Sustainable Development Commission

Tidal Power in the UK

Research Report 4 - Severn non-barrage options

An evidence-based report by AEA Energy & Environment for the Sustainable Development Commission

October 2007

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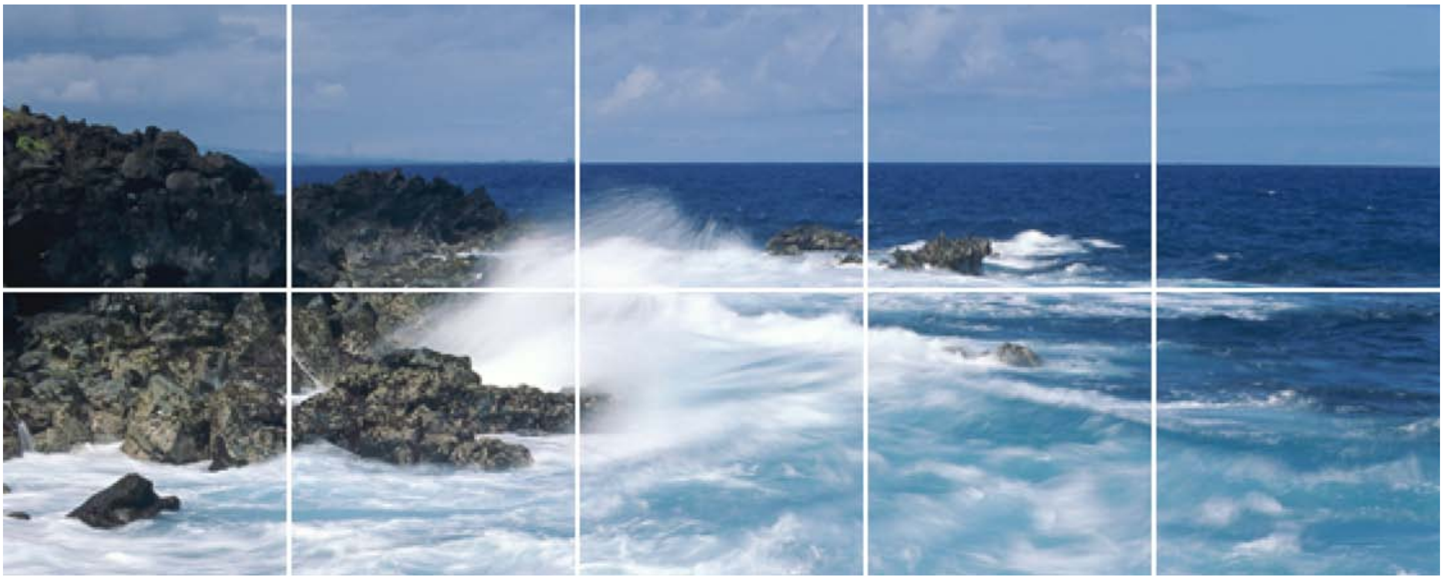

Severn Estuary Tidal Energy from Non-barrage Options

Review of non-barrage options for tidal energy in the Severn Estuary and the Bristol Channel.

Report to the Sustainable Development Commission

ED Number ED02700
Issue Number 1
Date 8th October 2007

The University of Edinburgh

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	Severn Estuary tidal energy from non-barrage options
Customer	Sustainable Development Commission
Customer reference	Tidal power project research contracts contract no. 4. ITT dated 13th October 2006
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File reference	
Reference number	ED ED02700 - Issue 1

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Executive summary

The Severn Estuary and Bristol Channel is a potential strategic tidal resource for the UK.

There are several technologies available, or under development, that have been proposed as potential candidates to exploit this resource. Some of these, notably a barrage between Cardiff and Weston, have been studied in detail over many years; there is a high degree of confidence in the costs, energy capture and environmental impacts for this scheme.

In more recent years other concepts have emerged such as the Swansea Bay Lagoon and the Shoots Barrage further upstream from the Cardiff-Weston scheme. These proposals have not been examined in as much detail and less confidence can be placed on the predicted costs, estimated energy output or environmental impact. Furthermore, tidal current technologies are now being researched and demonstrated. These technologies have been proposed as alternatives to barrages and lagoons. However, tidal current alternatives are at a very early stage in their development; their successful development is not guaranteed and their economic viability and environmental impacts remain uncertain.

The deployment of tidal current technologies is not well suited to the Severn Estuary, primarily because of the high tidal range and shallow depth. Most tidal energy concepts currently under development require a minimum water depth of 30m and a mean spring peak velocity of more than 2.5 m/sec. Although water depths in the Bristol Channel downstream of the Cardiff-Weston alignment are suitable for tidal current technologies the tidal current velocities are too low to make the technology economic especially when compared with other locations around the UK. Large-scale deployment of tidal current turbines could also obstruct busy shipping lanes.

It is possible that in the longer term other tidal current concepts will be developed that can be deployed in shallow water. If these are successful they could be used to exploit tidal energy from the Severn Estuary.

Large-scale development of any tidal energy technology in the Severn Estuary and Bristol Channel poses major long-term environmental issues. Construction of lagoons or barrages would change downstream open estuary areas as well as impounded intertidal areas. Once a barrage or lagoon was constructed a new estuarine regime would develop leading to loss and modification of the existing habitat. Progressive accumulation of sediment could eventually deplete the resource by reducing the volume of water available for power generation. The eventual fate of large-scale structures needs careful consideration. The modified intertidal regime within an impounded area would be radically altered if the barrier that had created it was removed. Moreover, large volumes of materials such as rock armour, crushed rock, geotextile materials and sand fill from embankments would need to be removed or dumped. This might cause unacceptable environmental impacts. Structures built from reinforced concrete would need to be refloated and taken to a suitable site for demolition and recycling.

One proposal suggested for decommissioning offshore lagoons is to remove the mechanical and electrical components and the power-house structure. The remaining civil works would be left in place to form an offshore reef. However, leaving residual structures would lead to residual liabilities for third parties. It is possible that a more detailed decommissioning programme may be necessary to gain consent. The Crown Estate requires developers to submit detailed proposals for decommissioning which include a funding mechanism such as a bond to pay for decommissioing. An environmental impact assessment of the proposed decommissioning programme would also be required. It is certainly not clear that any

structures would be allowed to remain in place once the tidal energy scheme ceased to operate. Complete removal may be a precondition for consent.

Tidal current arrays would also need to be fully decommissioned once they cease to become operational. Devices mounted on a monopile would require complete removal of the structure at least I -2 m below the sea bed comprised of rock but as much as 5 m for sea bed comprised of unconsolidated sediment. Gravity based concepts may need to be refloated to avoid a long-term obstruction hazard. Floating devices, moored to the sea floor have a distinct advantage because only the anchorage points would be left in place once each device was retrieved.

This report looks at the potential for alternative options to barrages across the Severn Estuary. Three different examples have been selected: two based on tidal lagoons; and a hypothetical tidal current array. The design concept for the lagoons and their estimated energy output and costs have been taken from published sources and inflated to 2006 prices for comparison. The tidal current array is based on a hypothetical 30 MW array off the north Devon coast near Lynmouth. We have based our tidal current appraisal on a pile-mounted concept such as that currently under development by the company Marine Current Turbines (MCT). Our appraisal has had to rely on published information on costs and performance of the MCT concept. The size of the array is arbitrary and does not imply that deployment would be restricted to developments at this scale. The study of a hypothetical array allows tidal current technology to be compared with the conventional alternatives and the implications for more extensive deployment of this technology in the Severn Estuary and Bristol Channel.

To generate the same amount of energy from the Cardiff-Weston barrage using tidal current technology would require an array of approximately 9,200 devices and cover an area of approximately 226 km^2 assuming that the performance matched all the devices in our 30MW tidal current case study. It should be stressed that depth constraints would severely constrain the numbers of devices within the Severn Estuary and Bristol Channel. Consequently this comparison should be regarded as purely illustrative. Moreover, the potential energy capture per turbine is higher in other regions compared with the Bristol Channel so fewer devices would required.

To put this comparison into context the entire UK tidal current resource is estimated to be 18 TWh/year [1]. The estimated annual energy output from the Cardiff Weston barrage is 17 TWh/year. The Pentland Firth, for example, is estimated to have 58% of the UK's tidal current resource equivalent to 10.4 TWh/year. If a larger twin rotor device were available, such as that described in Appendix 3 of this report, approximately 1,000 of them would be required to generate 10.4 TWh/year in the Pentland Firth; this is assuming array effects do not limit performance of the devices. This amount of energy is equivalent to about 60% of the Severn Barrage's annual output. An array of this size would occupy an area of about 22 km^2. By comparison the Severn Estuary covers an area of approximately 557 km^2 including an intertidal area of over 100 km^2.

