Programme Area: Marine

Project: Tidal Modelling

Title: Tidal Range Cost of Energy Model and Documentation

Abstract:

This deliverable is number 4 of 10 in the Tidal Modelling project and consists of a parametric Cost of Energy Model for tidal barrage and lagoon technologies. The deliverable consists of three elements; (a) an excel model with parametric representations of cost drivers such as size and arrangements of civils works, turbine choices, O&M choices etc; (b) a model report describing the model, assumptions and case study examples, and (c) a user guide. The model can be used in isolation, or with inputs provided manually from the Continental Shelf Models developed elsewhere in the project.

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)

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Tidal Range Cost of Energy Model Report

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EXECUTIVE SUMMARY

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 B&V and is part of the *Tidal Resource Modelling* (TRM) scope of work delivered by B&V as prime contractor.

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

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

This will be achieved through a series of work packages and, ultimately, ten deliverables of which this report forms part of Deliverable 4 (D4) of the TRM work, which is solely B&V's work.

D1 – Tidal resource characterisation
D2 – Continental Shelf Model (CSM) definition and requirements document
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D10 – Project dissemination

The objectives of this work package (D4) are to:

- Review construction and deployment methodologies and operational maintenance experience for tidal range technologies.
- Develop a flexible parametric CoE model (including construction, installation and annual costs) for tidal range technologies.
- Explore the limits of currently forseen tidal range technologies on CoE.

There are two main options to extract power from tidal range: tidal barrage and tidal lagoon. Both of these options operate by impounding a volume of water as the tide level changes and use the hydraulic head differential across the barrier structure to drive turbines and thus generate electricity. Tidal fences using closely packed tidal current turbines (sometimes with additional structures) have not been included in this report as a tidal range option because they extract power from tidal currents; this approach was agreed with the ETI.

There have been a number of studies carried out for sites across the UK that investigate the potential to generate electricity from tidal range. In particular, the Severn, the Mersey and the Solway estuaries have recently been subjects of feasibility studies. There is limited operation & maintenance (O&M) data available as there are very few existing tidal range power schemes worldwide. There are only two large scale tidal barrages which have been in operation for a significant period of time, namely: the

240MW Rance barrage in France and the 20MW Annapolis Royal barrage in Nova Scotia, Canada (SDC 2007). A 254MW barrage in Sihwa, South Korea, has recently been constructed and is currently running in test mode (yonhapnews 29/08/11).

Review of construction and deployment methodologies and operational maintenance experience

B&V conducted a general literature review of the construction and deployment methodologies associated with tidal range technologies, and subsequent annual O&M activities. The review covered existing turbine technologies and conventional means to construct rubble mound embankments and caisson structures, whilst also considering technological advancements being made in the industry (one of which is a Rolls-Royce turbine) and alternative civil engineering concepts. This review was then used to inform the parametric CoE model development.

Development of parametric CoE model

An objective of this work package was to develop a flexible parametric Cost of Energy (CoE) model for tidal range barrage and lagoon technologies. The base case components and their respective costs have been taken from the five schemes defined in the SEA study (DECC 2010), hereafter the ‘Severn schemes’. These schemes include three barrages of varying size (Cardiff-Weston, Shoots and Beachley) and two land connected lagoons (Welsh Grounds and Bridgwater Bay).

The Severn study developed detailed cost estimates for each of the Severn schemes based on preliminary designs - which have been used, where possible, as the basis on which to identify ‘cost trends’ for the CoE model. Given this, the CoE model follows a similar cost breakdown structure to that used as part of the Severn study to allow direct comparison between components and thus allow a means of cross-validation. In some cases, a simplified costing approach or additional cost information has been taken from the earlier Interim Options Analysis Report (IOAR) (DECC 2008). In the case of Rolls-Royce turbines, cost and design information has been taken from the SETS report (Rolls-Royce/ Atkins 2010). Details of various preliminary design recommendations, based on the SEA study, and assumptions made by B&V in developing the CoE model are provided to assist the user of the model.

The cost estimates in the Severn study are based on 1st quarter 2008 prices. As the purpose of the cost model is to provide a comparison between schemes, and it is likely that the user will wish to compare these costs to those from the Severn study, the costs have not been inflated to 2011 prices. The Rolls-Royce turbine costs have been taken from the 2010 SETS report.

The Severn schemes cost estimates do not include optimism bias[1]. Scheme costs including optimism bias can be found in the Impact Assessment (DECC[2] 2010). In order that the CoE model outputs remain comparable to the outputs of the SEA study, the CoE model does not include optimism bias. Optimism bias would probably be added as a constant percentage to all schemes as they are all likely to be at the same stage of development, and hence its exclusion does not affect the intended purpose of the CoE model which is to act as a comparator between schemes.

Summary of Results

To initially validate the CoE model, the governing input design variables for the five Severn schemes were entered into the model to enable a cross-comparison between costs published as part of the SEA study and the model outputs – this effectively acting as a first order validation of the CoE model. Table 1 shows the outputs of the CoE model for the five Severn schemes compared to the costs reported as part of the SEA study.

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[1] Optimism Bias, HM Treasury, Green Book, Appraisal and Evaluation in Central Government, 2011: “Demonstrated systematic tendency for appraisers to be over-optimistic about key project parameters, including capital costs, operating costs, works duration, benefits delivery.”

Table 1 Model outputs compared to original costs (costs in £m unless otherwise stated)

	Cardiff Weston			Shoots			Beachley			Welsh grounds			Bridgwater bay		
	Model	Severn data	Error	Model	Severn data	Error	Model	Severn data	Error	Model	Severn data	Error	Model	Severn data	Error
Pre construction	225	290	-22%	40	70	-43%	27	60	-55%	60	80	-25%	96	160	-40%
Construction	17182	17612	-2%	3007	3263	-8%	2152	2140	1%	4212	4708	-11%	7685	9143	-16%
Construction contingency	2577	2641	-2%	526	571	-8%	377	375	0%	842	941	-10%	1537	1832	-16%
Ancillary works	574	600	-4%	206	239	-14%	185	293	-37%	203	96	112%	330	270	22%
Measures to prevent and reduce adverse effects	150	750	-80%	150	290	-48%	150	330	-55%	150	283	-47%	150	353	-58%
Non inter tidal compensation	0	43	-100%	0	25	-100%	0	22	-100%	0	22	-100%	0	6	-100%
Intertidal habitat compensation (1:1)	632	632	0%	144	144	0%	115	115	0%	322	322	0%	95	95	-1%
Scheme cost including 1:1 compensatory habitat	21341	22568	-5%	4073	4602	-11%	3006	3335	-10%	5790	6452	-10%	9892	11859	-17%
Annual O&M	224	286	-22%	48	54	-12%	37	32	15%	58	56	3%	99	111	-11%
Cost of Energy (£/MWh)	159	160	0%	161	176	-9%	199	225	-12%	252	259	-3%	168	194	-13%

The results in Table 1 indicate that the CoE model replicates the CoE to within 15% of the figures published in the SEA study. This is a reasonable error margin considering that the model is based on (best-fit) cost trends using data from five schemes and a number of simplifications and assumptions. The embankment costs have been calculated from first principles and hence do not exactly match the published figures. Another significant factor in this error margin may be the accuracy of the input data used to model the five schemes in the CoE model. For example, the costs published in the SEA will have been based on detailed base data for the site (e.g. considering the true bathymetry of the seabed and numerous cross-structural cross-sections along the barrier) and indicative design, whilst the CoE model has adopted a number of broad-brush assumptions (e.g. an average seabed level for each type of impoundment structure). Therefore it is recommended that the user takes care in determining the scheme general arrangement data. One significant difference between the CoE model generated data and that published in the SEA is that in the CoE model the measures to prevent and reduce adverse effects are currently lower, as they do not include topographic modification. Topographic modification is not included in the CoE model because it is very site specific and because when the CSM has been built and provides its outputs, the total intertidal area lost will be an input to the CoE model and the CoE model assumes that the whole intertidal area is replaced through habitat compensation, rather than by a combination of topographic modification and habitat compensation. Non intertidal habitat compensation has not been allowed for in the model; hence, this reads 100% error, but it is a minimal cost and will not impact the CoE significantly.

Case studies (Limits of foreseen technologies)

Using the CoE model, B&V has investigated three case studies in order to explore:

1. The effect of the parameters for an ‘optimum’ site on the CoE for a standard technology;
2. The effect of the parameters for the ‘best case’ currently forseen technologies for a ‘base case’ site;
3. The effect of the parameters for an ‘optimum’ site for the ‘best case’ currently forseen technology.

In undertaking this exercise, the minimum CoE that may be achievable for a small number of sites can be represented by the ‘optimum site.’ The ‘base case’ site provides a representation of the average CoE achievable at multiple locations around the UK.

The CoE model has been run for both identified schemes with both bulb turbines and Rolls-Royce turbines being modelled. The inputs have been prepared based on D01, admiralty charts and information from the SEA (DECC 2010), and could be refined when the CSM is available. The results can be found in Table 2 which do not currently include compensatory habitat which could be added at a later date once the predicted inter-tidal area lost is available from the CSM.

Table 2 CoE model outputs

	Cost of energy (£/MWh)
Severn Outer - Bulb	126
Severn Outer - Rolls-Royce	135
Bridgwater Bay - Bulb	153
Bridgwater Bay - Rolls-Royce	159

The Bridgwater Bay bulb turbine scheme inputs have been generated using recommendations and assumptions made whilst developing the CoE model, rather than directly using the SEA data, in order to give fair comparison; hence, the CoE is slightly different from the CoE given in the validation.

For both schemes, the best case technology, solely based on the appraisal of CoE, would appear to be the conventional bulb turbine, although in reality the results are well within the error bands of the CoE model analysis, as discussed in terms of model limitations. It should also be noted that in both cases the site selected appears to be more favourable to the bulb turbines (especially for Bridgwater Bay).

Key findings & conclusions

B&V has conducted a general literature review of the construction and deployment methodologies associated with tidal range technologies, and subsequent annual O&M activities. It was concluded that bulb and Rolls-Royce turbines would be used in the CoE model. Bulb turbines represent a conventional technology whilst the Rolls-Royce turbine represents a novel turbine option. The Rolls-Royce turbine is at a relatively early stage of development and the CoE model should be updated by Rolls-Royce/ETI when more detailed design and cost information becomes available. The literature review identified a number of embankment construction methods. It was concluded that a conventional rubble mound embankment would be included in the CoE model as alternative solutions are relatively undeveloped. However, the user has the opportunity to enter a cost per m length for a novel embankment solution which can be used when these designs are further developed.

The design of a significant scheme such as a tidal power barrage or lagoon is a complex and time consuming matter that requires the consideration of various engineering disciplines such as civil, mechanical and electrical to develop a realistic site specific solution for detailed costing. Therefore, to accurately estimate costs for such a scheme using a simplistic CoE model is not possible. Nonetheless, using relatively refined design and cost data taken from existing scheme feasibility studies, particularly schemes proposed for the Severn estuary, it was possible to develop a series of cost relationships for various design, construction and other parameters which can be used to predict a series of indicative costs for similar parameters for various schemes. The combination of all these costs can be assessed against the predicted energy production of the scheme to determine a levelised CoE value which allows comparison on a like-for-like basis between schemes to help identify an optimum solution to be selected for further development.

To validate the CoE model, the governing input design variables for the five Severn schemes were entered into the model to enable a cross-comparison between costs published as part of the SEA study and the model outputs – this effectively acting as a first order validation of the CoE model.

B&V has selected an ‘optimum’ and a ‘base case’ site to explore the limits of the currently foreseen tidal range technologies through use of the CoE model. In undertaking this exercise, the minimum CoE that may be achievable for a small number of sites can be represented by the ‘optimum site.’ The ‘base case’ site provides a representation of the average CoE achievable at multiple locations around the UK. The ‘optimum’ site was selected to be Severn Outer Barrage and the ‘base case’ site to be Bridgwater Bay Lagoon. At each of these sites the CoE model was run for both bulb and Rolls-Royce turbines. For both schemes, the best case technology, solely based on the appraisal of CoE, would appear to be the conventional bulb turbine, although in reality the results are well within the error bands of the CoE model analysis. It should also be noted that in both cases the site selected appears to be more favourable to the bulb turbines (especially for Bridgwater Bay).

This analysis suggests that the Rolls-Royce turbines may have (i) a CoE advantage for a truly ‘average’ UK site (although there is no such site to directly compare both bulb and Rolls-Royce turbines); (ii) a practical advantage where bulb turbines cannot meet the 80% tidal range threshold without dredging (e.g. Cardiff -Weston, Morecambe Bay). It should be noted that the Rolls-Royce turbine is at an early stage of design and the cost and design information is not as well developed as for bulb turbines. The CoE model should be updated when more detailed information is available for Rolls-Royce turbines.

1 INTRODUCTION

1.1 Background

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 B&V 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 stream projects including resource assessment and project development, technology development, due diligence, cost of energy and policy development. Through working on these projects, B&V has gained a deep technical and commercial understanding of tidal energy projects in addition to simple resource assessments.

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

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

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1.2 Tidal range technology

There are two main options to extract power from tidal range: tidal barrage and tidal lagoon. Both of these options operate by impounding a volume of water as the tide level changes and use the hydraulic head differential across the barrier structure to drive turbines and thus generate electricity. Tidal fences using closely packed tidal current turbines (sometimes with additional structures) have not been included in this report as a tidal range option because they extract power from tidal currents; this approach was agreed with the ETI.

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The following sections of the introduction provide a discussion of the generally accepted methods, and potentially viable novel solutions, for the construction of tidal range power schemes and a summary of the O&M experience obtained from existing tidal barrages. Discussion of the technologies and operating regimes can be found in D01. These sections are intended to act only as a background to the main aim of this report, which is to describe the development of the parametric CoE model.

1.3 Tidal barrage

A tidal barrage is an impounding structure across a tidal estuary which controls flow into and out of the estuary in order to generate electricity. Typically the barrage will consist of four key parts: turbines (and their caissons), sluices (and their caissons), locks, and impounding embankments and/or plain caissons. Figure 1 shows a schematic example of a tidal barrage in the Severn estuary.

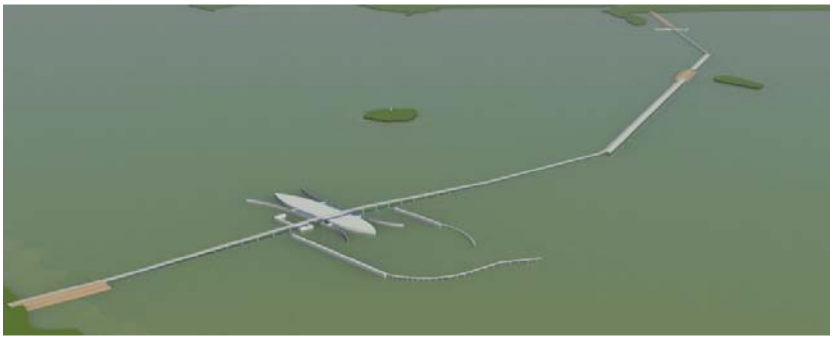

Figure 1 Cardiff Weston barrage (computer generated, DECC 2010)

1.3.1 Operating regime

There are four main methods of operating the barrage: ebb generation, ebb generation with high tide pumping, flood generation, and dual (ebb flood) generation. These are discussed in detail in D01 (Tidal resource characterisation). There are a range of factors which may affect selection of the operating regime including cost of electricity, number and length of generation periods per tide, water levels for navigation and habitat conservation. The Severn Tidal Power 'Strategy Environmental Assessment' (SEA), (DECC 2010), optimised and appraised a number of barrage and lagoon schemes (five schemes were selected for closer review) for the Severn estuary, as described in section 2.1, by considering all of these factors and identified the ebb generation mode of operation as being a suitable base case for the barrage schemes. The Mersey feasibility study (Peel Energy 2011) selected a scheme design which could operate in either ebb only or dual mode.

