.00 | 7.25 | 4.75 | 4.50 |
| H4 | 5.00 | 6.25 | 6.50 | 7.00 | 4.50 | 4.25 |
| H5 | 4.50 | 5.00 | 6.00 | 7.00 | 3.75 | 3.75 |
| H6 | 4.25 | 5.00 | 5.25 | 7.00 | 3.50 | 3.25 |
| H7 | 4.25 | 5.00 | 5.25 | 7.00 | 3.50 | 3.25 |
| H8 | 4.50 | 5.00 | 6.00 | 7.00 | 3.75 | 3.75 |
| H9 | 5.00 | 6.25 | 6.50 | 7.00 | 4.50 | 4.25 |
| H10 | 5.25 | 6.75 | 7.00 | 7.25 | 4.75 | 4.50 |
| H11 | 5.50 | 6.75 | 7.25 | 7.75 | 5.00 | 5.25 |
| H12 | 5.50 | 6.75 | 7.00 | 7.50 | 5.00 | 5.25 |

Rolls-Royce turbines input parameters

| Site | SF | MB | ME | DE | SO | SCW |
|---:|---:|---:|---:|---:|---:|---:|
| Mode | Dual | Dual | Dual | Dual | Dual | Dual |
| $N_{9m}$ | 0 | 0 | 0 | 0 | 352 | 900 |
| $N_{14m}$ | 750 | 320 | 40 | 55 | 800 | 165 |
| $A_{t9m}$ | 52.1 | 52.1 | 52.1 | 52.1 | 52.1 | 52.1 |
| $A_{t14m}$ | 126.1 | 126.1 | 126.1 | 126.1 | 126.1 | 126.1 |
| k | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 |
| $H_{min}$ | 1 | 1 | 1 | 1 | 1 | 1 |
| $R_1$ | 57.5906 | 57.5906 | 57.5906 | 57.5906 | 57.5906 | 57.5906 |
| $R_2$ | 39.1934 | 39.1934 | 39.1934 | 39.1934 | 39.1934 | 39.1934 |
| $R_3$ | -2.6943 | -2.6943 | -2.6943 | -2.6943 | -2.6943 | -2.6943 |
| $R_4$ | -0.0004 | -0.0004 | -0.0004 | -0.0004 | -0.0004 | -0.0004 |
| $U_1$ | 139.3550 | 139.3550 | 139.3550 | 139.3550 | 139.3550 | 139.3550 |
| $U_2$ | 94.8382 | 94.8382 | 94.8382 | 94.8382 | 94.8382 | 94.8382 |
| $U_3$ | -6.5195 | -6.5195 | -6.5195 | -6.5195 | -6.5195 | -6.5195 |
| $U_4$ | -0.0009 | -0.0009 | -0.0009 | -0.0009 | -0.0009 | -0.0009 |
| $S_1$ | -0.2629 | -0.2629 | -0.2629 | -0.2629 | -0.2629 | -0.2629 |
| $S_2$ | 0.6490 | 0.6490 | 0.6490 | 0.6490 | 0.6490 | 0.6490 |
| $S_3$ | 0.2085 | 0.2085 | 0.2085 | 0.2085 | 0.2085 | 0.2085 |
| $S_4$ | -0.0002 | -0.0002 | -0.0002 | -0.0002 | -0.0002 | -0.0002 |
| $V_1$ | -0.6362 | -0.6362 | -0.6362 | -0.6362 | -0.6362 | -0.6362 |
| $V_2$ | 1.5705 | 1.5705 | 1.5705 | 1.5705 | 1.5705 | 1.5705 |
| $V_3$ | 0.5044 | 0.5044 | 0.5044 | 0.5044 | 0.5044 | 0.5044 |
| $V_4$ | -0.0006 | -0.0006 | -0.0006 | -0.0006 | -0.0006 | -0.0006 |