Comparison of the technical options

Comparison of the different technical options are summarised in the table below; not all these options would be compatible. Construction of a Cardiff-Weston Barrage would effectively exclude options upstream of this alignment including the Russell Lagoons and the Shoots Barrage. The Swansea Bay lagoon could still be constructed but because of the reduction in tidal range caused by a Cardiff-Weston Barrage its energy capture would be reduced by about 5%. The tidal current array would also lose about 9% of its energy capture potential compared with an open estuary scenario.

Scheme	Number of turbines/devices	Capacity (MW)	Average annual output (GWh/year)	Annual CO2 saved (M tonnes)
Cardiff-Weston Barrage	216	8,640	17,000	7.3
Shoots Barrage	30	1,050	2,750	1.2
Russell Lagoons	63	2,835	6,480	2.8
Swansea Bay* Lagoon	24	60	124*	0.05
Swansea Bay Lagoon+	24	60	187+	0.08
Lynmouth Tidal Current Array	45#	30	83.16	0.04

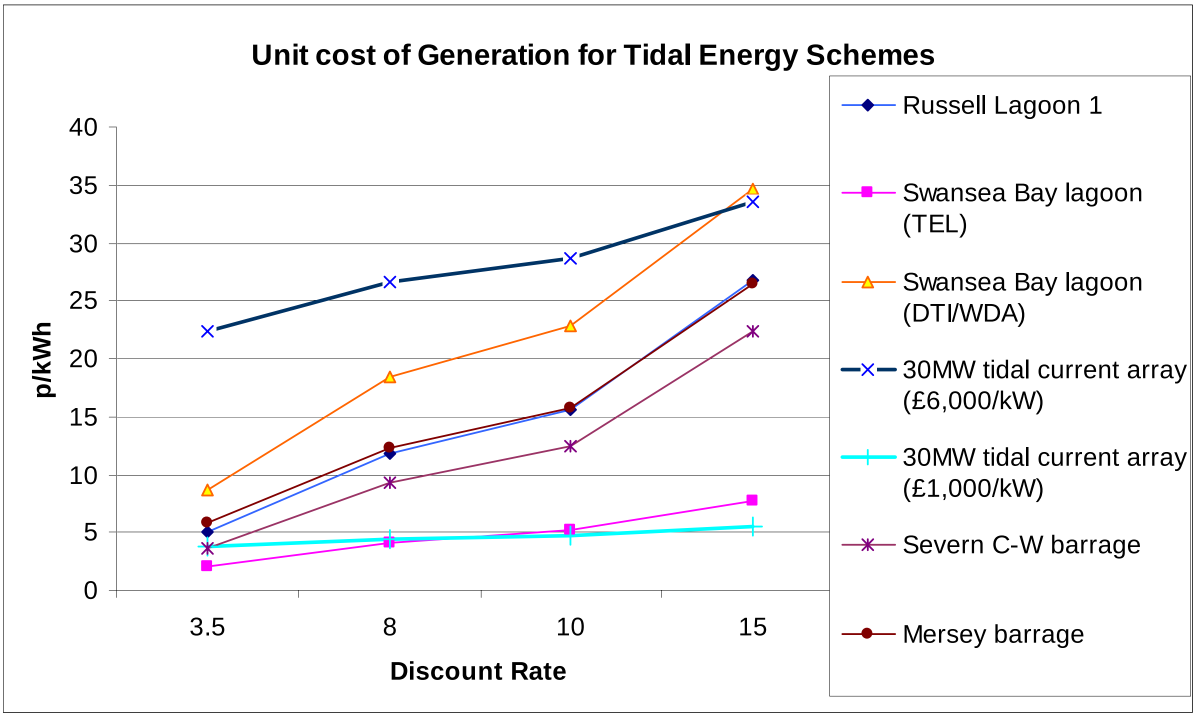
*Energy output estimated by DTI/WDA commissioned review [2]
+ Energy output estimated by Tidal Electric [3]
# Number of devices. Each device has two turbines

Construction of the Shoots Barrage would have a minimal effect on a lagoon built in Swansea Bay and on a tidal current array in the Bristol Channel of the size we have considered. Large lagoons built immediately downstream of the Shoots Barrage alignment would affect the hydraulic flow and therefore energy capture of the lagoons and the barrage. The artificial constriction of the estuary would increase current velocities and therefore sediment load, which could lead to additional detrimental accumulation of sediment within the Shoots Barrage impoundment.

The examples of the barrages and lagoons used in our assessment have been taken from published sources. These technologies have been compared with tidal current technology which is at a much earlier stage of development. There is no published information on tidal current arrays so we have used a hypothetical example of this technology for comparison. A comparatively small array size of 30 MW was selected as this is assumed to be broadly representative of the first generation of commercial deployment for this technology. This does not imply 30 MW should be regarded as an upper limit. Moreover, there are other tidal current technologies currently under development that could be deployed in deeper water. However, there is less information on the cost and performance of these alternatives in the public domain and we are unable to verify or compare these technologies with barrages or lagoons.

Unit cost of generation

The unit cost of generation for the different schemes is summarised in the following graph. The two barrage options for the Severn and the Mersey barrage have been included for comparison. Previous studies of the Cardiff-Weston barrage and the Mersey were investigated in some detail during the 1980s and early 1990s. Consequently they can be regarded as excellent benchmarks for other tidal energy schemes. Tidal current technology is still in an early stage of development. The unit cost of energy for this technology must be regarded as representative of the early stage of this technology. Experience from other technology sectors, for example wind energy, have shown that reductions in capital cost can be achieved with technical advances, experience and economies of scale. However, the extent of cost reduction that might be achieved for tidal current technologies is not known with any degree of confidence. We have therefore calculated the cost of energy for a range of different capital costs, starting betweenat £6,000/kW installed and £1,000/kW installed. £6,000/kW is the approximate capital cost of the SeaGen demonstration project, based on the published Government grant, with assumptions of how much of the grant is for the actual machine.



Two results are also presented for the Swansea Bay tidal lagoon. One is based on a published summary of a more detailed report commissioned by the developers, Tidal Electric (TEL); the other is drawn from a published independent review commissioned by the DTI and the Welsh Development Agency (WDA). The assumptions used by TEL to determine the costs of their proposed scheme have not been published and cannot therefore be substantiated. The cost basis and energy output are discussed in more detail in Appendix 2. As part of our study a third authority, Professor Mike Forde, Carillion Professor of the Institute for Infrastructure and Environment, at the University of Edinburgh, reviewed the technical criteria for embankment construction. He concluded that the cost basis for the independent review should be regarded as conservative, but the height and width of the embankment are appropriate for a structure exposed to wave attack. He also concluded that cost estimates without a detailed geotechnical survey are speculative.

Construction of lagoons in a high tidal range with strong currents would be challenging particularly in the Severn Estuary (upstream from Cardiff). The challenge faced by barrage construction would also be demanding particularly in the latter stages as complete closure is achieved. However, the techniques of caisson emplacement (i.e. prefabricated units), which apply to both concepts, have been examined in some detail.

Environmental Effects

Lagoons built on the scale of the Russell concept would occupy a large proportion of the open estuary increasing the current velocity in the remaining estuary. This situation could lead to excessive erosion and additional sediment transportation into the upper estuary. It might also exacerbate flooding by accentuating the tidal range between the lagoon embankments.

Changes to the existing hydrodynamic regime caused by the construction of lagoons will ultimately affect the sedimentary distribution within the intertidal and subtidal areas. It may also affect coastal features such as sand dunes, which rely on sediment derived from intertidal areas. Alterations to the hydrodynamic regime could also affect the broader estuarine ecosystem. Previous research has established clear links between sediment distribution, invertebrates and migratory birds. Changes to flow patterns may also affect migratory fish, which may become disorientated by unusual or intermittent flow patterns.

The significance of the Severn and its importance to the natural environment is recognised by extensive conservation designation. Much of the upper estuary has been accorded SSSI status and Special Protection Area (SPA) for avian features under the EC Birds Directive and the area is expected to become a possible Special Area of Conservation (SAC) for habitat and species features under the EC Habitats Directive. The estuary and the Wye and Usk rivers are recognised as having international conservation significance. They are identified as a Ramsar site under the Ramsar Convention, and an Important Bird Area (IBA) – a non-statutory site recognised as supporting internationally or nationally important numbers of birds. In addition both the Wye and Usk rivers are designated SAC status in recognition of their conservation value, which includes several species of fish including salmon and, in the case of the Wye, the type of river.