The selection of the operating regime has a strong influence on capital costs in terms of the number of turbines and sluices, the complexity of the turbines and the caisson dimensions. The SEA study assumed that for bulb turbines in dual generation a 'draft tube' would be required both upstream and downstream of the turbine to improve turbine efficiency, thus resulting in wider caissons than ebb only generation. Reversible bulb turbines required for dual generation will bear an additional cost to cover the complexities of the design.

Rolls-Royce has developed a bi-directional turbine with potentially improved efficiency for dual generation at low heads. The concept has been developed under the Severn Embryonic Technologies Scheme (SETS) in parallel with the SEA study. See section 1.5 for further details.

An alternative operating regime to achieve a more continuous generation can be adopted if two basins are created. However, the long lengths of embankment and, or, caissons required to form the barriers generally make two basin schemes less viable than single basin schemes (Baker 1991).

1.3.2 Turbines

Tidal Power (Baker 1991) identifies three types of turbine for tidal power generation: the rim generator turbine (sometimes referred to as 'Straflo'), the tubular turbine and the bulb turbine. It is suggested that the small differences between these designs will have relatively little influence on overall cost. The Rolls-Royce turbine mentioned above is described in section 1.5.

The Rance barrage has 24no. bulb turbines and the practical experience gained from this scheme and other low head run-of-river hydro schemes makes bulb turbines a common choice. Of the five schemes selected in the SEA study, three were designed with bulb turbines and two with Straflo. The Mersey study selected bulb turbines for the preferred scheme.

1.3.3 Working Caissons

It is generally accepted, for large tidal power schemes, that the sluices and turbines will be housed within 'working' caissons which are prefabricated structures that are floated to sea and sunk into position. The Severn Tidal Power Group considered an alternative method to construct caissons in-situ by using a temporary embankment to construct series of diaphragm walls; however, this method was not found to offer any advantage in time or cost (SDC 2007). The Rance barrage was constructed within the enclosure of two temporary cofferdams to provide shelter from tides, and which largely blocked the estuary for a number of years. This caused the water in the estuary basin to turn from sea water to fresh water and back again when the construction was complete; an environmental effect which would now be considered unacceptable.

The majority of preliminary scheme designs to date, including those developed as part of the Severn, Mersey and Solway studies (DECC 2010, Peel Energy 2011, Halcrow 2009 respectively), have selected a reinforced concrete caisson design as the base case for cost estimates. The floating draught and width of the caissons for a tidal power scheme are likely to be so great that they are unlikely to be accommodated by existing shipyards hence special facilities would need to be built. In 1987, the cost of 3no. shipyards required for the Severn barrage scheme was estimated at over 10% of the entire project cost (Baker 1991). Generally a square/rectangular caisson design has been progressed, rather than a circular design, for simplicity of housing the turbines and forming intersections. Figure 2 shows an example caisson design for a Cardiff-Weston barrage scheme.

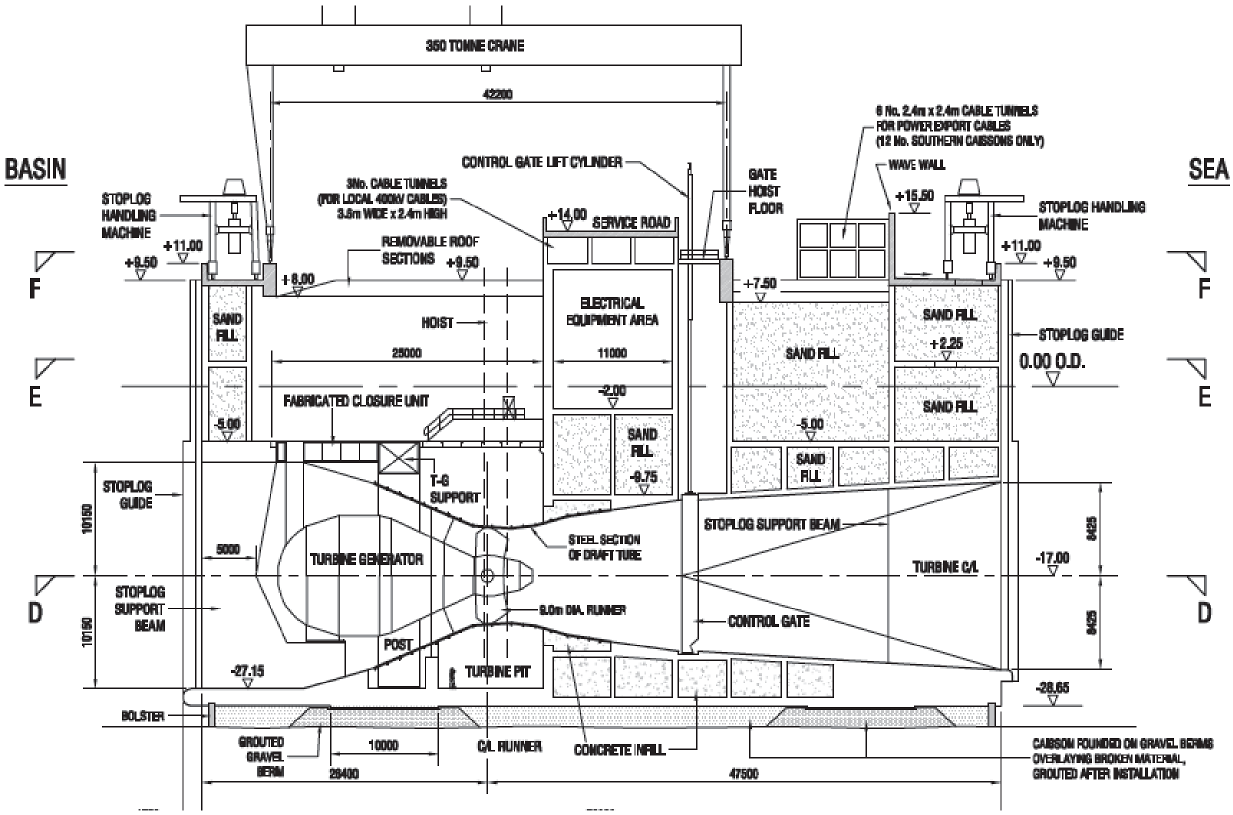

Figure 2 Cardiff Weston turbine caisson (DECC 2010)

An alternative design to reinforced concrete is the use of structural steel caissons. Steel caissons could be based on a ‘compartmentalised’ arrangement and will have a reduced weight, and hence smaller floating draught, so it may be possible to find a suitable existing shipyard for fabrication. Once in position the compartments surrounding the water passage would be infilled with concrete whilst compartments in more benign conditions could be ballasted with concrete or sand, which are methods of ensuring stability. An alternative means to enhance stability is the use of rock anchors which, as the name implies, could be used to further reduce the required weight for stability by anchoring the caisson to the seabed. The disadvantage of steel caissons is that they are likely to require a significant amount of mass concrete and sand ballast to achieve the same level of stability as reinforced concrete caissons (when not using rock anchors), which may offset any savings made in construction, and expensive corrosion protection is required due to the aggressive marine environment.

Post-emplacement works such as installation of piers and roadway, roofs and closure panels for barrage schemes are likely to be installed as precast units using a large floating crane (Baker 1991). Similarly, installation of the turbines will be carried out with barge and heavy lift crane (Baker 1991)

1.3.4 Sluices

Sluices are openings in the structure controlled by gates and usually housed in caissons. For ebb generation schemes, the sluices play a vital role by allowing the basin to refill. By its very nature, dual generation schemes may be able to operate without sluices as water passes through the turbines in both directions. There are a number of types of gate suitable for a tidal power scheme sluice, namely flap gate, vertical-lift wheeled gate, radial gate and rising sector gate. For sites with water depths greater than 20m at mean sea level the vertical-lift wheeled gate would be most suitable, while for shallower sites the radial gate is probably the best choice (Baker 1991). All four of the Severn schemes with sluices have water depths of around 20m or less at the sluices and use radial gates (DECC 2010).

1.3.5 Locks

Locks are required to permit navigation through the impoundment structure (or barrier), with the size and number of locks dependent on the current shipping traffic and navigation activities through the site. For an estuary which sees between 5,000 and 12,000 vessels movements a year, two locks should be provided, one of these being able to accommodate the largest vessel (Baker 1991). The Cardiff Weston barrage scheme has two large ship locks (DECC 2010), the smaller barrage options have a single ship lock and the lagoon schemes have a single lock to permit maintenance activities. The Mersey scheme has two large ship locks (Peel Energy 2011). Breakwaters may be necessary to provide sheltered access to the lock from the seaward side and guide walls will be needed on both the seaward and landward sides of the barrier to assist the vessel entering the lock. The locks will often be located outside the deep water channel as this is the location where the turbines will be operating which causes undesirable shipping conditions; therefore an approach channel will need to be dredged to allow vessel access to the lock.

1.3.6 Embankments and Plain Caissons

Depending on the width of the estuary and the length of the barrage, it is quite likely that the working parts of the barrage will not cover the whole length of the barrier. In this case, a rubble mound embankment, plain caissons or a combination of both, will typically be used to close the remaining gaps. In shallow waters, rubble mound embankments will be the least cost solution; however, the cost of an embankment does not increase linearly with water depth and in mean water depths greater than c.15m it may become less expensive to use plain caissons (Baker 1991). Plain caissons are also generally used for the transition from embankment to working caissons to allow the embankment slope to terminate a suitable distance away from the turbines and sluices so as not to infringe on any dredged channels and to minimise any embankment material being disturbed by the fast flowing waters near the turbines and sluices. All of the Severn schemes predominantly use rubble mound embankments with plain caissons for the transition only (DECC 2010).

A typical rubble mound embankment, such as that shown in Figure 3, for an estuary with a high tidal range will be based around a control mound of quarried rock which will be built first to achieve localised control over the tidal flows. The height of the control mound need not be higher than the mean high water of spring tides (MHWS). Rock fill will be significantly more expensive than sand, thus the side slopes of the control mound will be as steep as possible to limit material quantities; in moving water a slope of 1 in 2 has been assessed as reasonable (Baker 1991). Sand fill is then placed, in layers against this upstream slope of the control mound with the opposite end of each layer being contained by a smaller ‘containment mound’. The containment mounds can be made from a cheaper granular material such as mine waste. The Severn Tidal Power SEA (DECC 2010) assumes side slopes of 1 in 3 for the containment mounds.

The slopes of the embankment will be protected by either rock armour-stone or artificial precast concrete units (i.e. Accropode, Tetrapod, Dolos units) depending on the local sea conditions.

Artificial units have a history of use in highly energetic marine environments for maritime applications whereby a sufficient size of armour-stone cannot be quarried or is cost prohibitive to import to site. These units utilise their inherent interlinking properties, in addition to self weight, to provide a robust means to protect the embankment from wave erosion and to dissipate wave loads. The crest level of the finished embankment will be dependent on the local tide levels, storm surge and wave conditions and will be defined in accordance to acceptable overtopping (and run-up) limits.

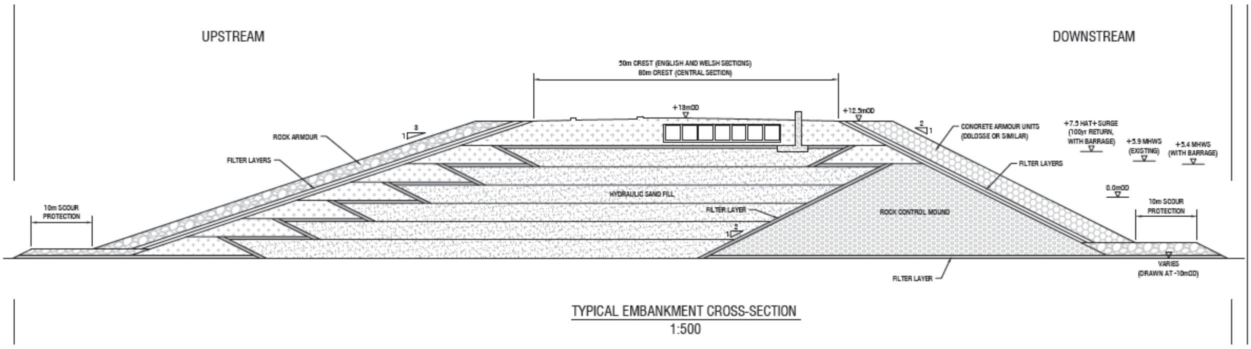

Figure 3 Cardiff-Weston embankment section (DECC 2010)

The construction of rubble mound embankments is a mature practice due to their prevalent use in maritime applications (i.e. ports and harbours) and the example described above is only one of many potential arrangements.

Construction of embankments below water level is likely to be carried out by a side dump barge (DECC 2010). Construction above water level is typically carried out by land based plant on top of the embankment. However, for sections of the embankment without land access, a floating pontoon to support the offloading of plant and materials could be constructed – this being an method considered for parts of the lagoons and a section of the Cardiff Weston barrage in the SEA (DECC 2010).

It is to be noted that a number of alternative solutions to plain caissons and rubble mound embankment have been investigated, many of which are discussed in Section 1.4.1 in relation to tidal lagoons.

1.3.7 Habitat compensation

The SEA considers the costs to provide inter-tidal habitat compensation under the Habitats Directive assuming the relevant criteria are met. Dependent on the quality of the habitat created, different ratios of lost area to compensatory area will apply.

1.3.8 Operations and Maintenance (O&M)

Operation of the turbines, sluices and locks will require a permanent team of staff. The SEA estimated staff numbers for each scheme based on figures from the Rance power plant. The study assumed £40,000 average salary, with overheads at 50% of salary. By allowing for insurance and annual maintenance contracts, the annual O&M costs were found to be approximately 1% of the capital cost. Additional costs would include major maintenance/refit to the turbines and gates every 20-40 years and dredging to maintain shipping channels. The SEA assumes that major maintenance/refit incurs 70% of the original mechanical and electrical (M&E) capital costs. Additional O&M data was requested from EDF; however, B&V were unable to obtain any information for use in the CoE model. If the user has access to additional O&M information, they are able to modify the percentage allowance of the scheme capital cost for annual O&M costs, as described in the user guide.