| Site | SF | MB | ME | DE | SO | SCW |
|---|---|---|---|---|---|---|
| Mode | Dual | Dual | Dual | Dual | Dual | Dual |
| $T_{start}$ | 5 | 5 | 5 | 5 | 5 | 5 |
| $L_1$ | -5.48 | -6.14 | -6.46 | -5.95 | -5.02 | -6.20 |
| $L_2$ | -4.38 | -4.91 | -5.17 | -4.76 | -4.02 | -4.96 |
| $L_3$ | -3.29 | -3.68 | -3.88 | -3.57 | -3.01 | -3.72 |
| $L_4$ | -2.74 | -3.07 | -3.23 | -2.98 | -2.51 | -3.10 |
| $L_5$ | -2.19 | -2.46 | -2.58 | -2.38 | -2.01 | -2.48 |
| $L_6$ | -1.10 | -1.23 | -1.29 | -1.19 | -1.00 | -1.24 |
| $L_7$ | 1.10 | 1.23 | 1.29 | 1.19 | 1.00 | 1.24 |
| $L_8$ | 2.19 | 2.46 | 2.58 | 2.38 | 2.01 | 2.48 |
| $L_9$ | 2.74 | 3.07 | 3.23 | 2.98 | 2.51 | 3.10 |
| $L_{10}$ | 3.29 | 3.68 | 3.88 | 3.57 | 3.01 | 3.72 |
| $L_{11}$ | 4.38 | 4.91 | 5.17 | 4.76 | 4.02 | 4.96 |
| $L_{12}$ | 5.48 | 6.14 | 6.46 | 5.95 | 5.02 | 6.20 |
| $H_1$ | 1.00 | 1.00 | 1.00 | 2.50 | 1.00 | 1.00 |
| $H_2$ | 1.50 | 1.25 | 1.75 | 2.50 | 1.25 | 1.25 |
| $H_3$ | 2.00 | 2.25 | 2.00 | 2.50 | 2.00 | 1.50 |
| $H_4$ | 2.50 | 3.00 | 3.00 | 3.00 | 2.25 | 2.50 |
| $H_5$ | 2.75 | 3.00 | 3.00 | 3.00 | 2.50 | 3.00 |
| $H_6$ | 2.75 | 3.00 | 3.00 | 3.00 | 2.50 | 3.00 |
| $H_7$ | 2.75 | 3.00 | 3.00 | 3.00 | 2.50 | 3.00 |
| $H_8$ | 2.75 | 3.00 | 3.00 | 3.00 | 2.50 | 3.00 |
| $H_9$ | 2.50 | 3.00 | 3.00 | 3.00 | 2.25 | 2.50 |
| $H_{10}$ | 2.00 | 2.25 | 2.00 | 2.50 | 2.00 | 1.50 |
| $H_{11}$ | 1.50 | 1.25 | 1.75 | 2.50 | 1.25 | 1.25 |
| $H_{12}$ | 1.00 | 1.00 | 1.00 | 2.50 | 1.00 | 1.00 |