Under these circumstances any development would require a detailed Environmental Impact Assessment that would need to include detailed hydraulic modelling to determine potential wider impacts. Developers would also have to demonstrate that they could offset the impacts of habitat that was either displaced or changed. Modelling would also be necessary to demonstrate that water quality conditions were not impaired.

Landscape/Seascape Issues

Large embankments would be visible from the shore, although their impact would change through each tidal cycle and at different times of the day. Developers would be expected to demonstrate the extent of these visual appearances from a series of photomontages. The tidal current technology based on monopiles, that has been reviewed in this study, would also be noticeable from the shore but as a series of linear structures above the sea surface.

Effects on Cultural Heritage

The Severn Estuary is noted for its archaeological value particularly due to the preservation potential of waterlogged alluvial sediments. There are a number of scheduled Ancient Monuments and other sites of archaeological interest along the coast-line. Construction of large lagoons could change flow patterns in the Severn Estuary, which might expose or affect these sites.

Effects on fishing

Both inshore fishing and recreational fishing in the Severn and its subestuaries could be affected by the construction of lagoons in the estuary. Firstly, the change in flow patterns could present a disruptive influence particularly for migratory fish. Small craft operating near power generation sites would need to be protected by extensive exclusion zones. There may be some positive benefits offered by tidal current arrays because they could provide permanent fishing exclusion zones, which would afford some localised protection of fish stocks.

Effects on Shipping

Lagoon development, and to a lesser extent tidal current arrays, would indirectly affect both commercial shipping and pleasure craft. Although lagoons avoid the necessity for locks there would be changes to current velocities during generation. Under these circumstances ship operators would need to be confident of the altered conditions as vessels move in and out of ports. Experience from the Mersey has demonstrated that ship movements can be simulated with reasonable confidence, but only with accurate hydraulic modelling. Pleasure craft would need to avoid operating power plants by respecting recognised exclusion zones.

Employment

Comparison with other proposed tidal schemes suggests that a scheme on the scale of the Russell lagoons could require a workforce of up 2,000 to construct. Indirect employment associated with development on this scale could lead to an additional 1,000 either in South Wales or the Avon area. Comparison with other tidal energy schemes suggests that the Swansea Bay lagoon could employ up to 1,000 during construction but over a shorter period.

A potential tidal current array development would create significant employment opportunities in the manufacture and installation of the devices; however it is unlikely that there would be significant demand for jobs in the local area once arrays become operational. The components and structure are more likely to involve centralised manufacture. A recent and relevant example of this has been the development of Ocean Power Delivery's Portugal wave power plant where the devices were manufactured remotely then shipped to the local area thus limiting the local benefit. There will, however, be the possibility of local employment during the construction phase. It is also realistic to assume that operation and maintenance procedures during the operational life of the project would provide local employment and economic benefit. Regional ports in South Wales such as Port Talbot could offer a suitable logistical base for a large offshore development.

References

1. Tidal technologies overview, a report to the Sustainable Development Commission May 2007
2. Tidal Lagoon Power Generation Scheme in Swansea Bay. A report on behalf of the Department of Trade and Industry and the Welsh Development Agency. URN number: 06/1051, 2006
3. Tidal Electric Limited - Feasibility Study for a Tidal Lagoon in Swansea Bay Executive Summary Atkins Consultants Ltd. http://www.tidalelectric.com/Web%20Atkins%20Executive%20Summary.htm

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1 Introduction

1.1 Background

This report reviews the tidal energy potential from the Severn Estuary and Bristol Channel using alternative technologies to barrages. The report examines three different examples of tidal energy technology to demonstrate the potential for exploiting energy from non barrage options. Two of these examples are based on bunded enclosures or lagoons which have been proposed for the Severn Estuary and other coastal areas with high tidal ranges. The third example is based on a tidal current technology which is one of a number of concepts currently under development in the UK and elsewhere.

In section 2 the different tidal energy options are compared and contrasted with the two main barrage options that have been proposed for the Severn Estuary. The relative compatibility of both barrage and non barrage technologies is compared in Section 2.2. The unit cost of energy is also compared for each technology. The environmental impacts of the different tidal energy technologies is summarised in Section 2.3 including landscape impacts and the longer term implications of climate change. The final section outlines the potential mitigation measures that may be necessary as a result of tidal energy development and the implications of environmental legislation.

The detailed background of each tidal energy technology is presented in the appendices. The first example (Appendix 1) was a concept first proposed in 1977 and has been named after its proponent, Russell. He proposed three separate bunded lagoons built out from the shore to form reservoirs. The second example (Appendix 2) is a more recent proposal to build a tidal energy lagoon in Swansea Bay. It would not be attached to the shore. The third example (Appendix 3) is a tidal current array situated off the coast of north Devon. The example is based on a concept currently under development by Marine Current Turbines. The position of each example, and the two barrage alignments are shown in Figure 1.1

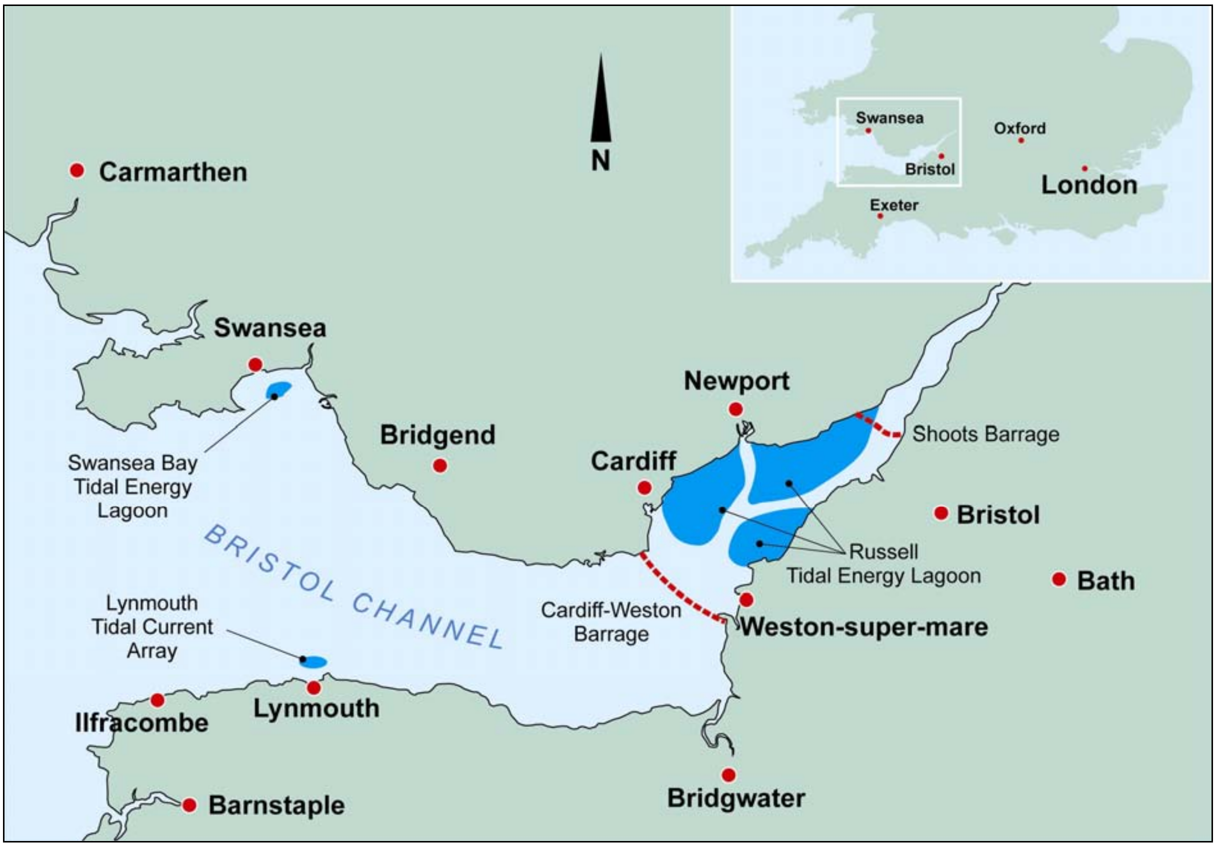

Figure 1.1 Location of the Russell Tidal Energy Lagoons, the Swansea Bay Lagoon and the Lynmouth Tidal Current Array. The position of the Cardiff-Weston and Shoots tidal energy barrages are shown for comparison.