1.4 Tidal lagoon

A tidal lagoon operates in a similar way to a barrage by impounding a volume of water in sites with significant tidal range. A tidal lagoon can be either a completely offshore enclosure (an ‘offshore lagoon’) or can be partially connected to land (a ‘coastal lagoon’). Two coastal lagoon schemes were shortlisted for study in the SEA, namely; the Welsh Grounds Lagoon, as shown in Figure 4 and the Bridgwater Bay Lagoon.

Figure 4 Welsh grounds lagoon (DECC 2010)

Tidal lagoon schemes typically include turbine caissons and long lengths of embankment. Whether the scheme also includes sluices depends on the proposed operating regime. Lagoon schemes operating in dual mode do not require sluices because all the water passes through the turbines, whilst ebb only generation schemes will include sluices to refill the basin. Of the two lagoon schemes defined in the SEA one was progressed as dual while the other was progressed as ebb only. For shore connected schemes, it may be necessary to include a lock for navigation, dependant on shipping at the site. For offshore schemes, a lock to allow access to the basin for maintenance activities is likely to be required.

Selection of turbines, sluices and working caissons will follow a similar method to that outlined for a barrage. As lagoons have long sections of barrier, its design can have a significant impact on the cost of the scheme. A description of a conventional rubble mound embankment for a barrage, but which could also be suitable for lagoons, can be found in section 1.3.6. The SEA adopted this conventional rubble mound embankment as the base case for the lagoon schemes on the basis that this would provide a reasonable estimate of cost for the feasibility stage whilst further investigation of alternative methods was being undertaken. Some of the alternative barrier designs for lagoons which were considered in the SEA are described in section 1.4.1.

1.4.1 Alternative Embankment Designs

1.4.1.1 Fleming Energy precast wall

Fleming Energy proposed three precast wall solutions for the Welsh Grounds Lagoon: a tied precast wall, a braced precast wall and precast box caissons. Following appraisal, the SEA concluded that the braced precast wall, shown in Figure 5, may be feasible with further development informed by site investigation. This concept is based on precast concrete wall panels braced by precast transverse panels and infilled with dredged material.

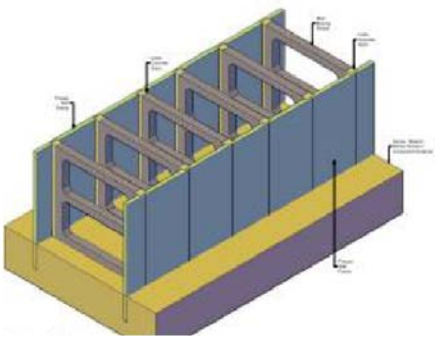

Figure 5 Fleming wall (DECC 2010)

1.4.1.2 *Geo-container embankment*

Tidal Energy Ltd proposed an alternative method of embankment construction, shown in Figure 6, using geo-synthetic containers ('geo-containers') filled with granular material to form the embankment slopes. The aim of the concept is to increase the steepness of the side slopes and thus reduce the embankment footprint and material quantities. The geo-containers would then be protected with a layer of rock armouring. The SEA considered using this method for the Bridgwater Bay Lagoon and initial indications showed that geo-container construction would be around 20% more expensive than conventional rock fill embankment.

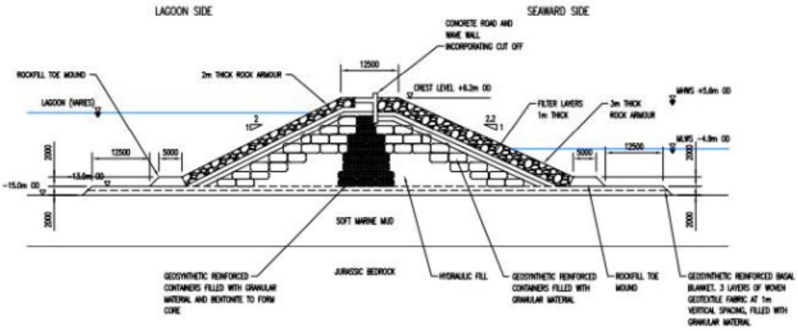

Figure 6 Geo-container embankment (DECC 2010)

1.4.1.3 *Halcyon pile supported wall panels*

The Halcyon wall, shown in Figure 7, is made of mini concrete caissons supported on precast piles which will be inserted into pre-drilled sockets in the underlying rock. Steel sheet piles will be used to toe through the sediment (i.e. mud) layer(s) below the mini caisson to form a barrier to minimise seepage under the caissons. The modular approach is intended to allow rapid construction with a bespoke catamaran jack-up barge. An access road could be placed on a superstructure supported by the columns. The SEA concluded that the Halcyon wall solution is technically viable and may be competitive with the conventional rock fill embankment, but further study is needed to develop the concept.

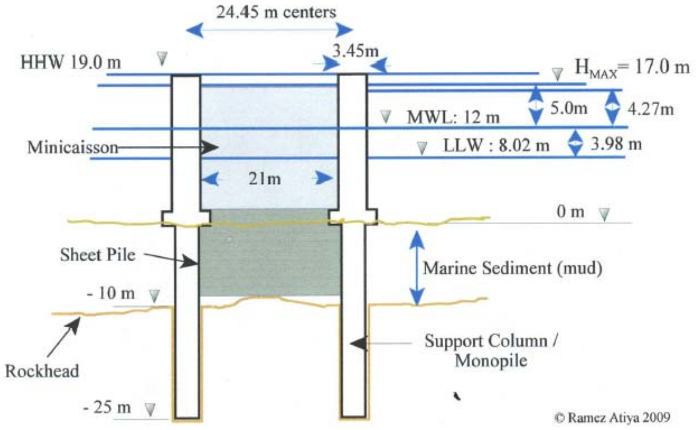

Figure 7 Halcyon wall proposal (DECC 2010)

1.4.1.4 Rubicon technology

Rubicon Marine proposed a box structure fabricated from glass fibre panels reinforced with a mesh of recycled rubber coated bead hoops sourced from disused tyres. The boxes would be filled with dredged material to achieve sufficient stability. The SEA concluded that there was currently insufficient evidence to inform any further study into the application of this technology to the lagoon scheme.

1.4.1.5 Other options

In 2007, the Sustainable Development Commission (SDC) carried out a study on tidal power in the UK which included consideration of three non-barrage options for the Severn estuary (SDC 2007). These included two lagoon options, namely: the Russell Lagoons and the Swansea Bay Lagoon. Russell proposed an alternative method for construction of the embankment involving a large temporary shield which would be filled with dredged sand followed by coarser material; however, the 1981 Department of Energy review concluded the technique was unlikely to be practical for barrage construction. The Swansea Bay Lagoon was proposed by Tidal Electric Limited (TEL). The design is based on a conventional embankment; however, the crest of the embankment would only be slightly above MHWS and would allow overtopping. The Department of Trade and Industry and the Welsh Development Agency (DTI/WDA 2006) commissioned a study into the scheme and the resulting CoE was significantly different from the CoE proposed by TEL. The DTI/WDA embankment is 3m taller than the TEL embankment and has slopes of 1 in 2.5 compared to 1 in 1.5, a design wave height of 5m rather than 4m is also considered.

The embankments designed for the Severn lagoon schemes (DECC 2010) are split into two access categories, allowing a slightly lower embankment height for sections not required for access to the power plant equipment. However, the lower embankment height is still significantly higher than MHWS and only allows occasional overtopping. The side slopes of the Severn schemes are 1 in 3, or 1 in 2 where a rock control mound is used, as previously described.

1.4.2 Offshore lagoons

Offshore lagoons require special consideration especially regarding access and grid connection. Construction of the caissons will be carried out in a similar manner to barrages and land connected lagoons and floated into position. Construction of the embankments will be carried out in the same manner described in Section 1.3.6 with a side dump barge and a pontoon for offloading plant and materials. As discussed in Section 1.3.3 post emplacement works are likely to be carried out from the sea for barrages and land connected lagoons; hence, there will be no difference in methodology for an offshore lagoon. However, it is possible that offshore lagoons will be located in more exposed locations which may restrict the window for carrying out these operations.

Maintenance for the turbine generators and gates is likely to be considerably more expensive as access will be from the sea only.

1.5 Very low head barrages

Very low head barrages are broadly similar to conventional barrages; however, they are intended to operate at lower heads. These types of barrages can be constructed using methods similar to conventional barrages and the reduced operating head can result in construction savings. Alternative structural options, such as the tidal power gate and tidal reef, have also been proposed, and are discussed below, along with advancements in turbine technology, with reference to the Severn, Mersey and Solway estuaries.

1.5.1 Severn developments

Rolls-Royce has recently developed a bi-directional turbine, known as the “Blue turbine” shown in Figure 8, which may have potential to increase the hydraulic efficiency and reduce the construction cost of a very low head barrage. The scheme aims to operate efficiently in both directions to maximise energy output and to cause less change to the tidal regime within the basin. Rolls-Royce/Atkins propose that the caissons for the Cardiff-Weston barrage could be reduced from 74m wide (ebb only) to 50m by using the new turbines which don’t require a draft tube and operate at reduced head (Rolls-Royce/ Atkins 2010). Operating at a lower head and slower speed means the turbine requires less submergence; hence the draft of the caisson could also be reduced. Rolls-Royce are hopeful that the turbine will be able to be installed and commissioned in a significantly shorter period than conventional turbines.

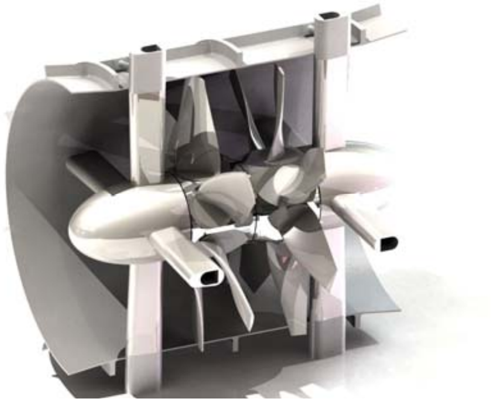

Figure 8 Rolls-Royce Blue turbine configuration (Rolls- Royce/Atkins 2010)

1.5.2 Solway developments

The very low head barrage schemes proposed for the Solway estuary operate in dual mode and use ECOBulb turbines manufactured by Andritz (Halcrow 2010). The ECOBulb is a single or double regulated axial turbine with a direct coupled low speed synchronous generator integrated into an air pressurised bulb. The turbines can operate at a range of heads from 2 to 15m (VA Tech Hydro 2011). The ECOBulb requires reduced water depth for operation and hence a higher foundation level can be used, resulting in reduced excavation and structure costs (Peel 2011).

1.5.3 Mersey developments

The Mersey feasibility study considered using ECOBulb turbines for the very low head barrage studied; however, it was concluded that they would have an unacceptable impact on fish due to their small size, fast rotational speed and number of turbines required for the location (Peel Energy 2011).

Initially the study considered using a moving gate concept with Hydromatrix technology. Hydromatrix is a patented technology comprising a grid of small bulb turbines built into a gate. The technology is already in use in gated spill ways, intakes, irrigation outlets and sluices. A series of these gates could be constructed across an estuary with embankments closing the remaining gaps. The gates would be raised during flood tide and lowered during the ebb tide for power generation (Peel Energy 2011). However, the gates were not progressed to later stages of the study due to operational issues. Other very low head turbines were considered to be insufficiently developed and hence the scheme assumed conventional bulb turbines.

An alternative method of very low head barrage construction referred to as the “tidal reef” is discussed at the ‘long list’ stage of the Mersey Tidal Power study (Peel Energy 2011). It proposes a structural arrangement where the turbines are housed in carrier modules above the reef wall. The turbine carrier modules would house four turbines and would be able to rotate. At 90 degrees it is proposed that vessels could pass through the structure and at 180 degrees the turbines would be reversed. However, the scheme was not progressed in the study as it was at a very early stage of development.

1.6 Spectral Marine Energy Convertor (SMEC)

The Spectral Marine Energy Convertor (SMEC) developed by VerdErg was selected as part of the Severn Embryonic Technologies Scheme (SETS). The technology is based on the venturi principle as shown in Figure 9. The Mersey study (Peel Energy 2011) classed the SMEC as a tidal fence. In accordance with this, and as there is limited information available for costing, the SMEC has not been included in the CoE model.

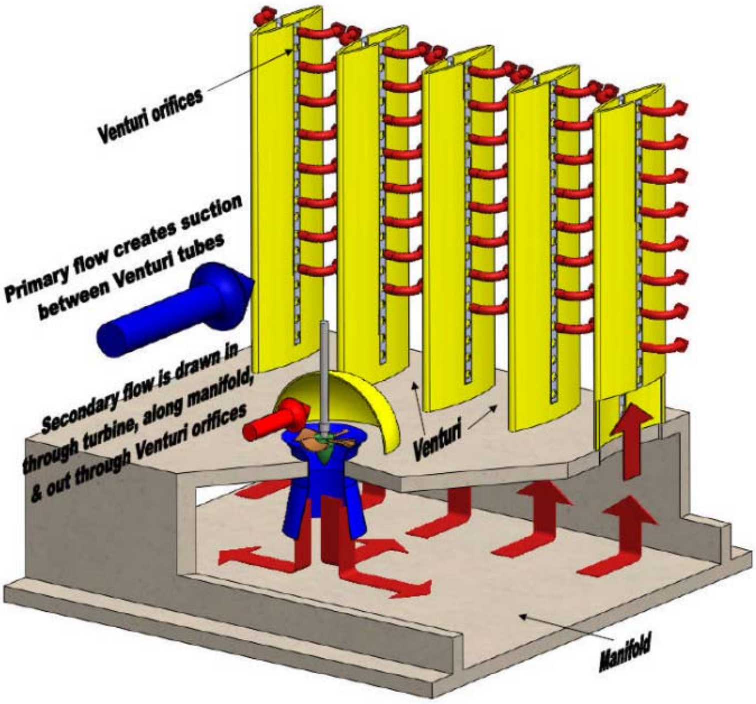

Figure 9 Spectral Marine Energy Convertor (VerdErg 2010)

2 COST OF ENERGY MODEL METHODOLOGY

2.1 Introduction

The aim of this work package was to develop a flexible parametric Cost of Energy (CoE) model for tidal range barrage and lagoon technologies. The base case components and their respective costs have been taken from the five schemes defined in the SEA study (DECC 2010), hereafter the 'Severn schemes'. These schemes include three barrages of varying size (Cardiff-Weston, Shoots and Beachley) and two land connected lagoons (Welsh Grounds and Bridgwater Bay). In addition to the five Severn schemes, the study also appraised variations of each as part of an optimisation exercise.

The Severn study developed detailed cost estimates for each of the Severn schemes based on preliminary designs which have been used, where possible, as the basis on which to identify 'cost trends' for the CoE model. Given this, the CoE model follows a similar cost breakdown structure to that used as part of the Severn study to allow direct comparison between components and thus allow a means of cross-validation. In some cases a simplified costing approach or additional cost information has been taken from the earlier Interim Options Analysis Report (IOAR) (DECC 2008). In the case of Rolls-Royce turbines, cost and design information has been taken from the SETS report (Rolls-Royce/ Atkins 2010).