| Site | TH | WA | HU | WB | KB | CU |
|---|---|---|---|---|---|---|
| Mode | Dual | Dual | Dual | Dual | Dual | Dual |
| $N_{9m}$ | 20 | 0 | 0 | 0 | 0 | 0 |
| $N_{14m}$ | 90 | 400 | 200 | 140 | 12 | 60 |
| $A_{t9m}$ | 52.1 | 52.1 | 52.1 | 52.1 | 52.1 | 52.1 |
| $A_{t14m}$ | 126.1 | 126.1 | 126.1 | 126.1 | 126.1 | 126.1 |
| k | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 |
| $H_{min}$ | 1 | 1 | 1 | 1 | 1 | 1 |
| $R_1$ | 57.5906 | 57.5906 | 57.5906 | 57.5906 | 57.5906 | 57.5906 |
| $R_2$ | 39.1934 | 39.1934 | 39.1934 | 39.1934 | 39.1934 | 39.1934 |
| $R_3$ | -2.6943 | -2.6943 | -2.6943 | -2.6943 | -2.6943 | -2.6943 |
| $R_4$ | -0.0004 | -0.0004 | -0.0004 | -0.0004 | -0.0004 | -0.0004 |
| $U_1$ | 139.3550 | 139.3550 | 139.3550 | 139.3550 | 139.3550 | 139.3550 |
| $U_2$ | 94.8382 | 94.8382 | 94.8382 | 94.8382 | 94.8382 | 94.8382 |
| $U_3$ | -6.5195 | -6.5195 | -6.5195 | -6.5195 | -6.5195 | -6.5195 |
| $U_4$ | -0.0009 | -0.0009 | -0.0009 | -0.0009 | -0.0009 | -0.0009 |
| $S_1$ | -0.2629 | -0.2629 | -0.2629 | -0.2629 | -0.2629 | -0.2629 |
| $S_2$ | 0.6490 | 0.6490 | 0.6490 | 0.6490 | 0.6490 | 0.6490 |
| $S_3$ | 0.2085 | 0.2085 | 0.2085 | 0.2085 | 0.2085 | 0.2085 |
| $S_4$ | -0.0002 | -0.0002 | -0.0002 | -0.0002 | -0.0002 | -0.0002 |
| $V_1$ | -0.6362 | -0.6362 | -0.6362 | -0.6362 | -0.6362 | -0.6362 |
| $V_2$ | 1.5705 | 1.5705 | 1.5705 | 1.5705 | 1.5705 | 1.5705 |
| $V_3$ | 0.5044 | 0.5044 | 0.5044 | 0.5044 | 0.5044 | 0.5044 |
| $V_4$ | -0.0006 | -0.0006 | -0.0006 | -0.0006 | -0.0006 | -0.0006 |

| Site | TH | WA | HU | WB | KB | CU |
|---:|---:|---:|---:|---:|---:|---:|
| Mode | Dual | Dual | Dual | Dual | Dual | Dual |
| $T_{start}$ | 5 | 5 | 5 | 5 | 5 | 5 |
| $L_1$ | -4.20 | -4.46 | -4.10 | -4.75 | -5.10 | -5.45 |
| $L_2$ | -3.36 | -3.57 | -3.28 | -3.80 | -4.08 | -4.36 |
| $L_3$ | -2.52 | -2.68 | -2.46 | -2.85 | -3.06 | -3.27 |
| $L_4$ | -2.10 | -2.23 | -2.05 | -2.38 | -2.55 | -2.73 |
| $L_5$ | -1.68 | -1.78 | -1.64 | -1.90 | -2.04 | -2.18 |
| $L_6$ | -0.84 | -0.89 | -0.82 | -0.95 | -1.02 | -1.09 |
| $L_7$ | 0.84 | 0.89 | 0.82 | 0.95 | 1.02 | 1.09 |
| $L_8$ | 1.68 | 1.78 | 1.64 | 1.90 | 2.04 | 2.18 |
| $L_9$ | 2.10 | 2.23 | 2.05 | 2.38 | 2.55 | 2.73 |
| $L_{10}$ | 2.52 | 2.68 | 2.46 | 2.85 | 3.06 | 3.27 |
| $L_{11}$ | 3.36 | 3.57 | 3.28 | 3.80 | 4.08 | 4.36 |
| $L_{12}$ | 4.20 | 4.46 | 4.10 | 4.75 | 5.10 | 5.45 |
| $H_1$ | 1.00 | 1.75 | 1.75 | 2.50 | 2.00 | 1.00 |
| $H_2$ | 1.00 | 1.75 | 1.75 | 2.50 | 2.00 | 1.25 |
| $H_3$ | 1.00 | 2.00 | 1.75 | 2.50 | 2.25 | 1.50 |
| $H_4$ | 1.75 | 2.25 | 2.25 | 2.50 | 2.50 | 2.50 |
| $H_5$ | 2.00 | 2.25 | 2.25 | 2.50 | 2.50 | 2.50 |
| $H_6$ | 2.00 | 2.50 | 2.25 | 2.50 | 2.50 | 2.50 |
| $H_7$ | 2.00 | 2.50 | 2.25 | 2.50 | 2.50 | 2.50 |
| $H_8$ | 2.00 | 2.25 | 2.25 | 2.50 | 2.50 | 2.50 |
| $H_9$ | 1.75 | 2.25 | 2.25 | 2.50 | 2.50 | 2.50 |
| $H_{10}$ | 1.00 | 2.00 | 1.75 | 2.50 | 2.25 | 1.50 |
| $H_{11}$ | 1.00 | 1.75 | 1.75 | 2.50 | 2.00 | 1.25 |
| $H_{12}$ | 1.00 | 1.75 | 1.75 | 2.50 | 2.00 | 1.00 |