In each of the three examples the background of the concept, the basis of its capital cost and energy output is explained. Assumptions that have been used to estimate costs and performance are clearly stated. The amount of embedded carbon used in the manufacture of the materials has been estimated and compared with the amount of carbon saved over the projected operating life. Regional, social and environmental impacts and benefits are considered in each case. All these examples are compiled from evidenced based material that has been published. Each appendix is fully referenced.

There is a glossary in Appendix 4 of technical terms and units that are used in this report.

In Appendix 5 there is an explanation of different generation modes for tidal energy barrages and lagoons to aid readers who are unfamiliar with tidal energy.

In Appendix 6 the methodology for calculating the unit cost of energy is explained.

The methodology used for estimating the embedded carbon is explained in Appendix 7.

Appendix 8 itemises the quantities of materials used in the construction of the Russell Lagoons.

Appendix 9 itemises the quantities of crushed rock and aggregate used in the construction of the Russell and Swansea Bay lagoons.

2 Alternative tidal energy options for the Severn Estuary and Bristol Channel

2.1 Compatibility of non barrage options with the Background

The Sustainable Development Commission (SDC) has commissioned a series of five studies to evaluate the UK's tidal energy resource and the wider implications of its potential development and its contribution to sustainable development. As part of this extensive review the SDC commissioned two contracts (3 and 4) to specifically examine the Severn estuary, because of its large tidal energy potential, and related commercial and regional interest. Contract 3, led by the consultants Black and Veatch, concentrated on the conventional barrage options which have been studied in some detail particularly by the Severn Tidal Power Group. Contract 4, led by AEA Energy and Environment, was commissioned to examine the alternative technical options to barrages that could be applied to the Severn Estuary and Bristol Channel. The key results from two barrage options investigated under Contract 3, the Cardiff-Weston and Shoots barrages, have been included for comparison.

The Severn Estuary-Bristol Channel system lies in the south-west of the UK, open to the Irish Sea and Atlantic beyond. The region is renowned for the extreme tidal range of 12.2 metres at mean spring tide. Many plans have been proposed over the past 100 years to attempt to harness the energy that such an excessive tidal range represents. The majority of these schemes have focussed on a tidal barrage, and more recently tidal lagoon technology options, as these systems directly exploit the potential energy that is available within the Severn Estuary-Bristol Channel system.

The high tidal range and associated tidal prism (the volume of water that is exchanged during each tide) in the Severn Estuary also generates strong currents on each ebb and flood tide. These currents become stronger on spring tides as the tidal prism increases. By placing free standing turbines in areas where the mean current exceeds 2.5m/sec it is possible to generate power. This concept has the advantage of removing the necessity for large civil structures required by barrages and lagoons. Some of the environmental effects caused by impounded basins are also avoided. Tidal current generators are, however, less accessible and therefore harder to maintain. The Bristol Channel is the home of the first full-scale tidal current device in the UK [2.1], and is under consideration as a potential site a future array of devices [2.2, 2.3].

There are a number of different tidal current technologies currently under development. Some rely on horizontal axis rotors either mounted on a secure foundation such as a monopile or floating devices anchored to the sea bed. Other concepts rely on gravity based designs which are secured to the sea floor by ballast. Rotor orientation can even be vertical. There are also hydrofoil concepts which translate motion induced by vertical oscillation into a rotorary drive to generate power.

Most of the UK's tidal stream resource is situated in water depths of 30m and where peak spring tidal current velocities are greater than 2.5m/sec or above. 58% of this resource is in or in close proximity to the Pentland Firth with a further 15% around the Channel Islands [2.4]. Conditions in the Bristol Channel are less favourable because the current velocity is lower than 2.5m/sec although there are areas of water with depths of between 25 and 40m. Higher current velocities are experienced in the Severn Estuary, but the comparatively shallow bathymetry precludes large (1 MW) devices. It is possible that smaller scale devices could be deployed that could operate in the Severn Estuary. One such device is being developed by Pulse Generation for operation in shallow waters such as estuaries. The device has two oscillating hydrofoils which convert the linear motion into a rotary motion. The device is at an early stage of development and information on performance has not been published. Deployment of a test device in the Humber Estuary is planned for 2007.

The amount of energy different technologies could convert from the Severn Estuary and Bristol Channel is evident from Table 2.1. To generate the same amount of energy from the Cardiff-Weston barrage using tidal current technology would require an array of approximately 9,200 devices and cover an area of approximately 226 km^2 assuming that the performance matched all the devices in the tidal current array off the coast of North Devon. (A detailed description of this case study is presented in Appendix 3). It should be stressed that depth constraints would severely constrain the numbers of devices within the Severn Estuary and Bristol Channel. Consequently this comparison should be regarded as purely illustrative. To put this comparison into context the entire UK tidal current resource estimated from the Tidal Technologies Overview [2.4] is 18 TWh/year. The estimated annual energy output from the Cardiff Weston barrage is 17 TWh/year. However, the potential energy capture per tidal current turbine is higher in other regions compared with the Bristol Channel so fewer devices would required than is suggested by this illustration.

The Pentland Firth, for example, is estimated to have 58% of the UK’s tidal current resource equivalent to 10.4 TWh/year. If a larger twin rotor device were available such as the one described in Appendix 3 approximately 10 GWh/year could be generated from this stretch of water. Assuming that mass deployment would not affect performance approximately 1,000 devices could generate 10.4 TWh/year equivalent to about 60% of the Severn Barrage’s annual output. An array of this size in the Pentland Firth would occupy at area of about 22 km^2. By comparison the Severn Estuary covers an area of approximately 557 km^2 including an intertidal area of over 100 km^2.

A marine energy resource assessment commissioned by the Welsh Development Agency has estimated that the theoretical shallow tidal current resource in the Bristol Channel and Severn Estuary (in water depth areas of <30m) is equivalent to a power output of 800MW if constraints imposed by navigation are taken into account. The deeper water resource within the Bristol Channel is estimated to be equivalent to a power output of 5,600MW [2.5]. This study has not attempted to present this resource as an annual energy output. One significant reason for the large scale of the resource is that this study used a lower threshold limit of 2.0m/sec on a mean spring tide. Because of the cube law relationship between current velocity and energy output (for tidal current energy conversion) a device with the same capacity would produce approximately double the amount of energy if it were situated in a site with a mean velocity of 2.5m/sec instead of a site with a mean velocity of 2.0 m/sec. At 3.0 m/sec the energy output would be more than threefold the output of a 2.0 m/sec site.

This report looks at the potential for alternative options to barrages across the Severn Estuary. Three different examples have been selected: two based on tidal lagoons; and a hypothetical tidal current array (Figure 1.1). The first case study examines the potential for three separate lagoons in the Severn Estuary between Cardiff and the River Wye (Figure A1.1) proposed by Russell in 1977 [2.6]. The second is a more recent tidal lagoon proposed by Tidal Electric for Swansea Bay [2.7]. The hypothetical tidal current array is based on the installation of an array of devices mounted on monopiles installed in an area downstream of the proposed Cardiff-Weston Barrage. This design of tidal current generator is currently under development by Marine Current Turbines (MCT) and is still in the early stages of development. There are no examples of full scale prototypes although one is currently in the final stages of assembly prior to installation in 2007.

Each case study briefly reviews the background to the concept including the construction technique, technology, energy capture and cost. The embedded carbon emissions have been estimated for each case study based on the amount of renewable energy generated over the life of each scheme and the embedded carbon used to manufacture the materials and in the construction of the schemes. The potential regional impacts including shipping, employment and leisure are also examined. Environmental impacts of each example are also outlined.

2.2 Compatibility of non barrage options with the Severn Cardiff-Weston Barrage and the Shoots Barrage

The different technology solutions for potentially exploiting tidal energy from the Severn Estuary and the Bristol Channel are listed in Table 2.1. Previous reviews of the tidal energy potential have concentrated on barrages which would create a permanent impoundment behind a structure extending across the entire estuary. Two options: the ‘Cardiff-Weston barrage’ between Lavernock Point and Brean Down; and the smaller ‘Shoots barrage’ immediately down stream of the second Severn road crossing have been independently reviewed for the Sustainable Development Commission [2.8]. The three non barrage options reviewed in this report are included for comparison.

Table 2.1 Comparison of tidal energy options for the Severn Estuary and Bristol Channel

Scheme	Number of turbines/devices	Capacity (MW)	Average annual output (GWh/year)
Cardiff-Weston Barrage	216	8,640	17,000
Shoots Barrage	30	1,050	2,750
Russell Lagoons	63	2,835	6,480
Swansea Bay* Lagoon	24	60	124*
Swansea Bay Lagoon+	24	60	187+
Lynmouth Tidal Current Array	45#	30	83.16

*Energy output estimated by DTI/WDA commissioned review [2.9]
+ Energy output estimated by TEL
# Number of devices. Each device has two turbines.