The cost estimates in the Severn study are based on 1st quarter 2008 prices. As the purpose of the cost model is to provide a comparison between schemes, and it is likely that the user will wish to compare these costs to those from the Severn study, the costs have not been inflated to 2011 prices. The Rolls-Royce turbine costs have been taken from the 2010 SETS report (see section 3.1 for discussion).

The Severn schemes cost estimates do not include optimism bias[2]. Scheme costs including optimism bias can be found in the Impact Assessment (DECC[2] 2010). In order that the CoE model outputs remain comparable to the outputs of the SEA study, the CoE model does not include optimism bias. Optimism bias would probably be added as a constant percentage to all schemes as they are all likely to be at the same stage of development, and hence its exclusion does not affect the intended purpose of the CoE model which is to act as a comparator between schemes.

The following sections detail the methodology used to develop the CoE model which can be used for any given barrage or lagoon scheme. Key assumptions, limitations and user defined inputs are also discussed.

2.2 Continental Shelf Model

Unless clearly identified within the following sections, much of the input information for the CoE model will be generated by the Continental Shelf Model (CSM) being developed as part of this ETI project. The key data generated by the CSM is as follows:

- Annual energy production.
- Turbine (operating regime, type, diameter, capacity, number of units, unit spacing).
- Sluices (gate width, number of units, unit spacing).
- Average seabed levels (turbine caissons (pre and post dredging), sluice caissons, plain caissons, rubble mound embankments).
- Tidal range (post construction).
- Intertidal area lost following construction.

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[2] Optimism Bias, HM Treasury, Green Book, Appraisal and Evaluation in Central Government, 2011: "Demonstrated systematic tendency for appraisers to be over-optimistic about key project parameters, including capital costs, operating costs, works duration, benefits delivery."

In addition to the CSM inputs, the user is required to specify 'user-defined' inputs which are discussed in the following sections, with recommendations (which may be used as default values) provided. The CoE model also includes a number of pre-set variables that are based on best estimates. Although the user can modify the pre-set variables, it is not encouraged without a full understanding of their meaning. A breakdown summary of the CSM and user defined inputs, and the pre-set variables, are provided in the CoE model User Guide which supports the model and complements this report.

In all cases where the scheme design has more than one value and the CoE model requires a single input, a weighted average should be calculated by the user. For example, in the event that scheme has a combination of different size turbines the user would calculate weighted averages for diameter, capacity, turbine spacing and caisson bed level.

2.3 General Arrangement of Scheme

The total length of the impoundment is a user defined input which can be estimated through measurement taken from available drawings/plans (i.e. admiralty charts), reference to past desk-top studies or from numerical models of the site (including the CSM). The total length of the turbines and sluice caissons can be estimated by multiplying the number of turbines/sluices by their spacing, as provided by the CSM model.

The remaining length of the impoundment is assumed to consist of plain caissons or rubble mound embankment. The length of each type of impoundment structure is dependent on local bathymetry and technical and economic considerations; however, it is recommended for the CoE model that the user assumes that an embankment is appropriate for mean water depths greater than 15m. The lengths of the embankment and plain caissons are user defined inputs and should be estimated using the same methods as detailed above. The locks are assumed to be located in modified plain caisson unit(s).

All levels input to the CoE model should be relative to Ordinance Datum (OD). Special care must be taken if using admiralty charts to convert from Chart Datum (CD) to OD.

The CoE model is pre-set to consider a typical design life of 120 years which is the same as was adopted for the Severn schemes.

2.4 Environmental Conditions

Many of the environmental and site conditions for the CoE model will be generated by the CSM; however, the user is required to define the local wave conditions and storm surge allowance at the site.

Details of existing extreme wave conditions at the site (the CoE model considers 1 year and 100 year return periods) are required to specify the top level of the caissons and for the design of the armour layer on the seaward side of the rubble mound embankment. The user will also require this data in order to define the crest level of the rubble mound embankment(s). In the absence of this information, these wave conditions can be derived from existing wave records based on measurements made at site or historic logs of observations made from ships. The records can be used to predict extreme wave conditions for the return periods using methods stated in BS6349-1:2000.

Locally generated waves within a lagoon basin or landside of a barrage, following construction, can be predicted with prior knowledge of the fetch and wind speed for a given period of time, in accordance with BS6349-1:2000. The locally generated waves are used to design the armour layer on the landward/basin side of the rubble mound embankment.

A common means to represent wave conditions is through use of the significant wave height (H_s) whereby the maximum wave height (H_{max}) (as required by the model) can be estimated to be $1.86H_s$

based on the Rayleigh distribution of waves. The CoE model does not require the input of wave periods.

The user is required to define a nominal storm surge parameter to allow for changes in water level for variations in atmospheric pressure, strong winds and geographical constrictions. In lieu of site specific information, a nominal storm surge allowance of 1.0m is recommended for input in the CoE model.

2.5 Caissons

2.5.1 Top level

The top level of all working (i.e. sluice and turbines caissons) and plain caissons has been taken as the amplitude of the maximum 1yr return period wave plus storm surge allowance above MHWS level. The "top level" refers to the top of the main body of the caisson. The access road is likely to be set at a higher level and there may be additional wave walls and other secondary structures which extend above the top level; however, the associated costs of these variations/additional structures is assumed to be included in the cost relationships of the main structure of the caissons.

2.5.2 Width

The plan dimension of the caissons perpendicular to the centre line of the impoundment barrier, hereafter the caisson 'width', is largely dependent on three requirements:

- Internal space to house equipment.
- Access along the top of the caisson.
- Stability of the caisson.

The internal space required for the turbines depends on the length of the draft tubes. For bulb turbines a single draft tube will be provided for ebb generation and a double draft tube for dual generation. Thus the caissons for dual schemes are likely to be wider. Figure 10 shows the correlation for the five Severn schemes between rotor diameter and caisson width. As only one of the Severn schemes is defined as a dual scheme, additional dual mode caisson widths have been taken from the scheme variations appraisal section of the study (DECC 2010).

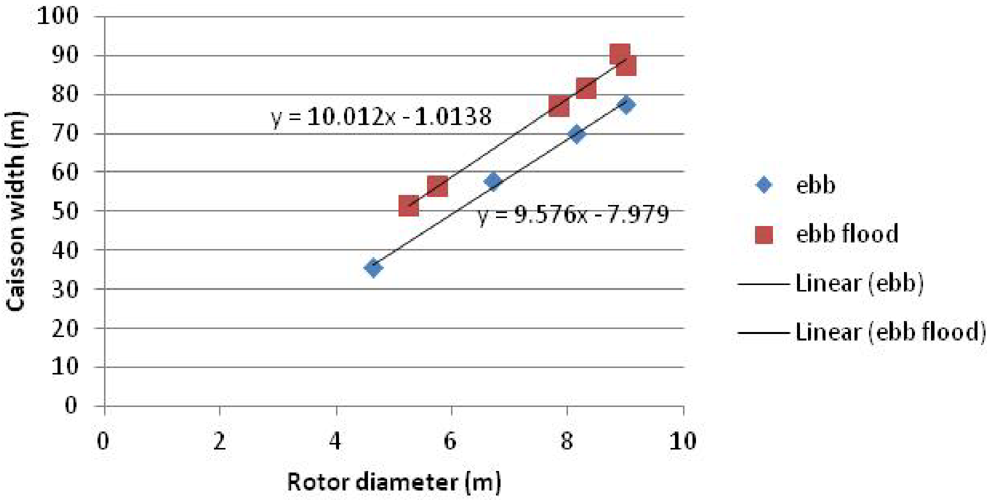

Figure 10 Bulb turbine caisson widths

This correlation has been used in the CoE model to estimate the caisson widths required for the commonly used bulb turbines (Straflo turbines are not considered in the model). The SETS study

(Rolls-Royce /Atkins 2010) proposes that the caissons housing Rolls-Royce turbines could be narrower (i.e. reduced width) than those for bulb turbines as they do not require a draft tube; the study suggests a turbine caisson width of 50m for a Cardiff-Weston equivalent scheme. This 50m dimension has been adopted in the CoE model as the caisson width for all Rolls-Royce turbines irrespective of scheme or site. It is possible for the user to refine this aspect as and when more detailed information becomes available.

The internal space requirements for sluice caissons will depend on the type and size of sluice gate. All the Severn schemes have used radial gates and Figure 11 shows the correlation between gate width and caisson width. It is assumed that radial gates provide a reasonable representation of the sluice cost for the purposes of this model.

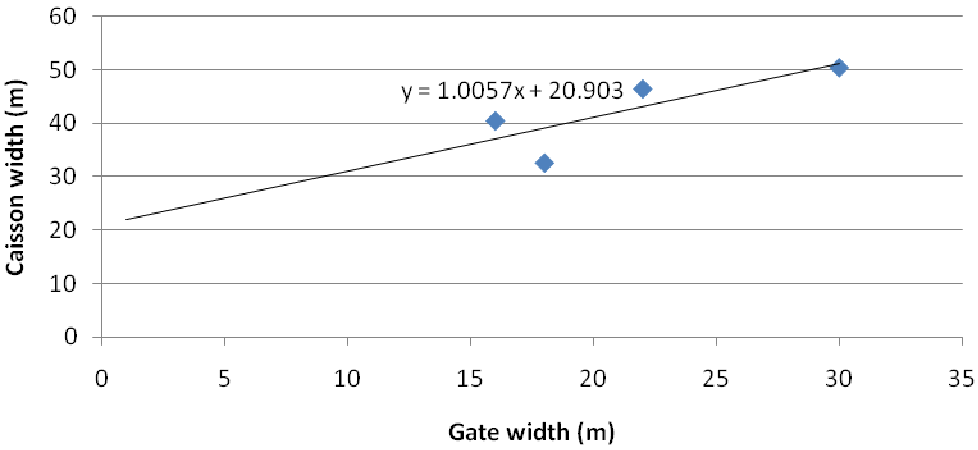

Figure 11 Sluice caisson widths

This correlation has been used in the CoE model to determine the width of the sluice caissons.

The width of the plain caissons is more difficult to predict as there is no internal equipment on which to develop a correlation. All of the Severn schemes have adopted a nominal plain caisson width of 45m, irrespective of water depth. This dimension is quite possibily governed by the width required for access along the top of the barrage or by stability criteria, although the driving factor is difficult to ascertain without access to the governing design work. For the CoE model, the width of the plain caisson is included as an user defined input to allow the user to vary the width; however, it is recommended that a minimum width of 45m is adopted for Access Category A and 25m for Access Category B. The SEA Options Definition Report (ODR) (DECC 2010) defines these categories as:

A. Access to the power house, sluices and locks. Access needs to be available under the majority of weather and tide combinations.
B. Access only to the impoundment barrier and transmission cables for inspection and maintenance purposes. Some restrictions on times of access are assumed to be acceptable.

Although it is probable that these dimensions could be refined following stability checks during preliminary design, it is currently assumed that both stated widths are sufficient to ensure the stability of the caissons based on the typical water depths being considered.

In summary, the width of the working and plain caissions considered by the CoE model are as follows:

- The width of a plain caisson is user-defined and is recommended to be taken as either 45m or 25m for Access Category A or B respectively.

- The width of the sluice caisson is dependent on the gate width and can be estimated from Figure 11. To ensure continunity of access, the width will not be less than the width of the plain caisson (Access Category A).
- The width of the turbine caisson is dependent on the type and diameter of the turbine, and the operating regime. Figure 10 can be used to determine the caisson width for a bulb turbine, with the width not being less than the width of the plain caisson (Access Category A). A nominal 50m width has been adoped for Rolls-Royce turbines.

2.5.3 Construction Cost

Figure 12 shows the (external) cross-sectional area of the working and plain caissons from the Severn schemes plotted against the construction cost per m length.

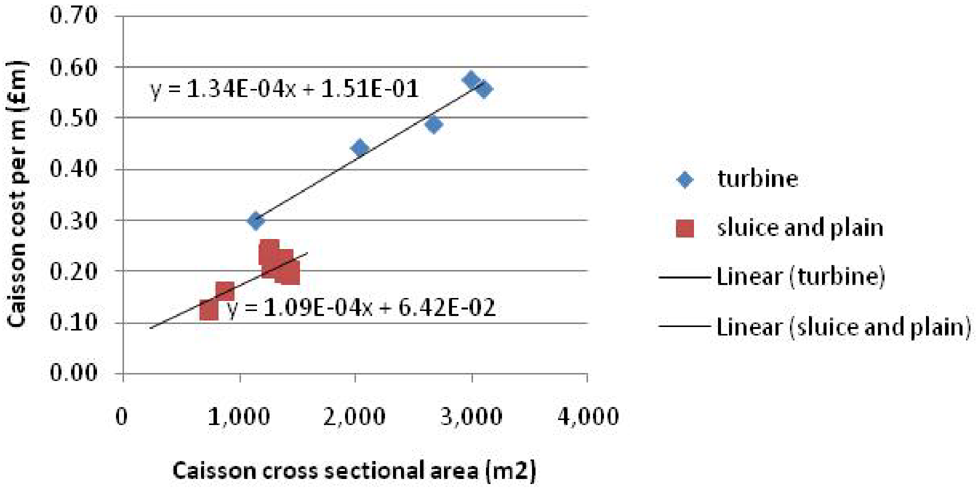

Figure 12 Caisson costs

The linear correlations for the working and plain caissons have been used to estimate construction cost trends (per m run) for the CoE model.

The total cost of the working caissons is calculated by multiplying these unit construction costs by the number of turbines/sluices and turbine/sluice spacing, as provided by the CSM. The total length of the plain caissons is a user defined variable, as described in section 2.3. It is to be noted that the CoE model does not allow for shared working caissons, that is, a caisson that jointly houses turbine and sluice equipment.

2.5.4 Construction facilities cost

Figure 13 shows the correlation between the capital cost of the (working and plain) caissons and the associated cost for construction facilities for the five Severn schemes which includes the establishment and removal of casting yards for the caissons. This correlation has been used in the model to provide an initial estimate of the construction facilities cost.

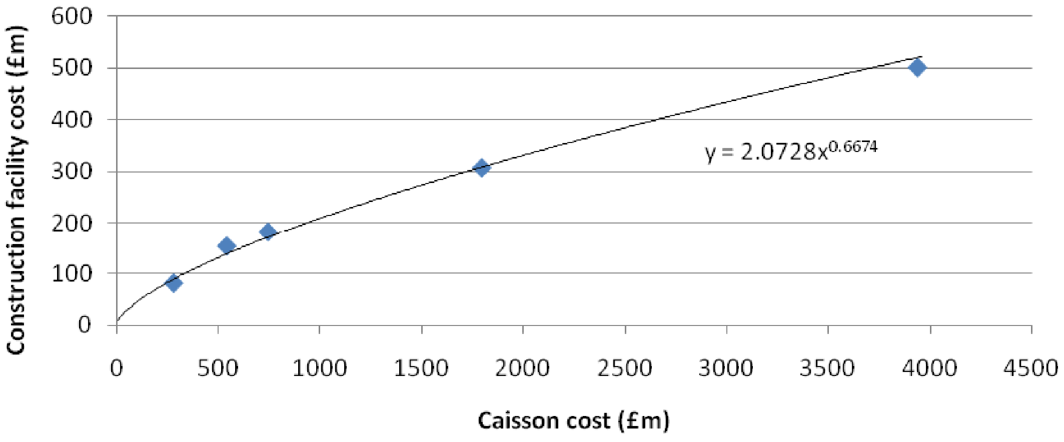

Figure 13 Caisson construction facilities cost

2.5.5 Installation cost

Figure 14 shows the correlation between the capital caisson cost and the caisson installation cost for the Severn schemes. The installation costs have been reduced so that they do not include costs for the dredging of the seabed to gain adequate water depth for the turbine caissons (note that seabed preparation dredging for the seating of the caisson foundations is included in these costs). These dredging costs are accounted for separately as potential schemes to be evaluated by the CoE model may require significantly more dredging to create adequate water depth for the turbines than that considered for the Severn schemes.