| Site | DW | OX | AB | RH | BB | MO | RB / DY |
|---|---|---|---|---|---|---|---|
| Mode | Dual | Dual | Dual | Dual | Dual | Dual | Dual |
| $N_{9m}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $N_{14m}$ | 220 | 16 | 40 | 30 | 110 | 14 | 100 |
| $A_{t9m}$ | 52.1 | 52.1 | 52.1 | 52.1 | 52.1 | 52.1 | 52.1 |
| $A_{t14m}$ | 126.1 | 126.1 | 126.1 | 126.1 | 126.1 | 126.1 | 126.1 |
| k | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 |
| $H_{min}$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| $R_1$ | 57.5906 | 57.5906 | 57.5906 | 57.5906 | 57.5906 | 57.5906 | 57.5906 |
| $R_2$ | 39.1934 | 39.1934 | 39.1934 | 39.1934 | 39.1934 | 39.1934 | 39.1934 |
| $R_3$ | -2.6943 | -2.6943 | -2.6943 | -2.6943 | -2.6943 | -2.6943 | -2.6943 |
| $R_4$ | -0.0004 | -0.0004 | -0.0004 | -0.0004 | -0.0004 | -0.0004 | -0.0004 |
| $U_1$ | 139.3550 | 139.3550 | 139.3550 | 139.3550 | 139.3550 | 139.3550 | 139.3550 |
| $U_2$ | 94.8382 | 94.8382 | 94.8382 | 94.8382 | 94.8382 | 94.8382 | 94.8382 |
| $U_3$ | -6.5195 | -6.5195 | -6.5195 | -6.5195 | -6.5195 | -6.5195 | -6.5195 |
| $U_4$ | -0.0009 | -0.0009 | -0.0009 | -0.0009 | -0.0009 | -0.0009 | -0.0009 |
| $S_1$ | -0.2629 | -0.2629 | -0.2629 | -0.2629 | -0.2629 | -0.2629 | -0.2629 |
| $S_2$ | 0.6490 | 0.6490 | 0.6490 | 0.6490 | 0.6490 | 0.6490 | 0.6490 |
| $S_3$ | 0.2085 | 0.2085 | 0.2085 | 0.2085 | 0.2085 | 0.2085 | 0.2085 |
| $S_4$ | -0.0002 | -0.0002 | -0.0002 | -0.0002 | -0.0002 | -0.0002 | -0.0002 |
| $V_1$ | -0.6362 | -0.6362 | -0.6362 | -0.6362 | -0.6362 | -0.6362 | -0.6362 |
| $V_2$ | 1.5705 | 1.5705 | 1.5705 | 1.5705 | 1.5705 | 1.5705 | 1.5705 |
| $V_3$ | 0.5044 | 0.5044 | 0.5044 | 0.5044 | 0.5044 | 0.5044 | 0.5044 |
| $V_4$ | -0.0006 | -0.0006 | -0.0006 | -0.0006 | -0.0006 | -0.0006 | -0.0006 |