It should be stressed that only some of these options will be compatible with each other. The construction of the largest single option, the Cardiff-Weston Barrage would effectively reduce the tidal range in the impounded estuary by approximately half compared with the present day open estuary. The energy output of a lagoon system built upstream of the barrage would be reduced by about 25% compared with an open estuary without a barrage and would be unviable. The compatibility of different options is summarised in Table 2.2.

A lagoon system, such as the Swansea Bay scheme built downstream of the Cardiff-Weston barrage would also be affected but to a lesser extent. The tidal range downstream of the barrage would be reduced by 0.2m on all tides at Swansea [2.10] which would reduce the energy output of the Swansea Bay lagoon by about 5%.

A barrage built further up the estuary along the Shoots alignment would also affect the tidal range downstream although its influence would be minimal for a lagoon built in Swansea Bay. Construction of lagoons between the Cardiff-Weston alignment and the Shoots barrage would affect the hydraulic flow into the upper estuary and significantly increase the current velocity in the open estuary. This is likely to increase the sediment load in the water column entering the Shoots impoundment potentially causing adverse accumulation. The Shoots barrage would also reduce the tidal range downstream by about 8% leading to a reduction in energy capture from the Russell lagoons. Because the sediment load in the estuary is already high any option for impoundment would need detailed evaluation to ensure the sediment distribution and accumulation could be accurately predicted.

It is possible that tidal current devices could be deployed within the Severn Estuary and Bristol Channel as an alternative to lagoons or barrages. However, the viability of this alternative is dependent on the current velocities, the depth of water and their successful development. For a monopile system the minimum requirements for a technically viable system is a mean spring tidal current velocity of 2.5m/sec and a water depth of at least 25 m. There are no suitable locations within the Severn Estuary that meet these criteria without obstructing shipping lanes. Turbines with smaller rotor diameters could be deployed but this would reduce energy capture potential and make the technology less economic. Moreover smaller turbines would still obstruct navigation channels. To avoid conflicts with shipping requirements tidal current devices would have to be deployed in even shallower water further reducing their economic viability. Much of the Severn Estuary is also covered with unconsolidated sediment which would present poor anchorage conditions.

Tidal current devices deployed within impounded basins either behind barrages or lagoons would be similarly constrained by a reduced current and water depth and would be even less viable than in open water areas of the Severn or Bristol Channel. A tidal current array built off the north coast of Devon would be affected by a barrage built along the Cardiff-Weston alignment. It has been estimated that the energy output of an array in this area could be reduced by as much as 9% [2.8]. A barrage built along the Shoots alignment is further away and is less likely to have a significant affect on a tidal current array in this area.

Table 2.2 Compatibility of Different Tidal Energy Technology Options for the Severn Estuary and Bristol Channel.

Technical Option	Potential Combinations	Compatibility
Cardiff-Weston (C-W) Barrage	Russell Lagoons	Large impoundments upstream of a C-W alignment would have reduced energy output making them economically unviable.
	Swansea Bay Lagoon	A small lagoon downstream of the barrage would be compatible but would have a 5% loss of energy. The amount of energy loss of downstream lagoons depends on their proximity to the C-W alignment.
	Tidal Current arrays	Tidal current arrays built in deeper water downstream from the barrage would be compatible but would have a loss of energy depending on the distance to the C-W alignment. Tidal current arrays upstream of the barrage would not be viable because of the reduction in current velocity.

Shoots Barrage	Russell Lagoons	Large impoundments downstream of a Shoots alignment would have reduced energy output making them less economically viable. Changes in hydraulic flow could increase sediment loading and therefore sediment accumulation upstream of the barrage.
	Swansea Bay Lagoon	A small lagoon downstream of the barrage would be compatible but there would be some loss of energy. The amount of energy loss of downstream lagoons depends on their proximity to the Shoots alignment.
	Tidal Current arrays	Tidal current arrays built in deeper water downstream from the barrage would be compatible but would have a minor loss of energy depending on the distance to the Shoots alignment.
Lagoons – open Estuary (i.e. no barrages)	Russell Lagoons	Large impoundments in the Severn Estuary would be compatible with smaller lagoons such as the Swansea Bay scheme but there would be significant changes to the estuary's hydrodynamic regime (see Section 2.3.2)
	Swansea Bay Lagoon	This scheme would be compatible with both the larger Russell Lagoons and the Tidal Current arrays in the Bristol Channel
	Tidal Current arrays	The tidal current array would be compatible with lagoon systems.
Tidal Current – open Estuary (i.e. no barrages or lagoons)	Tidal current technology is viable in the Bristol Channel but most proposed systems require a minimum water depth of 25m and a peak spring current in excess of 2.5m/sec	Tidal current arrays are viable if they are located in the Bristol Channel but are constrained by depth in the Severn Estuary. There are some concepts, in an early developmental stage, that are designed for shallow water deployment which might be suitable for the Severn Estuary (see Appendix 3).

2.2.1 Economic comparison of different tidal energy options

The re-evaluation of the barrage options for the Severn also allows a comparison of the unit cost of energy with the non barrage options studied as part of this review (Figure 2.1). In each case a discounted cash flow analysis has been performed over an assumed technical life of 120 years in the case of the barrages and lagoons and over 20 years for the tidal current example. The basis of the underlying costs and energy output are explained in the following three appendices. The four discount rates selected (3.5%, 8%, 10% and 15%) have been used for all the tidal energy assessments to ensure consistency.

The basis for the barrage options have been separately evaluated but are explained in detail in a parallel review [2.8]. The Mersey barrage has also been included for comparison [2.11, 2.12]. The tidal energy from the Mersey was studied in detail during the late 1980s and early

1990s by another construction consortia and has been included to provide a reliable and robust comparison.

A simple comparison between these different options needs to be treated with some caution. The published information on the Russell Lagoon concept is limited because the concept was rejected as uneconomic and not studied in any detail. The barrage options have been the subject of detailed evaluation and provide a rigorous basis for comparison. The tidal current array is based on a hypothetical concept of a technology early in its development and consequently the upper limit presented here should be regarded as representative of the early stage of this technology [2.13]. As the technology develops the unit cost of energy should fall as experience grows and with economies of scale. However, there are considerable uncertainties related to the development of the technology and future cost projections can not be guaranteed.

Two results are presented for a hypothetical Lynmouth tidal current array. The higher values for the unit costs of generation represent an upper capital cost estimate of £6,000/kW installed; the lower value represents a capital cost of £1,000/kW installed. This range in cost values reflects the current uncertainty on the actual capital cost and the possible extent of cost reduction which might be achieved as the technology develops.

The cost and energy output data for Swansea Bay are based on limited published information [2.7]. The DTI and WDA commissioned an independent review of this scheme which concluded that the scheme would cost over three times the estimate published by the developers, Tidal Electric [2.9]. The DTI/WDA review also concluded that the energy output would be lower. A full discussion of these differences is included in Appendix 2. The unit cost of generation based on the developers evaluation and the DTi/WDA review have been included for comparison.