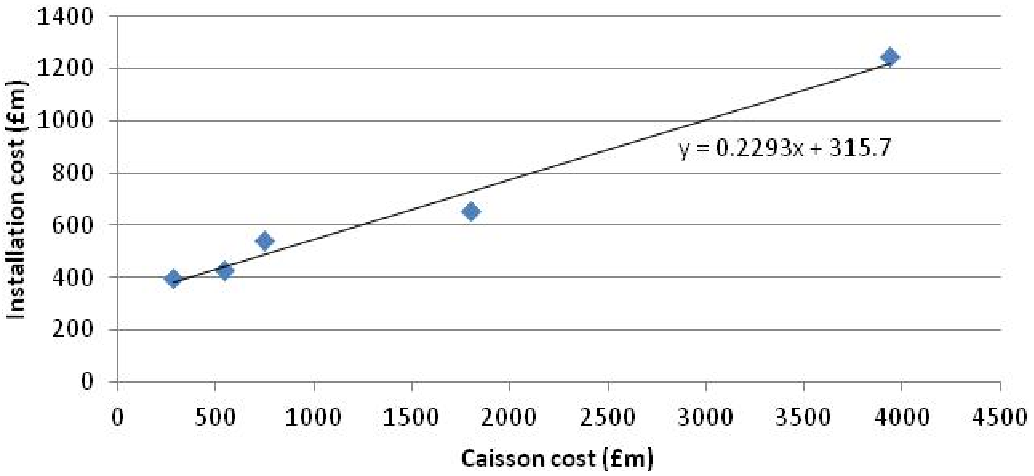

Figure 14 Caisson installation costs (excluding dredging for caisson placement)

2.5.6 Dredging to increase water depth

As discussed above, dredging to increase water depth for the turbine caissons (to avoid cavitation) has been calculated as a separate item from caisson installation costs. The average pre- and post-construction seabed levels under the turbine caissons have been included as user-defined inputs to the CoE model and will be generated by the CSM. The CoE model uses these levels to estimate an average depth of a dredged channel along the total length of the turbine caissons.

The user is required to enter side slopes of the dredged channel. The dredged slopes can vary from, say 1 in 1 to 1 in 10 depending on the seabed and environmental conditions, as described in BS 6349-

5:1991; however, it is likely that the slopes will be governed by hydraulic constraints and for the purpose of this study it recommended that a 1 in 10 slope is adopted. A nominal flat bed allowance to both the seaward and landward/basin sides of the caissons has been set to 10m – thus the width of the flat dredged channel will equal the width of the turbine caisson + 20m.

Using this information, together with the total length and width of the turbine caissons, the CoE model calculates the dredge volume required for the turbine caissons. The cost of dredging this volume is calculated in the model based on rates considered by the SEA ODR during the scheme optimisation stage, as follows:

Hard rock	£86.4/m^3
Weathered rock/gravel	£57.6/m^3
Soft material	£8/m^3

The CoE model requires the user to assign a percentage of the dredged volume to these rates. In lieu of site specific information, it is recommended that 100% of the dredged volume is (conservatively) assumed as being ‘hard rock’, but the user can alter the applied percentages to suit a specific site. It is to be noted that the ‘preparation’ dredging required to seat all working and plain caissons has been included in the caisson installation costs (section 2.5.5). Dredging for the navigational approach channel is considered as part of the lock costs (see section 2.7).

2.6 Embankments

The embankments costs in the CoE model have been calculated assuming a rubble mound embankment design as used in the Severn schemes (see Figure 3 for the Cardiff-Weston scheme). There is opportunity for the user to enter two different sets of embankment categories, Access Category A and Access Category B. These categories also describe plain caissons, see section 2.5.2 for definitions. The total length of embankment for a scheme is defined by the user, as described in section 2.3.

It is recommended that the rubble mound embankment proposed for the Severn schemes is taken for initial studies, although the user has the option to enter a cost per m length for an alternative bespoke or novel embankment solution.

2.6.1 Crest height

The crest level of the embankment is dependent on the local water level, storm surge allowance and wave conditions and is ultimately governed by acceptable overtopping discharges. The user is able to input the crest level of the embankment. In line with the Severn schemes, it is recommended that for Access Category A the crest level equates to: MHWS + user defined storm surge allowance + run-up of the 1yr return period maximum wave height + contingency of 0.5m. For Access Category B it is recommended that, the crest level equates to: MHWS + a nominal 0.5m storm surge allowance + run up of the 2month return period maximum wave height + contingency of 0.5m. For the purpose of this study, the run-up is assumed to simply extend to a height of H_{max} (~1.86Hs) above MHWS.

The crest of the rock control structure has been taken as MHWS whilst the discrete containment mounds, which facilitate the layering of the core sand material during construction, are pre-set to each be 3m in height (see section 1.3.6).

2.6.2 Crest width

The crest width of the embankment will be determined by allowances for service road, cable reserve, and access to embankment slope. The user is able to input the crest width depending on site specific requirements. It is recommended that a crest width of at least 25m is used for Access Category A and at least 16m for Access Category B based on the crest widths used in the Severn schemes. The crest widths of the control mound, if applicable, and the containment mounds (see section 1.3.6) have both been pre-set as 5m.

2.6.3 Side slopes

For the purpose of this study, it is recommended that the baseline embankment design for the Cardiff-Weston scheme is adopted (see section1.3.6) which includes the use of a rock control mound and a number of containment mounds. For lagoons a rock control mound will only be required for closure sections. The side slopes of the rock control mound can be assumed to be 1 in 2 and hence, where a rock control mound is included, the outside side slope will also be 1 in 2. In this case, the inside side slope will be constructed using containment mounds and the slope of the mounds, and hence the inside side slope, is recommended to be 1 in 3. If a rock control mound is not required, then both slopes will be constructed with containment mounds and have a recommended incline of 1 in 3.

The outside side slope refers to the slope on the seaward side of a barrage and offshore lagoon. Inside slope refers to the slope on the basin-side of an offshore lagoon or the landside of a barrage.

2.6.4 Wave protection

The wave protection for the embankment has been sized based on the wave height (100yr return period) using Hudson’s equation. This is a rough means to size the armour layer for costing and should be refined at preliminary design stage. For both access categories, the CoE model is pre-set to consider rock armour-stone on the inside slope and artificial precast-concrete armour units on the outside slope, as shown in the baseline Cardiff-Weston embankment design. Given widespread use in maritime applications, and the relative ease of their preliminary design and sizing, single layer Accropode artificial units have been used as a basis for this CoE model rather than Dolosse units as shown in Figure 3.

The CoE model is pre-set to consider densities of 2400kg/m^3 and 2650kg/m^3 for reinforced concrete and rock respectively. The dimensionless stability coefficient, for (rough angular) armour-stone placed in 2 layers and Accropode units placed in a single layer, as used in Hudson’s equation have been selected in accordance with BS 6349-7:1991 and manufacturers’ information. For the design of armour-stone, the incoming waves are assumed to be ‘breaking’ as they propagate towards the embankment. The wave height used to design the Accropode unit has been taken as the smaller value of the 100 year significant wave height or 80% of the average water depth at the toe of the embankment during MHWS (i.e. depth limited waves).

2.6.5 Underlayers/filter layers

Using the baseline Cardiff-Weston rubble mound embankment solution as an example, the function of the underlayer is to act as a filter between the control mound/containment mounds and the armour layers, to provide a stable bed for the armour layer and to protect the finer material of these mounds. The filter layer protects the loss of the sand fill through the control mound/containment mounds. The CoE model quantifies the underlayer/filter-layers as follows:

- An underlayer will be required between the core of the embankment and the artifical concrete units. The CoE model assumes that the underlayer will consist of 2 layers of rock with a median mass equivalent to one-tenth of the nominal mass of the artificial unit.
- An underlayer will be required between the core of the embankment and the rock armour-stone. The CoE model assumes that the underlayer will consist of 2 layers of rock with a median mass equivalent to one-tenth of the median mass of the armour-stone.
- A nominal 0.4m thick filter layer of rock will be applied along the complete interface between the sand core and the control mound/containment mounds.

The CoE model also assumes that a 3m layer of containment mound rock material lies immediately below the crest level, as shown on Figure 3.

2.6.6 Cost estimation

Based on the assumptions discussed, above the CoE model calculates the quantities of material and applies the following pre-set unit costs. These unit costs have been derived from the SEA IOAR (DECC 2008).

Control structure rockfill	50	£/m^3
Containment mounds	20	£/m^3
Filter layers/underlayers	40	£/m^3
Sand core	7	£/m^3
Armour-stone (1-3 tonnes)	70	£/m^3
Precast armour units	150	£/m^3

2.6.7 Construction facilities

Figure 15 shows the relationship between embankment construction costs and the associated cost of the construction facilities, based on the Severn schemes. This relationship has been used to estimate the embankment construction facilities costs in the CoE model.

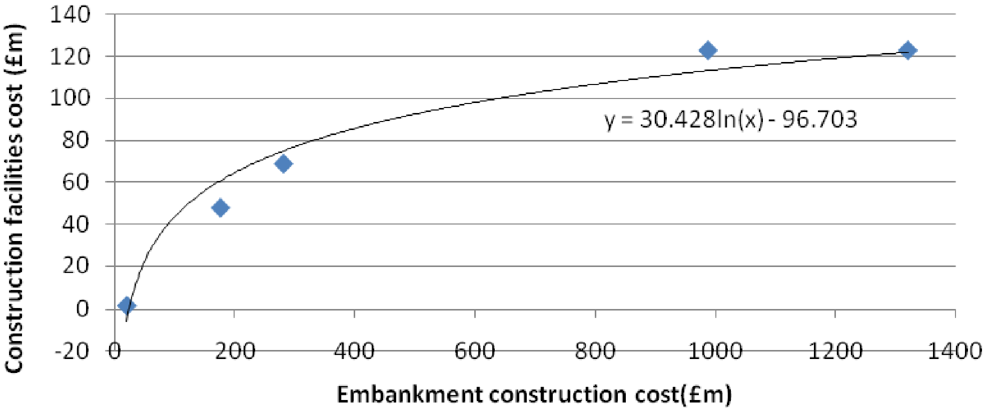

Figure 15 Embankment construction facilities cost

2.6.8 Fit out works

Figure 16 shows the relationship between the rubble mound embankment crest plan area and embankment fit out works for the Severn schemes. Embankment fit out works includes the service road and concrete service ducts between substations. This relationship has been used in the CoE model to estimate the cost of the embankment fit out works.

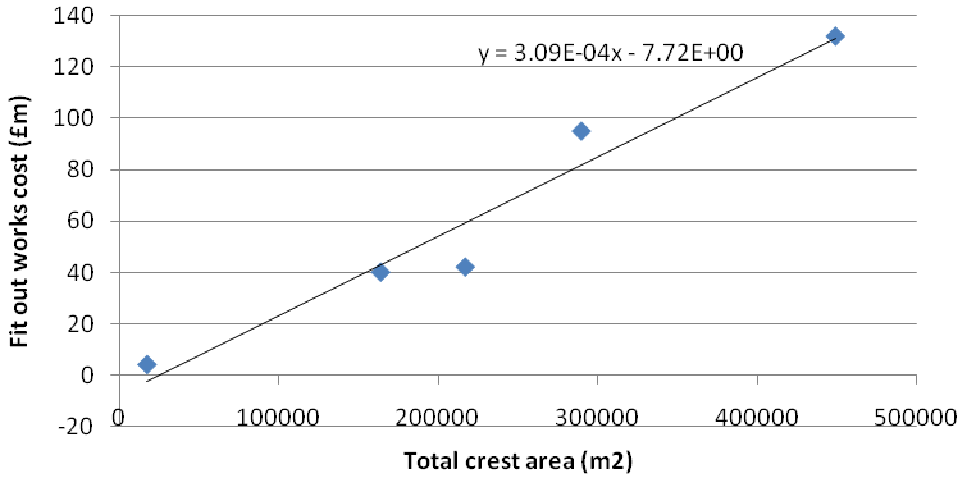

Figure 16 Embankment fit out works costs

2.6.9 Connection to public roads

A provisional allowance of £25m, as used in the Severn ODR, has been pre-set in the CoE model for connection to public roads/existing infrastructure and is applied to all potential schemes.

2.7 Locks

The lock breadth, length and depth (sill level) have been estimated from the maximum vessel dimensions based on PIANC guidelines (PIANC 2009) to predict the required lock volume to accommodate a single vessel at a time assuming a 1m under keel clearance at Mean Low Water Springs (MLWS). The user is required to specify the particulars (length, beam, draught) of the largest vessel and whether, or not, tug assistance is required for vessels entering the lock as this influences the plan dimensions of the lock. If data is not available (say from the Harbour Authority or local Ports), it is recommended that locks to accommodate vessels (with tug assistance) with 400m (length) x 60m (beam) x 16m (draught) particulars are adopted for the CoE model for the largest barrage schemes or those located in busy navigation routes (e.g. Cardiff-Weston scheme). A vessel (with no tug assistance) of at least 100m (length) x 22m (beam) x 7m (draught) particulars should be adopted for all barrage schemes and lagoons – this being approximately the particulars of a typical dredger.

Figure 17 shows the correlation between lock volume at MHWS and lock cost for the Severn schemes and also for the Mersey preferred scheme (Peel Energy 2011). The cost per lock includes dredged approach channel, guide walls, breakwaters, landing area, bascule bridges and lock gates.