| Site | DW | OX | AB | RH | BB | MO | RB / DY |
|---|---|---|---|---|---|---|---|
| Mode | Dual | Dual | Dual | Dual | Dual | Dual | Dual |
| $T_{start}$ | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| $L_1$ | -5.95 | -6.10 | -7.45 | -7.45 | -8.25 | -5.45 | -5.15 |
| $L_2$ | -4.76 | -4.88 | -5.96 | -5.96 | -6.60 | -4.36 | -4.12 |
| $L_3$ | -3.57 | -3.66 | -4.47 | -4.47 | -4.95 | -3.27 | -3.09 |
| $L_4$ | -2.98 | -3.05 | -3.73 | -3.73 | -4.13 | -2.73 | -2.58 |
| $L_5$ | -2.38 | -2.44 | -2.98 | -2.98 | -3.30 | -2.18 | -2.06 |
| $L_6$ | -1.19 | -1.22 | -1.49 | -1.49 | -1.65 | -1.09 | -1.03 |
| $L_7$ | 1.19 | 1.22 | 1.49 | 1.49 | 1.65 | 1.09 | 1.03 |
| $L_8$ | 2.38 | 2.44 | 2.98 | 2.98 | 3.30 | 2.18 | 2.06 |
| $L_9$ | 2.98 | 3.05 | 3.73 | 3.73 | 4.13 | 2.73 | 2.58 |
| $L_{10}$ | 3.57 | 3.66 | 4.47 | 4.47 | 4.95 | 3.27 | 3.09 |
| $L_{11}$ | 4.76 | 4.88 | 5.96 | 5.96 | 6.60 | 4.36 | 4.12 |
| $L_{12}$ | 5.95 | 6.10 | 7.45 | 7.45 | 8.25 | 5.45 | 5.15 |
| $H_1$ | 2.25 | 3.00 | 3.00 | 2.00 | 1.00 | 3.00 | 1.75 |
| $H_2$ | 2.25 | 3.00 | 3.00 | 2.00 | 1.00 | 3.00 | 1.75 |
| $H_3$ | 2.25 | 3.00 | 3.00 | 2.00 | 2.00 | 3.00 | 2.00 |
| $H_4$ | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 2.75 |
| $H_5$ | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 2.75 |
| $H_6$ | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 2.75 |
| $H_7$ | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 2.75 |
| $H_8$ | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 2.75 |
| $H_9$ | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 2.75 |
| $H_{10}$ | 2.25 | 3.00 | 3.00 | 2.00 | 2.00 | 3.00 | 2.00 |
| $H_{11}$ | 2.25 | 3.00 | 3.00 | 2.00 | 1.00 | 3.00 | 1.75 |
| $H_{12}$ | 2.25 | 3.00 | 3.00 | 2.00 | 1.00 | 3.00 | 1.75 |