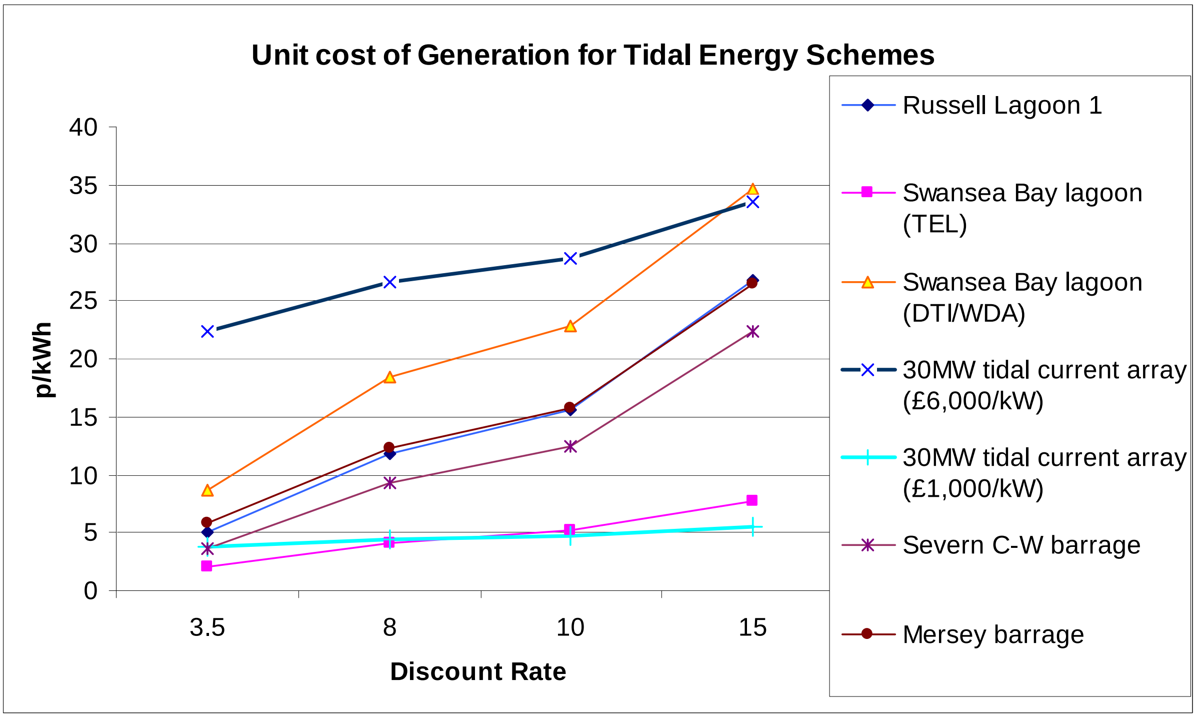

Figure 2.1 Unit cost of generation for (p/kWh) verses discount rate (%) for different tidal energy technologies that could be deployed in the Severn Estuary or Bristol Channel.

Key
C-W = Cardiff Weston

2.3 Environmental Impacts of non barrage options

Tidal energy schemes that are reliant on impoundment would require the building of large civil structures. As with any large-scale construction project, there could be effects on the surrounding environment stemming from movements and temporary residence of materials and work force, and change in character of the land (and sea bed) actually built upon. In addition to this, tidal energy projects built in estuaries would be harnessing one of the major forces responsible for shaping and controlling the estuarine environment. As a consequence the pattern of the tides would be altered, which would, in turn, be expected to influence the estuarine environment and its surroundings. In the case of the Severn Estuary the natural accentuation of the tidal range will mean that any changes to the open estuary will need careful and rigorous assessment so that the changes caused by development can be accurately predicted. Because there are a number of potentially significant impacts tidal energy developers will need to ensure that they can fully address both existing and proposed environmental legislation.

The non barrage options for the Severn Estuary that are likely to have the greatest impact are lagoon systems because they would not only change the hydrodynamic regime (water flow) in and out of an impounded basin also around the structure. For lagoon schemes on the scale of the Russell concept these changes would be significant. The impact of tidal current arrays will locally reduce the current velocity and therefore cause some impact. However, as previously discussed the potential for large scale deployment is limited in the Severn Estuary and Bristol Channel.

The specific environmental sensitivities that relate to the lagoon systems and the tidal current array are described in the appendices that relate to each scheme.

2.3.1 Hydrodynamics

The hydrodynamic characteristics or the pattern of the flow of water in estuaries are determined by a combination of the solar and lunar gravitational effects, estuary morphology, waves and river flows. In hypertidal estuaries with mean tidal ranges in excess of 6 m, the hydrodynamic characteristics are dominated by the tidal range which creates a large tidal prism or change in total volume of water within an estuary. As the tidal prism is larger on spring tides than on neaps, a greater volume of water movement occurs through a single tidal cycle which consequently raises the current velocities. This effect is accentuated in hypertidal estuaries which carry high sediment loads and tend to be well mixed. Tidal energy schemes would fundamentally change the hydrodynamic regime, which requires careful evaluation in advance not only to determine potential energy yields but also to assess post-barrage changes in sediment transport, effluent dispersion and ecology.

Previous hydraulic modelling of flows shows that the greatest effects would be within the immediate vicinity of barrages as water flowed through sluices and turbines. Upstream of barrages currents would be reduced by a factor of two, although peak currents on a flood tide would be changed less because of the necessity to maximise flow during the incoming tide

[2.14]. Whilst similar effects will occur with tidal lagoons the pattern of flow will differ because lagoons do not form a complete barrier across the estuary.

Salinity levels are also critically determined by hydrodynamic forces which often fluctuate markedly from fresh water conditions to near-marine conditions. Without any definitive evidence the changes to salinity within lagoon systems are not known. However, if they are completely isolated from the coast and have no fresh water input the salinity levels are likely to remain comparable with the salinity levels in the open estuary. Detailed modelling would be necessary to determine how salinity levels fluctuate.

2.3.2 Sediments

The pattern and distribution of estuarine sediments is dependent upon the relative dominance of tidal range, wave climate and river discharge. Within estuaries the cyclical fluctuation in water levels creates a distinct zonal pattern from sub-tidal sediments which are permanently submerged, to inter-tidal sand banks and mudflats, which are usually fringed by saltmarsh that receives only periodic inundation. Sediments are continuously eroded and often redistributed within estuaries, which are characterised by areas of net accumulation and erosion. In the Severn Estuary, for example, there is an estimated 30 million tonnes of temporary fine sediments which are often re-suspended during storm or flood events [2.15].

There are also specific sedimentological phenomena, notably fluid mud, which are unique to some estuaries particularly those such as the Severn which have high suspended sediment loads. Fluid mud is a suspension of fine clay mineral particles (<75 microns) which appears as a discreet layer just above the estuary bed during certain states of the tide. It is notably prevalent in the Severn Estuary where it forms pools in the deeper parts of the estuary particularly during neap tides [2.16].

Construction of tidal energy barrages or lagoon systems built on a large scale would fundamentally change the pattern of tidal currents and therefore sedimentation. For this reason it is important to understand active sedimentological processes and the way in which they would be affected by barrage or lagoon projects. Extensive site-specific sedimentary studies have been carried out notably on the Severn and Mersey [2.12, 2.14, 2.17], as part of a wider environmental evaluation. Changes in sedimentary regime can be predicted by using sediment transport models, which can mathematically simulate net loss or gain of sediment. The validity of these models is partly dependent on comparison with naturally occurring processes. Collection of “base-line” data on sediment loads, fluvial flow, and wave forces, as well as in-situ and laboratory analysis of sedimentary properties to determine relative vulnerability to erosion, has been an integral part of previous studies [2.12, 2.13, 2.17].

It should be stressed that lagoons built on the scale of the Russell concept would have a profound effect on the sediment distribution of the Severn Estuary. The smaller scale scheme proposed for Swansea Bay is likely to influence sediment movement and distribution although the extent of the structure’s influence on sediment movement is unknown. In both cases detailed sediment transport models would need to be developed and validated to predict changes in and around lagoons to determine not only the rate of sediment accumulation within the impounded basin but also to determine whether any localised accretion or erosion of local beaches could occur.

Tidal current arrays will also influence sediment movement within their immediate vicinity because of a localised reduction in current velocity. These effects are likely to be less pronounced, however, the extent of the impact will depend on the scale of development.

Tidal current devices deployed in the Severn Estuary would be exposed to a water column with a high fine grained sediment load which might affect their performance.

Changes in sedimentation will invariably affect parts of the estuarine ecosystem and are therefore of key importance. The link between sediment type and migratory wading bird populations has often been observed. A survey of sediments [2.18] from 25 estuaries was carried out in parallel with a complementary survey of wading bird populations on the same estuaries to determine the extent of this correlation which is discussed under Section 2.3.8.

2.3.3 The estuarine ecosystem

Animals and plants that depend upon estuaries for all, or some of their lives, are highly adapted to the unique combination of physical and chemical conditions found there. They have evolved to thrive under fluctuating salinities, temperatures, water movements and, in the case of inter-tidal organisms, periodic exposure to air. One consequence of these harsh conditions is that estuaries characteristically contain relatively few species of plants and animals, but those species present are often very abundant. Because plant and animal communities are shaped by the physical and chemical conditions imposed by tidal conditions in estuaries it is likely that alterations in these conditions will also result in changes to these communities.

Many of the animal and plant communities in Britain's estuaries are important to man, for example as food (fish and shellfish stocks), coastal protection (saltmarshes), sport (fish and wildfowl populations) and recreation (bird watching), or have a conservation value. Those species not of direct interest to man are critically important for the sustenance of the exploited populations because of the close interrelationships of the estuarine food web; without rich invertebrate populations there would be no flocks of wading birds or flatfish.