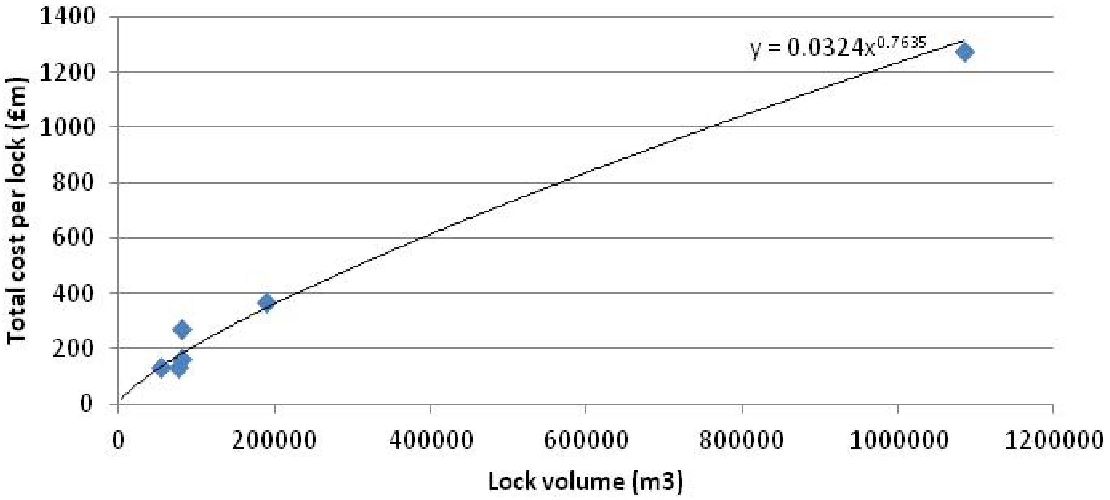

Figure 17 Total cost per lock

The number of locks needed for a barrage scheme can be estimated based on the following simple guidelines (Baker 1991):

- For an estuary with less than 5,000 vessels movements per year, a single lock should be provided.
- For an estauary with between 5,000 and 12,000 vessels movements per year, two locks should be provided.
- For an estuary with more than 12,000 vessles per year, additional locks should be provided. In this instance, and for the purpose of this study, three locks have been adopted by the CoE model.

The CoE model gives the opportunity for the user to specify one of these three classifications for a barrage scheme. For lagoons with no expected vessel traffic, a single lock should be provided in order to permit vessels to undertake maintenance activities to the basin-side of the structure - therefore the user should specify less than 5,000 vessel movements per year.

2.8 Mechanical and Electrical (M&E)

2.8.1 Gates (excluding lock gates)

There are three different radial gates that have been considered by the Severn schemes, each with a different width. The unit costs estimated for these, as specified in the IOAR, have been plotted against gate width as shown in Figure 18. Only radial gates have been included in the model. As discussed in section 1.3.4, for water depths greater than 20m vertical lift gates may be a preferred option; however, the difference in cost of these gates will have a minimal impact on the overall cost of energy. The costs of the lock gates have been included in the lock costs.

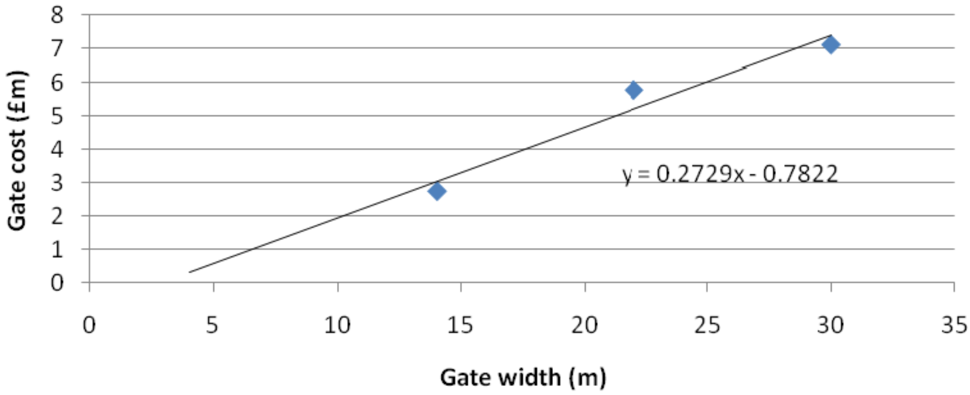

Figure 18 Sluice gate cost (including stop-log built in parts)

This correlation has been used in the CoE model to estimate the cost of the sluice gates, including stop-log built in parts. There are additional gate costs such as stop-log panels and temporary bulk heads which are not provided at each gate location. Figure 19 shows the correlation between gate costs and additional gate costs for five of the preliminary scheme designs detailed in the IOAR. This correlation has been used in the CoE model to calculate the additional gate costs.

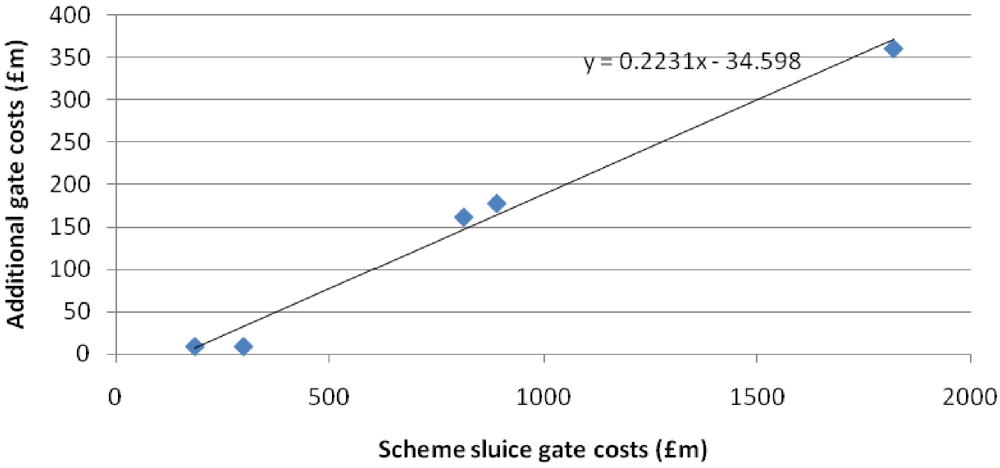

Figure 19 Additional gate costs (temporary bulkheads and stop-log panels)

2.8.2 Turbine generators

The ODR includes a cost scaling rule used at the scheme optimisation stage to estimate the cost of the generation equipment. The cost scaling factor (£m/MW) for different sized bulb turbines, according to the ODR, can be estimated as 3.6581 x $(MW)^{-0.548}$. An additional 12.5% is added to the cost for reversible turbines. 5% is added to the cost to cover engineering fees and 25% is added for delivery, erection and commissioning. Figure 20 shows these relationships plotted alongside the estimated costs for the Severn schemes. In the plot, a reduced value of 10% (from 30%) has been added to the ODR rules to cover engineering fees, delivery, erection and commissioning as this provides a much stronger correlation with the data points for the Severn schemes costs – which can be assumed to have benefited from a more rigorous costing exercise. The plotted ODR relationships, with the 10% and, where applicable, 12.5% allowances, have been used in the CoE model to estimate the cost of bulb turbines.

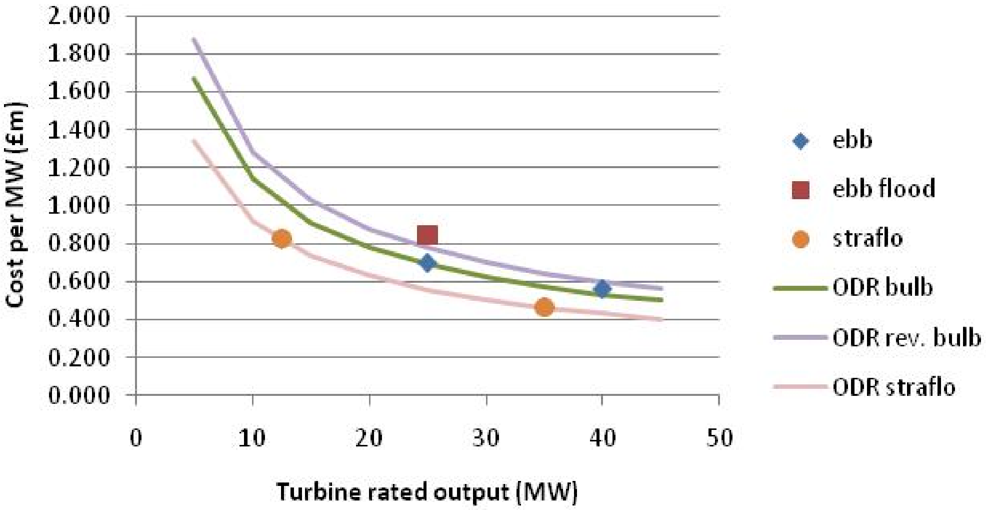

Figure 20 Turbine generator costs

The Rolls-Royce turbine costs have been estimated based on the rate of 0.85£m/MW included in the SETS report (Rolls-Royce/ Atkins 2010).

2.8.3 Grid connection

Figure 21 shows the correlation between scheme installed capacity and grid connection cost for the Severn schemes. The costs include principal transmission equipment components between generator terminals and connection to the substation. The costs do not include grid reinforcement which it is assumed would be carried out by the National Grid and recovered through system use tariffs. These tariffs have been included in the O&M costs.

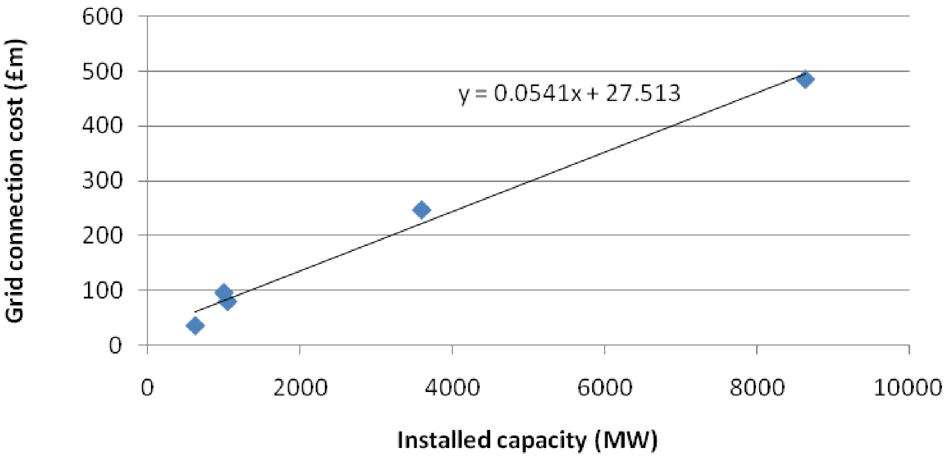

Figure 21 Grid connection cost

2.8.4 Cranes

The costs of the turbine handling gantry and stop-log handling cranes have been plotted against the cost of the gates and the turbines to determine a costing relationship. This correlation has been used in the CoE model to estimate the cost of the cranes. Cranes required to operate the lock(s) are included in the lock costs (see section 2.7)

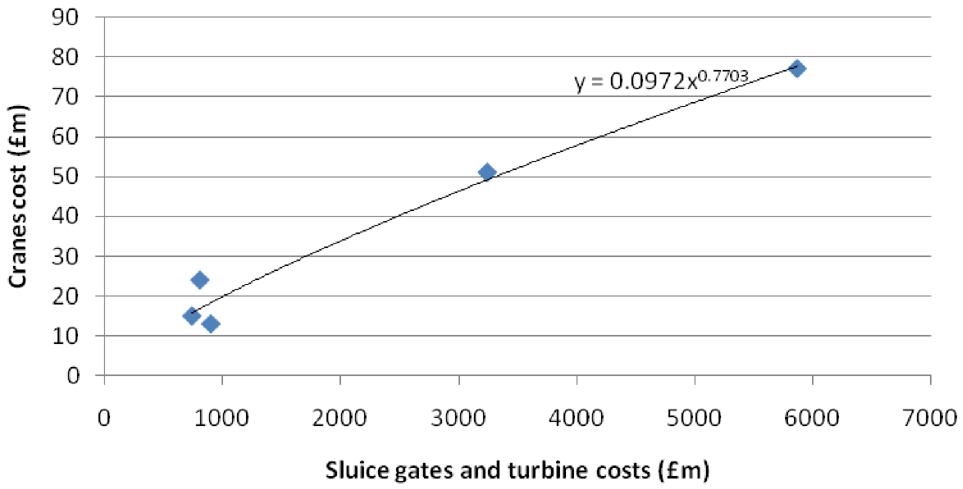

Figure 22 Cranes cost

2.9 Other Costs

2.9.1 Pre-construction

Pre-construction costs have been based on the following assumptions as used in the IOAR. The following percentages have been pre-set in the CoE model.

Project management	0.25% of total construction cost
Design (up to procurement stage)	25% of total design cost
Site investigation	1.25% of civil engineering construction cost
Environmental Impact Assessment and Consents	0.3% of total construction cost

2.9.2 Preliminaries and site overheads

The cost for preliminaries and site overheads has been estimated in the ODR to be 13.5% of the civil engineering construction costs for schemes over £5bn and 15% for less costly schemes. These percentages have been pre-set in the CoE model.

2.9.3 Surface buildings

Surface building costs include powerhouse buildings, on barrage/lagoon substation buildings, control centre, visitors centre and sundry operational buildings. Figure 23 shows the correlation between scheme installed capacity and surface building cost for the Severn schemes. The smaller barrage schemes (Shoots and Beachley) are not included in the correlation as they have unusually high buildings costs.

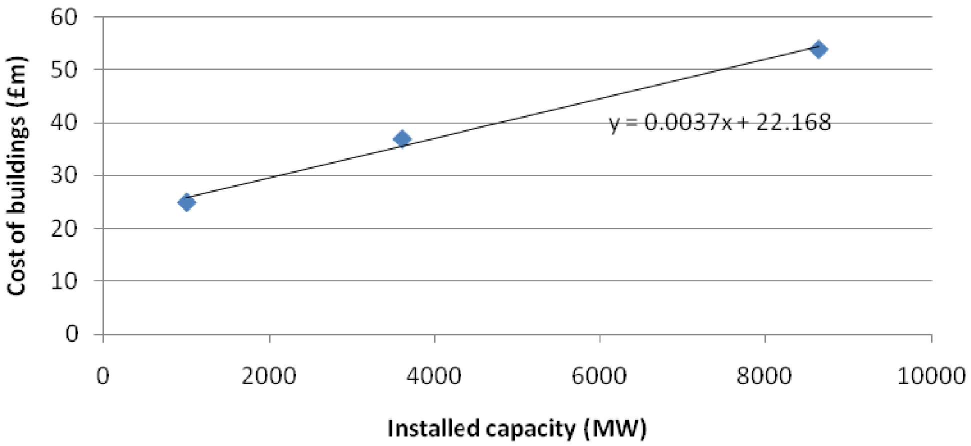

Figure 23 Surface building cost

2.9.4 Detailed Design

Detailed design costs have been estimated, as in the ODR, at 1% of the civil engineering construction costs (excluding caisson installation and dredging). Note that this phase is not to be confused with pre-construction design costs identified in section 2.9.1. An allowance of 1% has been pre-set in the CoE model.

2.9.5 Site investigation

A provisional sum of £2m has been included to cover site inspection costs. This is the average cost of site inspection for the Severn schemes.

2.9.6 Contractors ‘on costs’, insurances and profits

Contractors ‘on costs’, insurances and profits have been estimated, as in the ODR, at 9.25% of the civil construction and M&E costs (excluding turbine generators for which these are included in the £/MW cost, see section 2.8.2). An allowance of 9.25% has been pre-set in the CoE model.

2.9.7 Construction contingency

The construction contingency applied to the Severn schemes is varied between 15 and 20% of the total construction costs, depending on the accuracy of the cost estimates. In the CoE model the construction contingency has been included as a user input and can be modified. Given the very nature of this costing tool, it is recommended that 20% is adopted for ‘optioneering’ potential schemes.