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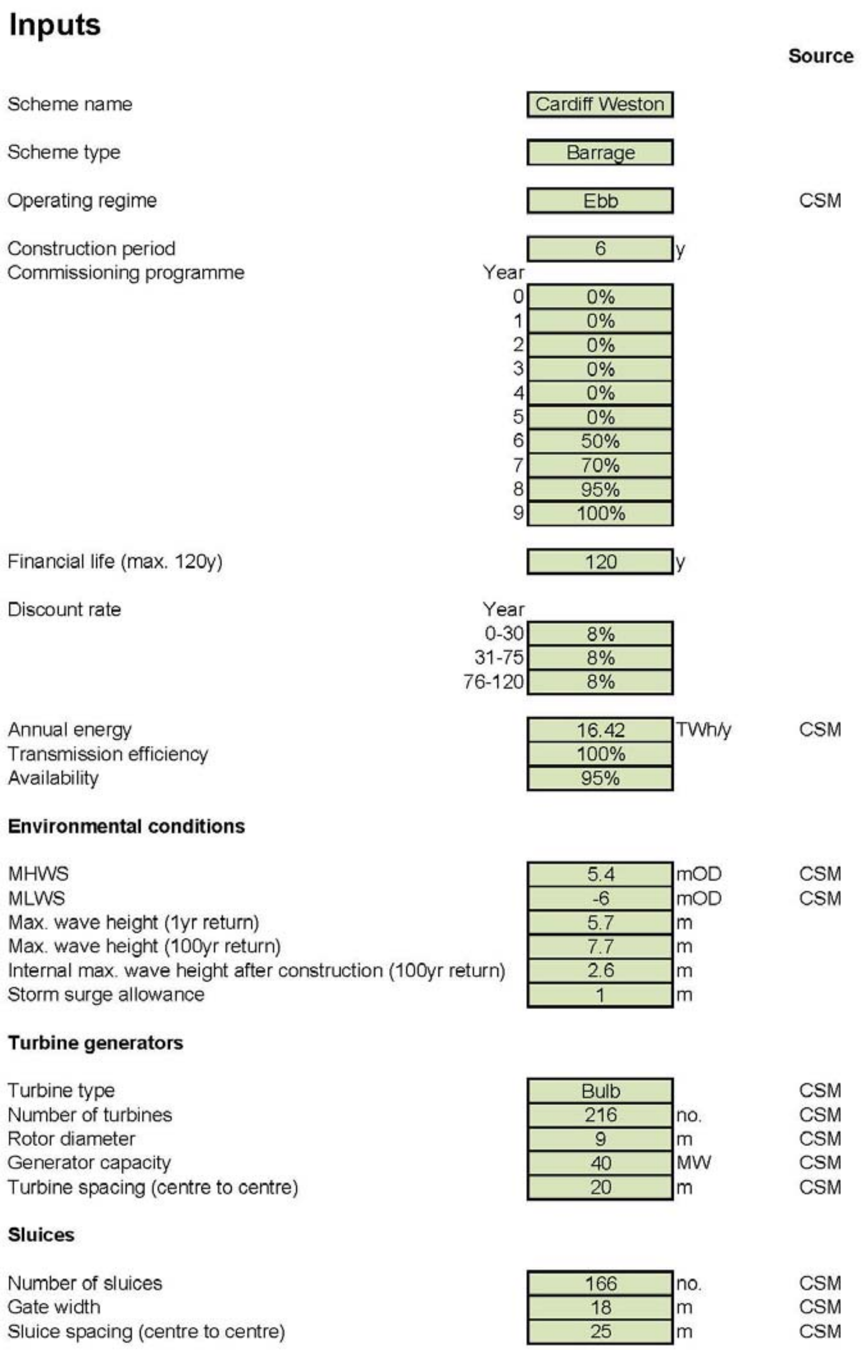
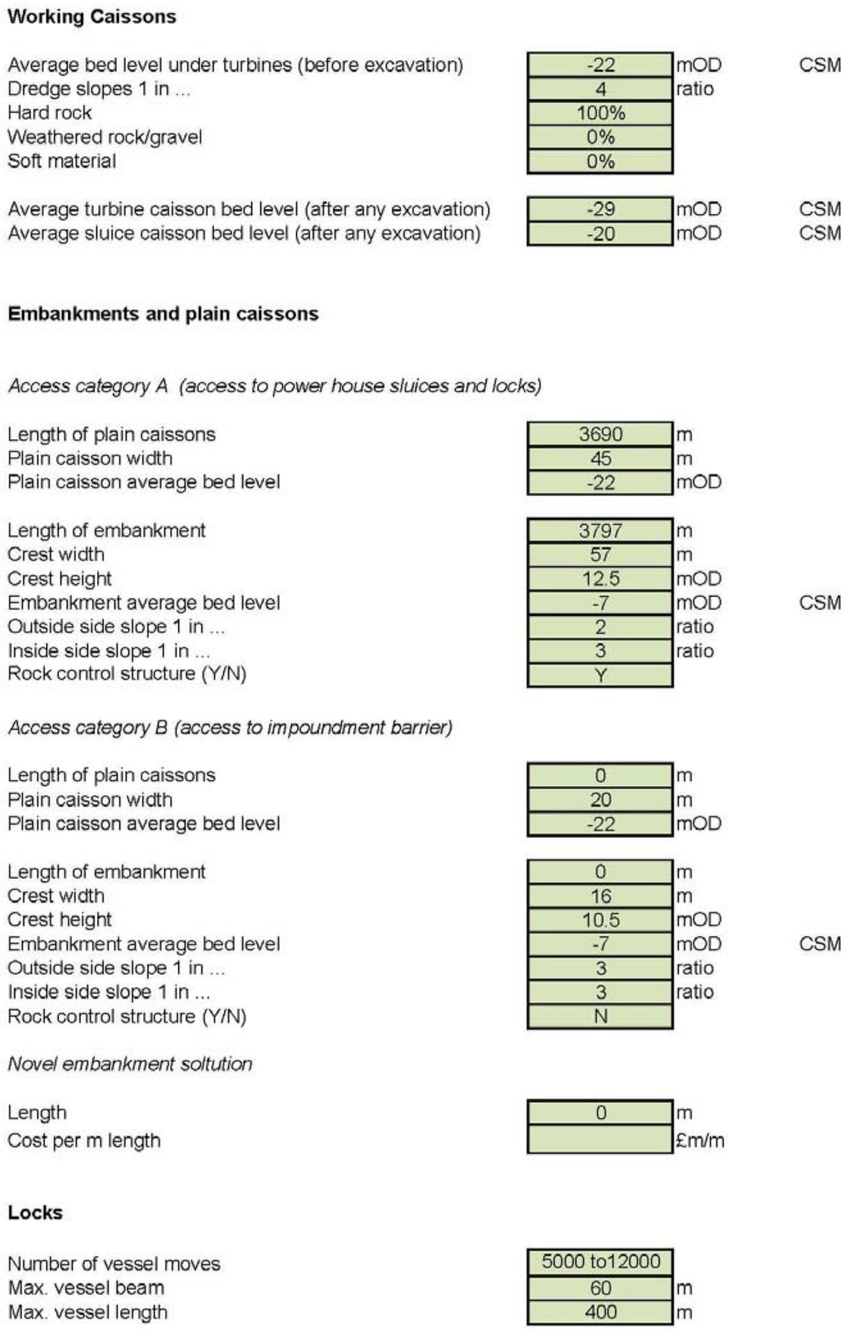
# APPENDIX C – COST OF ENERGY MODEL INPUT REQUIREMENTS