2.3.4 Primary productivity: algae

Light penetration of the water column is a function of the water turbidity and, since turbidity is likely to decrease within an impounded basin, compared with the open estuary, it is possible that phytoplankton productivity within lagoons may increase. Whilst such increases in productivity may be beneficial, it is possible that certain "nuisance" phytoplankton species might increase to problem levels (known as phytoplankton "blooms"). Such species include "red tide" phytoplankton, which produce toxins harmful to man, and *Phaeocystis*, a common UK species that forms unpleasant mucus-based scum when present in high concentrations.

A series of experiments were conducted to establish whether post-barrage conditions would favour such species, and also to investigate the possibility that zooplankton, the natural grazers of phytoplankton, may be able to control nuisance blooms [2.19]. This investigation found that post-barrage salinity and turbidity conditions were unlikely to favour growth of the toxic species investigated and that zooplankton would not control blooms of these species if they occurred. *Phaeocystis* was considered better able to exploit the conditions in the outer part of the barrage basin, and would also not be extensively grazed by zooplankton. Site-specific studies concluded that turbidity levels in the post-barrage Severn would remain too high for significant changes in phytoplankton productivity [2.20]. It is not possible to conclude with any certainty that phytoplankton blooms would occur within lagoons. Nevertheless predicting the conditions that could lead to blooms would be essential.

2.3.5 Primary productivity: saltmarsh

Saltmarshes play an important role in estuarine ecosystems, acting as a potentially significant source of detritus for the food chain and as a sink and source of sediments, as well as providing an important habitat for a range of animals. Because of their ability to stabilise sediments and dissipate wave action, saltmarshes also provide protection from shoreline erosion for some areas of estuaries. Changes in the tidal regime and wave climate arising from lagoon development may lead to alterations in the extent and composition of the marshes in an estuary particularly if they were developed on a large scale.

2.3.6 Invertebrates

Estuaries may contain stocks of invertebrates that are of commercial importance to man, such as cockles and shrimp, and there are specialised estuarine invertebrate species and communities that are of intrinsic conservation interest because of their restricted distribution. The main reason for examining the invertebrate populations in the context of tidal power, however, is the crucial part they play in the estuarine food chain. Invertebrates in and on the estuary bed (macrobenthos and meiobenthos) and in the water column (zooplankton) are responsible for consuming the abundant detrital matter, and less abundant primary plant material, making these energy and nutrient sources available to the fish and bird populations feeding on the invertebrates.

Benthic invertebrate populations have been surveyed in the Severn [2.20]. The estuary supports a number of invertebrate communities, and contain sediments with invertebrate numbers ranging from nearly zero (typically on the low-lying, coarse sediment banks) to very dense. Further studies on the sub-estuaries of the Severn (the Wye, Bristol Avon and Usk) showed that they support invertebrate densities similar to or higher than the main estuary, and hence are likely to contribute significantly to the overall ecology of the system [2.21]. It is not clear what impact lagoon systems would have on invertebrate populations. If they completely inundate intertidal areas then there are likely to be significant changes in the invertebrate population. It is also possible that changes in sedimentation in adjacent open estuary or coastal waters will affect invertebrate communities. The extent that this could occur would need to be determined through a combination of sediment transport and ecological modelling.

Further surveys of the invertebrate populations of the Severn and surrounding estuaries have been carried out in conjunction with sediment and bird surveys, in an attempt to correlate all three elements and provide a method of predicting post-barrage densities of shorebirds [2.22]. Analyses showed that the invertebrate fauna of the Severn was significantly different from all the other estuaries, and was characterised by lower densities and smaller individuals of the important species. This phenomenon has been attributed to the high turbidity and low sediment stability in the estuary. Displacement or modification of intertidal habitat would need to be carefully evaluated not only because of the ecological implications but also to ensure compliance with environmental legislation, particularly the Habitats Directive.

2.3.7 Fish

Britain's estuaries are at the interface between salt and fresh water and provide an important feeding and breeding area for a wide range of fish species. In addition to this, there are migratory species of fish that must pass through an estuary in order to complete their life cycle, such as salmon, eels and sea trout. Many fish populations rely on estuaries for food, reproduction or as a passageway, and are of considerable importance to commercial and recreational fisheries. Some species are of conservation significance by virtue of their rarity or geographical isolation.

Initial investigations on the Severn have identified fish stocks of commercial, recreational and conservation significance. In the Severn several species are fished commercially or have economic importance include, cod, whiting, plaice and eels. Significant levels of sea angling for these, and other species, also occurs [2.20]. Species of conservation significance in the Severn include the allis, twaite shad, bass, eels and northern rockling [2.20].

The Severn and its sub-estuaries are also of key importance for salmon. Concern has been growing in recent years because of the decline in this migratory species. Consequently, the Environment Agency has launched a programme of Salmon Action Plans (SAPs) for the principal salmon rivers in England and Wales including the Tawe, Afan, Ogmore, Taff, Usk, Wye and Severn [2.23]. The Usk and Wye have also been designated as Special Areas of Conservation (SAC) in an attempt to restore their favourable conservation status. The Agency's review highlighted that the degradation of freshwater and estuarine environments is thought to be the key problem, together with lower marine survival [2.23].

Although tidal energy lagoons may not affect fish populations to the extent that a barrage might there are important considerations to take into account. Firstly, fish could be drawn through turbines where they will be subject to potential damage from turbine blades [2.24]. This review concluded that excluding fish from turbine draft tubes using mesh screens would be expensive to install and maintain, because of clogging with waterborne debris. A possible alternative identified is the use of behavioural barriers, such as lights or sound fields, that would discourage fish from entering protected areas around the barrage. Two possible sound deterrence methods were laboratory tested [2.25], one based on an examination of the sounds most likely to be audible to a particular size and species of fish, and the other based on a broad sweep of sound frequencies. Both were found to alter the behaviour of a range of species and represent potential acoustic deterrence methods. The broad sweep signal has been tested under full field conditions at the cooling water intakes of a power station on the Severn with limited success [2.26]. This suite of experiments has subsequently led to modifications in the design of the equipment which will need further development and field trials. Experience has shown that exclusions or diversion rates of between 60-100% can be achieved for fresh water systems. However, if acoustic systems are to be effective in estuaries there will also need to be a greater understanding of the interaction between different species of fish and the structure of sound fields created by acoustic deterrence systems [2.26].

The Environment Agency has expressed concern that migratory fish may be affected by hydrodynamic changes to estuaries. Migratory fish are known to respond to changes in river flows [2.27 – 2.29]. It is possible that periodic flows caused by banks of turbines generating on the ebb tide may present a disruptive stimulus to fish. This indirect impact clearly needs to be understood. Changes to water quality and flow problems have been identified as key issues for fisheries under the Water Framework Directive [2.30].

2.3.8 Birds

Britain's estuaries provide winter feeding grounds for 1.5 million wading birds and wildfowl, and many of the estuaries suitable for tidal power generation are acknowledged to have nationally or internationally important over-wintering populations. The use of habitat within an estuary varies from species to species, some using saltmarsh and surrounding fields for roosting areas and the mudflats as feeding grounds, and some roosting on mudflats whilst feeding in saltmarshes or fields. The construction of a barrage or lagoon system has the potential to affect top predators such as birds in several ways: existing inter-tidal feeding areas may become permanently submerged, whilst some may be exposed for an altered period; the nature of the sediments may change, altering the abundance of the invertebrates that birds feed on; safe roosting areas may be altered; and, finally, increased recreational pressures may lead to greater disturbance.

Before the numbers and distribution of birds can be predicted for a post-barrage estuary or a lagoon development it is important to understand how they use the existing estuary. Consequently wildfowl and wader distributions on the Severn estuary has been monitored over four winters since 1987/88. The intertidal area of the estuary was divided into discrete counting areas and low-tide counts were made on a number of occasions throughout the winter at each count area. In addition, the bird usage of the inter-tidal area was calculated throughout the tidal cycle for a smaller number of sites. These studies have confirmed that bird populations are highly variable, both between winters and within a single winter, and that birds are very unevenly distributed across the estuaries. On the Severn, half the birds were typically found on just 12% of the inter-tidal area and 90% of all the birds were confined to less than 40% of the area. Over the four years of the survey it was possible to identify the areas that were consistently favoured by large numbers of birds. These areas would be the most important to preserve, or re-create, after the development of a tidal energy scheme [2.14, 2.17, 2.20, 2.31-2.35].

Despite the high variability of bird numbers, studies have shown that it should be feasible to detect changes in populations of many of the bird species [2.36]. Consistent decreases in bird numbers are easier to detect than constant increases, although for some of the least numerous and most variable species it would be impossible to detect reliably even a 50% change in numbers over a realistic monitoring timescale.