2.9.8 Ancillary works

Ancillary works include alterations of port infrastructure and approach channels, pumping systems to tidal outfalls, improvements to tidal or sea defences and erosion protection measures for tidal defences. Figure 24 shows the correlation of ancillary works costs and installed capacity for the Severn schemes. This correlation has been used in the CoE model to estimate the cost of ancillary works.

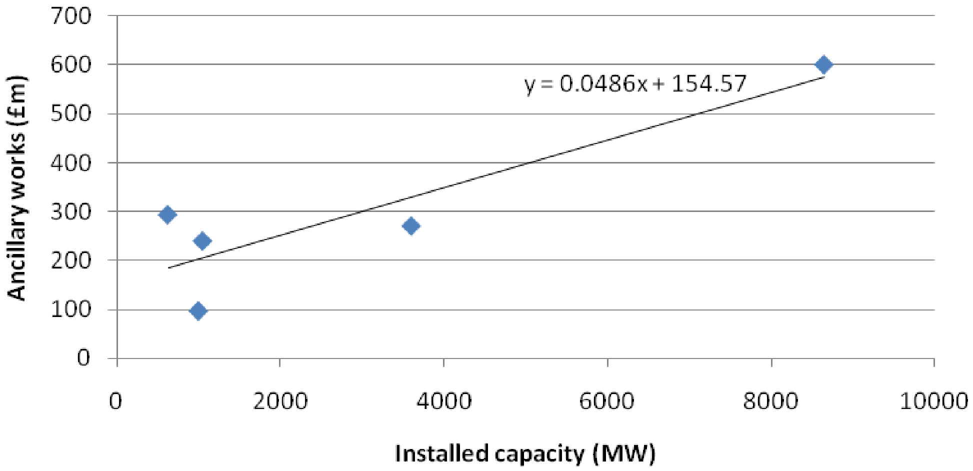

Figure 24 Ancillary works costs

2.9.9 Measures to prevent and reduce adverse effects

Measures to prevent and reduce adverse effects include items such as relocation of locks, delivery of construction materials by alternative routes, increased drainage provision and beach recharge. A provisional sum of £150m has been pre-set in the CoE model for these measures. Topographic modification is also included in this category for the Severn schemes. In the CoE model it is assumed that no topographic modification is implemented and the full intertidal habit loss will be compensated (see section 2.9.11).

2.9.10 Non intertidal habitat compensation

Non intertidal habitat compensation measures for the Severn schemes include items such as Shad introduction programmes and freshwater wetland creation. These costs are not included in the CoE model as they are considerably smaller than the intertidal habitat compensation and are very site specific.

2.9.11 Intertidal habitat compensation

The CoE model provides the user with the opportunity to enter a land area of intertidal habitat lost as a result of the scheme, which will be an output from the CSM. The user can also input the ratio of habitat compensation. The ratio of intertidal habitat compensation will depend on the quality of the replacement habitat. If the replacement habitat is of an equivalent quality to the existing habitat then a ratio of 1:1 may be used. If the replacement habitat is of a poorer quality then ratios of 2:1 or 3:1 may be used. The user can input the cost rate for intertidal habitat creation. The rate used for the Severn schemes is £45k per hectare. In lieu of more detailed information, a 1:1 ratio and £45k per hectare is recommended.

2.9.12 Decommissioning

Decommissioning costs have not been included in the Severn schemes as they will not be realised until the end of the design life which, once discounted, will be a nominal present day value. Therefore decommissioning costs have not been included in the CoE model.

2.10 Operations and Maintenance (O&M)

The operations and maintenance (O&M) costs have been estimated as being 1% of the total capital cost in line with the ODR. A percentage of 1% has been pre-set in the CoE model. This estimate does not include major maintenance/refit to the gates and turbines, or maintenance dredging. O&M costs for offshore lagoons may be higher as there will be no access from land. However, due to the limited information available the costs have not been increased for offshore lagoons.

The IOAR assumes that major maintenance/refit occurs at 40 year internals and incurs 70% of the M&E cost. These variables have been pre-set in the CoE model.

Annual maintenance dredging to maintain the navigational channel and fluvial capacity have been plotted against total lock cost in Figure 25. Dredging volumes for barrages have been estimated from the trend shown and dredging volumes for lagoons have been assumed to be zero. The cost of maintenance dredging has then been calculated based on a pre-set value of £5/m^3, as used in the ODR.

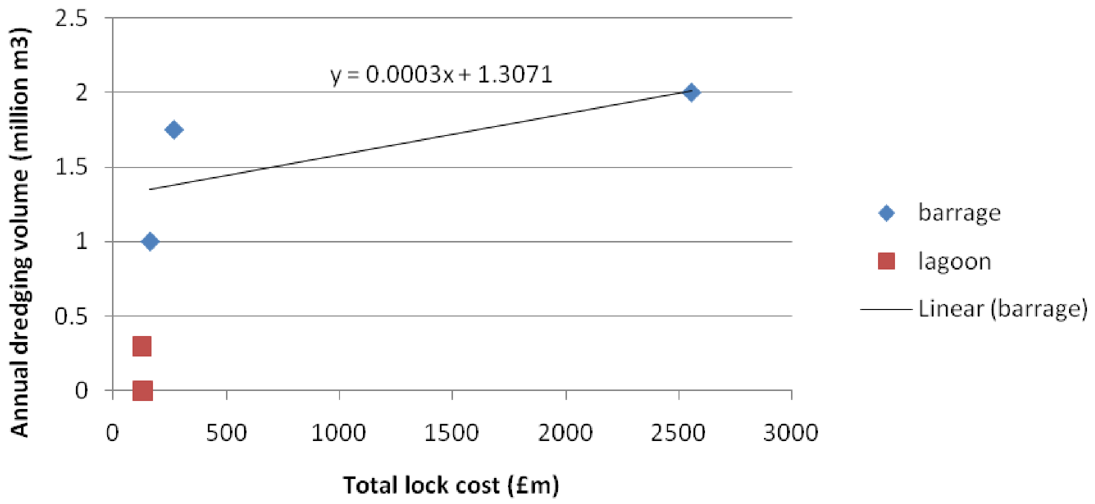

Figure 25 Annual dredging volume

It is assumed that there is no requirement to complete any annual 'energy yield' maintenance dredging in the vicinity of the turbines due to the relatively fast flows which will discourage deposition of sediment.

2.11 Cost of Energy

The indicative CoE (£/MWh) for the design life of the scheme calculated by the CoE model is based on a simplified discounted cash flow analysis using the following formula:

Where:

- The design life (years) of the scheme is pre-set in the cost of energy model as being 120 years. The user enters the financial life of the scheme, which will define the length of time within which the Present Value calculations are operated. The maximum value which can be entered is 120 years as this the design life of the Severn schemes (the ODR assumes that the financial life is the same as the design life of the scheme).
- Present Value (PV) equivalents are functions of the adopted discount rate (%) which will be defined by the user. The CoE model allows the user to modify the discount rate for three pre-

set periods during the course of the design life – namely yr0 to yr30, yr31 to yr75 and yr76 to yr120 for a120 year design life.

- Present value scheme capital cost (£) is a function of the capital cost and the construction period. Present value O&M costs (£) are a function of the annual O&M costs, major maintenace costs and periods, construction period and design life.
- Present value energy production (MWh) is a function of the design life, construction & commissioning periods and the annual energy produciton (MWh/yr). The annual energy production is site and scheme specific and will be generated by the CSM for input into the CoE model. The opportunity to model availability and transmission efficiencies is discussed below.

The CoE model allows the user to consider the construction programme, which can be a significant duration for such large schemes. The user is required to state a construction period which is automatically used to divide the scheme capital cost into equally proportioned annual costs spread over the construction period. The CoE model automatically starts the annual O&M (inc. dredging) costs following completion of the construction period.

The CoE model allows the user to input a construction and commissioning programme for the first 10 years (i.e. yr0 to yr9). This profile will allow construction (0% generation), commissioning (say, for example, ramp up of 50%, 70% or 90% generation over consecutive years) and full operation (100% generation) periods to be modelled on a year by year basis between yr0 to yr9.

The user also has the option to input the transmission efficiencies and availability. In lieu of more specific information, it is recommended that a blanket value of 100% is adopted for transmission efficiency (as this tool is designed for comparative purposes and the value is likely to be high). Transmission efficiencies may have more significant effect for offshore lagoons and in this case an appropriate reduction in transmission efficiency could be used. An availability of 95% is recommended in line with the ODR. The availability percentage may be adjusted to reflect a more detailed maintenance plan, for example if one turbine is assumed to be under maintenance at all times. Alternatively, following the logic outlined in D01, Section 5.24, additional turbines can be included in the CoE model (compared to the CSM) with the availability in the CoE model set to 100%.

3 MODEL VALIDATION

3.1 Model validation

To validate the CoE model, the governing input design variables for the five Severn schemes were entered into the model to enable a cross-comparison between costs published as part of the SEA study and the model outputs – this effectively acting as a first order validation of the CoE model. Table 3 shows the outputs of the CoE model for the five Severn schemes compared to the reported costs.

Table 3 Model outputs compared to original costs (costs in £m unless otherwise stated)

	Cardiff Weston			Shoots			Beachley			Welsh grounds			Bridgwater bay		
	Model	Severn data	Error	Model	Severn data	Error	Model	Severn data	Error	Model	Severn data	Error	Model	Severn data	Error
Pre construction	225	290	-22%	40	70	-43%	27	60	-55%	60	80	-25%	96	160	-40%
Construction	17182	17612	-2%	3007	3263	-8%	2152	2140	1%	4212	4708	-11%	7685	9143	-16%
Construction contingency	2577	2641	-2%	526	571	-8%	377	375	0%	842	941	-10%	1537	1832	-16%
Ancillary works	574	600	-4%	206	239	-14%	185	293	-37%	203	96	112%	330	270	22%
Measures to prevent and reduce adverse effects	150	750	-80%	150	290	-48%	150	330	-55%	150	283	-47%	150	353	-58%
Non inter tidal compensation	0	43	-100%	0	25	-100%	0	22	-100%	0	22	-100%	0	6	-100%
Intertidal habitat compensation (1:1)	632	632	0%	144	144	0%	115	115	0%	322	322	0%	95	95	-1%
Scheme cost including 1:1 compensatory habitat	21341	22568	-5%	4073	4602	-11%	3006	3335	-10%	5790	6452	-10%	9892	11859	-17%
Annual O&M	224	286	-22%	48	54	-12%	37	32	15%	58	56	3%	99	111	-11%
Cost of Energy (£/MWh)	159	160	0%	161	176	-9%	199	225	-12%	252	259	-3%	168	194	-13%

The results in Table 3 indicate that the CoE model replicates the CoE to within 15% of the figures published in the SEA study. This is a reasonable error margin considering that the model is based on (best-fit) cost trends using data from five schemes and a number of simplifications and assumptions. The embankment costs have been calculated from first principles and hence do not exactly match the published figures. Another significant factor in this error margin may be the accuracy of the input data used to model the five schemes in the CoE model. For example, the costs published in the SEA will have been based on detailed base data for the site (e.g. considering the true bathymetry of the seabed and numerous cross-structural cross-sections along the barrier) and indicative design, whilst the CoE model has adopted a number of broad-brush assumptions (e.g. an average seabed level for each type of impoundment structure). Therefore it is recommended that the user takes care in determining the scheme general arrangement data, as described in section 2.3.

One difference between the CoE model generated data and that published in the SEA is that in the CoE model the measures to prevent and reduce adverse effects are currently lower, as they do not include topographic modification. Topographic modification is not included in the CoE model because it is very site specific and because when the CSM has been built and provides its outputs, the total intertidal area lost will be an input to the CoE model and the CoE model assumes that the whole intertidal area is replaced through habitat compensation, rather than by a combination of topographic modification and habitat compensation. Non intertidal habitat compensation has not been allowed for in the model; hence, this reads 100% error, but it is a minimal cost and will not impact the CoE significantly.

It is noted that the embankment costs for the Bridgwater Bay Lagoon scheme shows a significant difference, it is thought that this is due to an inconsistency in the ODR regarding the length of the embankment. If the longer length of embankment (quoted in the ODR report summary, but not shown in the ODR drawings) is used, then the error on CoE is reduced to -7%.

The cost of Rolls-Royce turbines has been taken from the SETS study in 2010. The cost of turbines typically represents around 30% of the total scheme cost; hence, a deflation of costs by c. 10%, to represent a 2008 equivalent cost, would only result in a reduction of the CoE of c.3%.

3.2 Model Limitations

Using existing data from feasibility studies for various schemes for the Severn, B&V has been able to develop the parametric CoE model to provide a preliminary estimate of the key costs and the CoE to allow comparison between various tidal range barrage and lagoon schemes. However, there are various limitations and constraints that the user should consider when using the model, these are as follows:

- This CoE model allows the user to make indicative comparisons between tidal range barrage and lagoon schemes to inform high level decision making and should not be considered a design tool.
- The CoE model is based on empirical data and therefore, in the strictest sense, the model should only be used within the boundaries set by the input data. B&V has considered a wide spectrum of possible schemes that should reflect the majority of those that could be deemed feasible and therefore the CoE model should remain suitable for comparative purposes for most schemes, especially where their parameters are within the bounds of those used to contruct the model. However, there are a number of instances whereby extrapolation of the cost trend lines based on the cost data from the Severn estuary schemes do not pass throught the origin. In such cases, it may be that a (item or activity) parameter will be assigned zero, or a negative, cost. This issue would only apply if an improbable value was assigned to the parameter. Rather than force all trend lines to pass through the origin, which may skew the cost trend line which will impact the costs for the majority of feasbility schemes, the CoE

model simply defaults to zero cost in the event that the trend line yield a negative cost. Given this, the user is required to give due consideration to any aspect of the outputs (such as zero cost values) that appears suspicious and, when required, should perform sensitivity studies to develop confidence in the outputs.

- The cost relationships are based on 1st Quarter 2008 rates. Although this is sufficient for like-for-like comparison, the costs would need to be inflated to the current year equivalent prices to determine a true present day cost.
- The CoE model is based on general layout and geometry details taken from existing feasibility studies for various schemes and engineering judgement has been applied to identify the likely governing cost variables for various components and activities. However, without access to the initial design work that was undertaken as part of these studies, B&V is not able to validate these governing cost variables.
- Throughout the calculation worksheets of the CoE model, there are a number of unit rate and nominal sum costs which are constants within the model. These constants have been taken from the same cost data that was used to develop the costs relationships that form the basis of the CoE model. Whilst it would be possible for the user to modify these constants, it is not recommended to ensure a consistent approach to costing.
- In all cases where the scheme design has more than one value and the CoE model requires a single input, a weighted average should be calculated by the user. For example, in the event that scheme has a combination of different size turbines the user would calculate weighted averages for diameter, capacity, turbine spacing and caisson bed level. In addition, the CoE model does not consider caissons jointly shared by turbines and slucies.
- The model only considers Bulb and Rolls-Royce turbines. If cost estimates are required for other turbines then the user will need to enter the costs directly into the cost summary worksheet (see the User Guide).
- The cost and design details in the CoE model for the Rolls-Royce turbines are based on less detailed data than bulb turbines as the Rolls-Royce turbine is at an earlier stage of development. The CoE model should be updated when more detailed information is available for Rolls-Royce turbines.