## Inputs

| | | | | Source |
|---|---|---|---|---|
| Scheme name | | Cardiff Weston | | |
| Scheme type | | Barrage | | |
| Operating regime | | Ebb | | CSM |
| Construction period | | 6 | y | |
| Commissioning programme | Year | | | |
| | 0 | 0% | | |
| | 1 | 0% | | |
| | 2 | 0% | | |
| | 3 | 0% | | |
| | 4 | 0% | | |
| | 5 | 0% | | |
| | 6 | 50% | | |
| | 7 | 70% | | |
| | 8 | 95% | | |
| | 9 | 100% | | |
| Financial life (max. 120y) | | 120 | y | |
| Discount rate | Year | | | |
| | 0-30 | 8% | | |
| | 31-75 | 8% | | |
| | 76-120 | 8% | | |
| Annual energy | | 16.42 | TWh/y | CSM |
| Transmission efficiency | | 100% | | |
| Availability | | 95% | | |
| **Environmental conditions** | | | | |
| MHWS | | 5.4 | mOD | CSM |
| MLWS | | -6 | mOD | CSM |
| Max. wave height (1yr return) | | 5.7 | m | |
| Max. wave height (100yr return) | | 7.7 | m | |
| Internal max. wave height after construction (100yr return) | | 2.6 | m | |
| Storm surge allowance | | 1 | m | |
| **Turbine generators** | | | | |
| Turbine type | | Bulb | | CSM |
| Number of turbines | | 216 | no. | CSM |
| Rotor diameter | | 9 | m | CSM |
| Generator capacity | | 40 | MW | CSM |
| Turbine spacing (centre to centre) | | 20 | m | CSM |
| **Sluices** | | | | |
| Number of sluices | | 166 | no. | CSM |
| Gate width | | 18 | m | CSM |
| Sluice spacing (centre to centre) | | 25 | m | CSM |



**Working Caissons**

| | | | |
|---|---|---|---|
| Average bed level under turbines (before excavation) | -22 | mOD | CSM |
| Dredge slopes 1 in ... | 4 | ratio | |
| Hard rock | 100% | | |
| Weathered rock/gravel | 0% | | |
| Soft material | 0% | | |
| Average turbine caisson bed level (after any excavation) | -29 | mOD | CSM |
| Average sluice caisson bed level (after any excavation) | -20 | mOD | CSM |

**Embankments and plain caissons**

*Access category A (access to power house sluices and locks)*

| | | | |
|---|---|---|---|
| Length of plain caissons | 3690 | m | |
| Plain caisson width | 45 | m | |
| Plain caisson average bed level | -22 | mOD | |
| Length of embankment | 3797 | m | |
| Crest width | 57 | m | |
| Crest height | 12.5 | mOD | |
| Embankment average bed level | -7 | mOD | CSM |
| Outside side slope 1 in ... | 2 | ratio | |
| Inside side slope 1 in ... | 3 | ratio | |
| Rock control structure (Y/N) | Y | | |

*Access category B (access to impoundment barrier)*

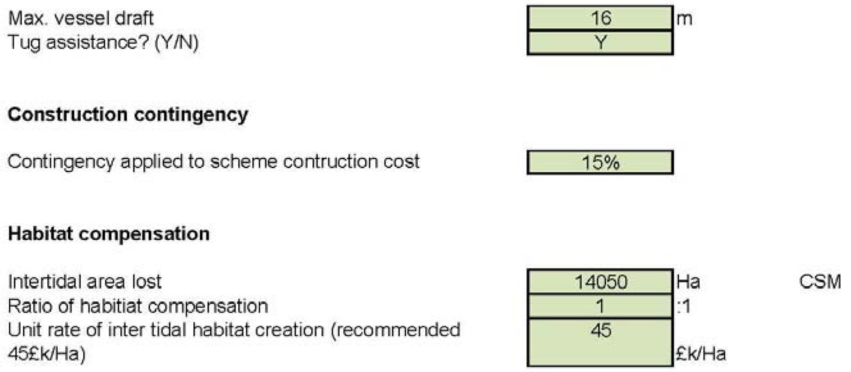
| | | | |
|---|---|---|---|
| Length of plain caissons | 0 | m | |
| Plain caisson width | 20 | m | |
| Plain caisson average bed level | -22 | mOD | |
| Length of embankment | 0 | m | |
| Crest width | 16 | m | |
| Crest height | 10.5 | mOD | |
| Embankment average bed level | -7 | mOD | CSM |
| Outside side slope 1 in ... | 3 | ratio | |
| Inside side slope 1 in ... | 3 | ratio | |
| Rock control structure (Y/N) | N | | |

*Novel embankment soltution*

| | | |
|---|---|---|
| Length | 0 | m |
| Cost per m length | | £m/m |

**Locks**

| | | |
|---|---|---|
| Number of vessel moves | 5000 to12000 | |
| Max. vessel beam | 60 | m |
| Max. vessel length | 400 | m |



| | | | |
|---|---|---|---|
| Max. vessel draft | 16 | m | |
| Tug assistance? (Y/N) | Y | | |

**Construction contingency**

| | | | |
|---|---|---|---|
| Contingency applied to scheme contruction cost | 15% | | |

**Habitat compensation**

| | | | |
|---|---|---|---|
| Intertidal area lost | 14050 | Ha | CSM |
| Ratio of habitiat compensation | 1 | :1 | |
| Unit rate of inter tidal habitat creation (recommended 45£k/Ha) | 45 | £k/Ha | |