4 CASE STUDIES

B&V has investigated three case studies in order to explore the:

1. Effect of the parameters for an ‘optimum’ site on the CoE for a standard technology;
2. Effect of parameters for the ‘best case’ currently forseen technologies for a ‘base case’ site;
3. Effect of the parameters for an ‘optimum’ site for the ‘best case’ currently forseen technology.

In undertaking this exercise, the minimum CoE that may be achievable for a small number of sites can be represented by the ‘optimum site.’ The ‘base case’ site provides a representation of the average CoE achievable at multiple locations around the UK.

4.1.1 Site selection

Site selection has been based on the results of D01 (Tidal resource characterisation). This report includes preliminary estimates of the annual energy production for 22 potential schemes based on 0-d modelling. The report includes an indicative measure of energy/cost (a high ratio is better), as shown in Table 4. It is important to note that the figures are not intended to allow comparison between bulb turbines and Rolls-Royce turbines – see D01. The report also provides energy outputs for bulb turbines in ebb only mode; however, these do not maintain 80% of the tidal range, which is a modelling constraint, and hence have not been used here.

From these figures, the ‘optimum’ scheme has been selected as Severn Outer. This is the best case for bulb turbines in Table 4. The Severn Outer is shown as slightly below the best case for Rolls-Royce turbines (the best case is Cardiff Weston); however, it has been selected for Rolls-Royce turbines as well to allow comparison with bulb turbines at the same site.

To select a ‘base case’ scheme, the indicative measure of energy/cost has been averaged across all schemes. The purpose of selecting a base case is to explore the effect of the parameters of the ‘best case’ currently foreseen technology. Assuming that the best case currently foreseen technology is the Rolls-Royce turbine (as no other ‘novel’ turbines have been assessed), the base case has been selected as Bridgwater Bay. The closest value to the average is actually the Humber; however, this scheme does not represent an average site as it has more shipping than any other site in the table. There are three schemes with indicators slightly higher than the average; the Wash, Dee-Wirral and Bridgwater Bay. Bridgwater Bay has been selected as there is more information currently available since it is the most developed and best known of all these sites. Bridgwater Bay has also been run with dual mode bulb turbines to allow comparison (although it should be noted that in this case Bridgwater Bay is not reflective of an average site).

Table 4 Indicative measure of energy/cost

Location	Indicative measure of energy/cost	
	Dual, Bulb	Dual, Rolls-Royce
Solway Firth	10.3	8.4
Duddon	-	-
Morecambe Bay	-	9.9
Mersey	6.5	8.2
Dee-Wirral	9.7	8.1
Severn Outer	18.3	8.9
Severn Cardiff-Weston	-	10.0
Thames	-	3.8
The Wash	7.9	6.9
Humber	-	5.1
Wigtown Bay	4.8	4.1
Kirkcudbright Bay	2.4	1.9
Cumbria	2.6	1.9
Dee-Wirral	8.6	7.0
Oxwich Bay	3.0	2.5
West Aberthaw	3.7	2.6
Rhoose	3.7	2.4
Bridgwater Bay	11.6	7.0
Morte Bay	2.3	2.0
Rye Bay	3.7	3.0
Dymchurch	3.1	2.5
Average	6.4	5.3

🟧	Optimum scheme (selected)
🟩	Base Case scheme (selected)
▨	Optimum scheme (not selected)
▧	Base Case scheme (not selected)

4.1.2 CoE Model – Design Inputs

Without the benefit of the CSM outputs, B&V has considered the following when appraising both the Severn Outer and Bridgwater Bay schemes.

- Both schemes will adopt a dual generation operating regime.
- The performance parameters of each scheme (annual energy production, number of turbines, turbine capacity) for both the Rolls-Royce and conventional bulb turbine technologies have been taken from D01. A combination of two different sizes of Rolls-Royce turbines have been specified for the Bridgwater Bay scheme; hence, a weighted average has been calculated for both the diameter and capacity variables for input into the CoE model.
- The spacing of the turbines has been taken from D01. The total length of the turbine caissons for each scheme has been taken as the turbine spacing multiplied by the number of turbines.
- There are no sluices required for either scheme.
- The total length of the impoundment has been taken from D01.
- Having deducted the length of the working (turbine) caissons from the total length of impoundment, the remaining non-working length is considered to consist of plain caissons and rubble mound embankment(s). The proportion between both structures has been estimated through measurement from the local admiralty chart(s) where the embankment solution has been adopted for water depths less than 15m at Mean Sea Level (MSL).
- Average pre- and post- seabed levels for the turbine caissons have been estimated from D01. The average seabed levels for the plain caisson and embankment(s) have been estimated from the admiralty charts.
- The construction and commissioning programmes for both schemes have been taken from the SEA study whereby the programmes for the Severn-outer scheme are assumed to be similar to those defined for the Cardiff-Weston scheme although this is probably optimistic.
- Tide levels have been taken from either the SEA study (Bridgwater Bay) or admiralty tables for the local measuring gauge station (Minehead – Outer Severn).
- Wave conditions for the Severn-outer scheme are assumed to be similar to the Cardiff-Weston scheme as detailed in the SEA study, although this is optimistic. Existing wave conditions for the Bridgwater Bay scheme have been taken from the SEA study. Internal wave conditions after construction are best estimates based on a reduction of the Cardiff Weston internal wave height.
- The crest width of the Access Category A embankment for the Severn-Outer scheme has been taken as 57m, which is the average crest width of the Cardiff-Weston scheme embankment. All other caisson and embankment widths adhere to the recommendations in the report.
- Intertidal area lost has not been included in the case studies and this should be updated when the CSM is complete.
- Unless stated above, all remaining CoE model inputs have been taken as the recommended/pre-set values described in section 2.

A summary of the design assumptions for both schemes are provided in Table 5.

Table 5 CoE model inputs

Input Variable	**Severn Outer Scheme**		**Bridgwater Bay**	
Scheme	Barrage	Barrage	Lagoon	Lagoon
Operating Regime	Dual	Dual	Dual	Dual
Discount Rate (%)	8	8	8	8
Construction Period (years)	6	6	5	5
Commissioning Prog. (% availability):				
Yr 0 to Yr 4	0	0	0	0

Yr 5	0	0	75	75
Yr 6	50	50	100	100
Yr 7	70	70	100	100
Yr 8	95	95	100	100
Yr 9	100	100	100	100
Environment Conditions				
MHWS (mOD)	5.2	5.2	5.6	5.6
MLWS (mOD)	-4.4	-4.4	-6.0	-6.0
H_{max} (1 yr return period) – seaward	5.7	5.7	5.5	5.5
H_{max} (100 yr return period) - seaward	7.7	7.7	7.7	7.7
H_{max} (1 yr return period) –land/basin side	2.6	2.6	1.5	1.5
Working Parameters				
Annual Energy Production (TWh/yr)	45	24.1	6.9	4.1
Turbine Technology	Bulb	Rolls-Royce	Bulb	Rolls-Royce
Turbine Diameter (m)	9	12.5	9	14
Turbine Capacity (MW per unit)	18	6.5	30	13.6
Number of Turbines	875	1152	120	110
Turbine Spacing (m)	20	13.5	20	15
Sluice Gates	n/a	n/a	n/a	n/a
Av. Seabed level pre-dredge – Turbines (mOD)	-25.0	-25.0	-19.0	-19.0
Av. Seabed level post-dredge – Turbines (mOD)	-28.0	-25.0	-25.0	-21.0
Non-working Parameters				
Access Category A:				
Length of Plain Caissons (m)	500	2200	800	800
Width of Plain Caissons (m)	45	45	45	45
Average seabed level - Plain Caissons (mOD)	-12.9	-20.0	-22.0	-22.0
Length of Embankment (m)	2000	3648	6780	8070
Crest Width of Embankment (m)	57	57	25	25
Average seabed level – Embankment (mOD)	-7.0	-10.0	-10.0	-10.0
Rock Control Structure? (Y/N)	Y	Y	N	N
Access Category B:				
Length of Plain Caissons (m)	n/a	n/a	n/a	n/a
Width of Plain Caissons (m)	n/a	n/a	n/a	n/a
Average seabed level - Plain Caissons (mOD)	n/a	n/a	n/a	n/a
Length of Embankment (m)	n/a	n/a	4520	5380
Crest Width of Embankment (m)	n/a	n/a	16	16
Average seabed level – Embankment (mOD)	n/a	n/a	-10.0	-10.0
Rock Control Structure? (Y/N)	N	N	N	N
Novel Embankment Solution? (Y/N)	**N**	**N**	**N**	**N**
Locks				
No. of Vessel Movements	5k to 12k	5k to 12k	<5k	<5k
Vessel Particulars:				
Length (m)	400	400	100	100
Beam (m)	60	60	22	22
Draught (m)	16	16	7	7
Tug Assistance? (Y/N)	Y	Y	N	N
Construction Contingency	20%	20%	20%	20%
Area of Intertidal Habitat Lost (Ha)	0	0	0	0

4.1.3 Results

The CoE model has been run for both identified schemes with both bulb turbines and Rolls-Royce turbines being modelled. The inputs, as described in section 4.1.2, have been prepared based on D01, admiralty charts and information from the SEA (DECC 2010), and could be refined when the CSM is available. The results can be found in Table 6 which do not currently include compensatory habitat which could be added at a later date once the predicted inter-tidal area lost is available from the CSM.

Table 6 CoE model outputs

	Cost of energy (£/MWh)
Severn Outer - Bulb	126
Severn Outer - Rolls-Royce	135
Bridgwater Bay - Bulb	153
Bridgwater Bay - Rolls-Royce	159

The Bridgwater Bay bulb turbine scheme inputs have been generated using the methods discussed above, rather than directly using the SEA data, in order to give fair comparison; hence, the CoE is slightly different from the CoE given in the validation.

For both schemes, the best case technology, solely based on the appraisal of CoE, would appear to be the conventional bulb turbine, although in reality the results are well within the error bands of the CoE model analysis, as discussed in terms of model limitations in Section 3.2. It should also be noted that in both cases the site selected appears to be more favourable to the bulb turbines, as discussed above (especially for Bridgwater Bay). This analysis suggests that the Rolls-Royce turbines may have (i) a CoE advantage for a truly ‘average’ UK site (although there is no such site to directly compare both bulb and Rolls-Royce turbines); (ii) a practical advantage where bulb turbines cannot meet the 80% tidal range threshold without dredging (e.g. Cardiff -Weston, Morecambe Bay).

It should be noted that the Rolls-Royce turbine is at an early stage of design and the cost and design information is not as well developed as for bulb turbines. The CoE model should be updated when more detailed information is available for Rolls-Royce turbines.

5 KEY FINDINGS & CONCLUSIONS

B&V has conducted a general literature review of the construction and deployment methodologies associated with tidal range technologies, and subsequent annual O&M activities. The review covered existing turbine technologies and conventional means to construct rubble mound embankments and caisson structures, whilst also considering technological advancements being made in the industry and alternative civil engineering concepts.

It was concluded that bulb and Rolls-Royce turbines would be used in the CoE model. Bulb turbines represent a conventional technology whilst the Rolls-Royce turbine represents a novel turbine option. The Rolls-Royce turbine is at a relatively early stage of development and the CoE model should be updated by Rolls-Royce/ETI when more detailed design and cost information becomes available. The literature review identified a number of embankment construction methods. It was concluded that a conventional rubble mound embankment would be included in the CoE model as alternative solutions are relatively undeveloped. However, the user has the opportunity to enter a cost per m length for a novel embankment solution which can be used when these designs are further developed.

The design of a significant scheme such as a tidal power barrage or lagoon is a complex and time consuming matter that requires the consideration of various engineering disciplines such as civil, mechanical and electrical to develop a realistic site specific solution for detailed costing. Therefore, to accurately estimate costs for such a scheme using a simplistic CoE model is not possible. Nonetheless, using relatively refined design and cost data taken from existing scheme feasibility studies, particularly schemes proposed for the Severn estuary, it was possible to develop a series of cost relationships for various design, construction and other parameters which can be used to predict a series of indicative costs for similar parameters for various schemes. The combination of all these costs can be assessed against the predicted energy production of the scheme to determine a levelised

CoE value which allows comparison on a like-for-like basis between schemes to help identify an optimum solution to be selected for further development.

To validate the CoE model, the governing input design variables for the five Severn schemes were entered into the model to enable a cross-comparison between costs published as part of the SEA study and the model outputs – this effectively acting as a first order validation of the CoE model. A discussion on the validation of the CoE model, and inherent limitations, is provided in sections 3.1 and 3.2.

B&V has selected an ‘optimum’ and a ‘base case’ site to explore the limits of the currently foreseen tidal range technologies through use of the CoE model. In undertaking this exercise, the minimum CoE that may be achievable for a small number of sites can be represented by the ‘optimum site.’ The ‘base case’ site provides a representation of the average CoE achievable at multiple locations around the UK. The ‘optimum’ site was selected to be Severn Outer Barrage and the ‘base case’ site to be Bridgwater Bay Lagoon. At each of these sites the CoE model was run for both bulb and Rolls-Royce turbines. For both schemes, the best case technology, solely based on the appraisal of CoE, would appear to be the conventional bulb turbine, although in reality the results are well within the error bands of the CoE model analysis, as discussed in terms of model limitations in Section 3.2. It should also be noted that in both cases the site selected appears to be more favourable to the bulb turbines, as discussed above (especially for Bridgwater Bay). This analysis suggests that the Rolls-Royce turbines may have (i) a CoE advantage for a truly ‘average’ UK site (although there is no such site to directly compare both bulb and Rolls-Royce turbines); (ii) a practical advantage where bulb turbines cannot meet the 80% tidal range threshold without dredging (e.g. Cardiff -Weston, Morecambe Bay). It should be noted that the Rolls-Royce turbine is at an early stage of design and the cost and design information is not as well developed as for bulb turbines. The CoE model should be updated when more detailed information is available for Rolls-Royce turbines.

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.

Availability – the percentage of time that the turbines are available to generate power. This accounts for outages due to routine maintenance or malfunction of some or all of the turbines.

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).

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.

CSM – Continental Shelf Model.

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

Ebb only generation – power generation on only the ebb tide.

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

Flood only generation – power generation on only the flood tide.

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.

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

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

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.

Maximum wave height – the wave height (trough to crest) of the highest wave.

MHWS – mean high water (at spring tide).

MLWS – mean low water (at spring tide).

MSL – mean sea level.

OD – Ordinance Datum. For the British Isles, OD is taken as mean sea level at Newlyn, Cornwall. Care should be made to distinguish between OD and the local Chart Datum (CD) which is typically taken as the lowest astronomical tide (LAT) at a given location.

Significant wave height – the mean wave height (trough to crest) of the highest one third of the waves.

Storm surge – changes in water level due to variations in atmospheric pressure.

Transmission efficiency – the percentage of generated power transmitted to the grid.

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