Predicting the effects lagoon systems could have on bird numbers will depend on the extent and location of intertidal areas they will affect. If the lagoon completely displaces an intertidal feeding area then the bird population will be displaced permanently. It is also possible that lagoons could change the sediment distribution of the surrounding intertidal areas affecting their ecology including bird distributions. The link between sediment type, invertebrate and bird distribution has been established although other factors need to be taken into consideration. The interaction between these elements needs to be carefully understood so that changes can be predicted. It also needs to be recognised that bird numbers can fluctuate as they migrate between estuaries, for example from east to west coast during harsh winters. Climate change can be expected to further complicate estuarine ecosystems partly because of predicted increases in extreme conditions but also because sea level rise will alter the intertidal areas and sediment distribution.

2.3.9 Landscape implications

The development of both tidal energy lagoons, and tidal current arrays would be expected to take account of impacts on the landscape. This would require a full landscape/seascape character assessment, including photomontages from key viewpoints and areas of high use within an identified Zone of Theoretical Visibility (ZTV). They would also need to take account of cumulative impacts for example new overhead power cables or access roads. If developments were close to an area with a landscape designation such as an AONB or a National Park account would need to be taken of development policies that relate to designated regions. Some account would also need to be taken of the personal experience of the impact of comparable developments on land and seascapes elsewhere.

2.3.10 Potential climate change impacts

The potential for climate change to impact on existing and developing energy generation technologies is a necessary concern when developing strategies or project development over a long timescale. Renewable energy generation is generically perceived as being sensitive to envisaged climate change effects [2.37, 2.38]. In the case of tidal current energy generation, early work suggests that this is not considered to be nearly as significant a concern [2.39].

Lagoon systems are likely to be affected by climate change. Firstly, rising sea levels will need to be taken into account in the design, particularly the height of the structure and therefore amount of materials required. Increased storm frequency and intensity will also need to be considered, particularly for structures that will be open to exposed westerly weather systems.

The fundamental mechanism behind generation of tidal currents is gravitational interaction of the Earth-Sun-Moon system. This sets the tidal current resource apart from most other renewable technologies such as wind, hydro, wave and solar technologies, which are primarily driven by the climate system and are therefore potentially sensitive to changes in climate. We suggest that the only obvious direct impacts of climate change on tidal current device operation will be sea level rise and alterations to the wave climate. The range of sea level rise by the year 2100 reported from the IPCC (Intergovernmental Panel on Climate Change) varies between 0.18m-0.59m metres dependent upon the various assumptions made during the analysis [2.40]. As first generation technologies are expected to be deployed in water depths pf about 30 metres, the impact of even the most extreme simulations of sea level change are expected to have a modest impact on the strength of tidal currents [2.39]. The impact of changes to the wave climate would be a more immediate concern for tidal current technologies, as the devices have to be designed to withstand loadings on the structure from the most severe envisaged combination of tidal, wave, wind and barometric pressure conditions. Wave impact on the structure is a significant design consideration, and therefore any increase in the loading theoretically acting on the structure would require careful consideration.

2.4 Mitigation and Legislation

2.4.1 Mitigation

Potential large-scale developments in estuaries will invariably lead to habitat modification or loss. Under these circumstances developers would be obliged under the Habitats Directive to offset the loss by creating an alternative habitat. For schemes undertaken as mitigation or compensation the new habitat must maintain a favourable nature conservation status or removal of any adverse effects arising from the proposed development to maintain the integrity of the site. This could require the provision of alternative feeding or roosting areas for those birds affected particularly if they are displaced from a designated site.

Guidance on the creation and maintenance of alternative habitat clearly indicates that detailed modelling would be necessary not only to predict the changes caused by development but also that the alternative habitat could be sustained [2.41]. Moreover, post development monitoring of habitats would be an essential element and would have to include contingency plans as part of the design stage. This has important implications for any development in the Severn but particularly for schemes on the scale of the Russell Lagoons. It may not be possible to compensate for the loss of habitat or the potential disruption because of the extent of area affected and lack of alternative habitat.

2.4.2 Legislation and Regulatory authorities

The main environmental and consent legislation that is relevant to tidal energy schemes summarised below [2.42, 2.43]

- Electricity Act 1989. From generating stations with a capacity of >50MW consent is required under Section 36. The Secretary of State may impose conditions to control and mitigate impact. For example measures to prevent the potential interference with recognised sea lanes essential to international navigation.

- Coast Protection Act 1949. Compliance with this act requires consent prior to the removal or deposition of any part of the seashore lying below the level of Mean High Water Springs

- Town and Country Planning Act 1990. This act covers planning consent requirements for onshore structures such as overhead cables.

- EC Birds Directive (79/409/EEC and EC Habitats Directive (92/43/EC). This legislation covers the protection and potential impacts on internationally designated nature conservation sites including Special Protection Areas designated under the Birds Directive, Special Areas of Conservation designated under the Habitats Directive and sites designated under the Ramsar Convention to protect wetlands of international importance. The legislation is designed to protect the whole ecosystem and the full range of habitats and species recognised under international and national designation.

- EC Water Framework Directive (200/60/EC). This legislation establishes a framework for managing water resources.

- EC Environmental Impact Assessment Directive (85/337/EEC). This legislation stipulates the requirements for detailed environmental impact assessments.

- Wildlife & Countryside Act 1981. This act governs the designation of the nationally designated nature conservation sites and the potential impacts on these sites.

- Food & Environment Protection Act 1985. This act governs the environmental impact of construction works including the disposal of dredged material below mean high water mark of spring tides (MHWS).

- Water Resources Act 1991. The act covers requirements for consented discharges and approval of works affecting flood defences.

In addition, the introduction of the proposed Marine Bill will lead to a planning framework for offshore developments. It is anticipated that this legislation will take account of other factors such as marine nature conservation including designated Marine Protected Areas. The legislation could lead to the implementation of regional marine plans that include policies for the sustainable development of the marine environment. The legislation should provide a more comprehensive link that integrates both marine and terrestrial planning issues. The proposed legislation is therefore directly pertinent to lagoons and tidal current arrays.

The regulatory authorities which have statutory responsibilities for estuaries in England and Wales include the Environment Agency, Countryside Council for Wales (CCW) and Natural England (NE). The designation of areas which have specific conservation status are covered by CCW and NE.

The importance of coastal environments for conservation, and the related consequences for flood and coastal defence have been recognised through an initiative called the Coastal Habitat Management Plans (CHaMPs). CHaMPs are intended to provide a framework for managing European and Ramsar Sites that are located on or adjacent to dynamic coastlines such as the Severn Estuary. These plans are a strategy for the UK Government to fore fill its obligations under the Habitats and Bird Directives and the Ramsar Convention to avoid damage or deterioration to Natura 2000 and Ramsar sites that might be caused by flood defence measures. The CHaMPs initiative is being undertaken jointly between Natural England, the Environment Agency and the Centre for Coastal and Marine Sciences [2.44]. In addition the Agency is actively involved in the creation of Shoreline Management Plans (SMP) which promote a strategic approach to flood and coastal defence based on a detailed understanding of natural processes, planning issues and environmental issues. The likely shoreline changes over the next 30 to 100 years will be estimated and the predicted impact of the SMP on coastal processes will be reviewed. The intention is to ensure that any changes to the shoreline management will take account of Natura 2000 sites when selecting appropriate coastal defence options. The intended aim will be to integrate CHaMPs into SMP to achieve this goal [2.44].

The Environment Agency is also represented on Sea Fisheries Committees who are comprised of elected representatives from local authorities. Committees that have responsibility for Welsh waters also include appointees from the National Assembly for Wales. These committees promote and enforce fisheries bylaws, monitor fishing and the health of fisheries. They are also a key point for liaison with other stakeholders who have interests in fisheries. Their remit extends up to six nautical miles from the coast.

The Agency also has responsibility for discharge consents and water quality which will need to incorporate the Water Framework Directive (WFD).

It is clear from the environmental legislation that any tidal energy development within the Severn Estuary or the Bristol Channel would require a detailed Environmental Impact Assessment (EIA) to ensure compliance with existing and proposed legislation. Lagoons built either as isolated structures, or as extensions from the existing shore line, would need to include detailed hydrodynamic models to predict flows in and out of the impounded basins and between the embankment and coast. Hydraulic modelling is fundamental not only to predicting changes to current velocities but also to changes in sediment movement, water quality and flooding risk. The impact assessment of tidal current arrays will need to assess changes to the hydraulic regime within the vicinity of the array and the related affects to the habitat.

Lagoon construction would require extensive dredging of sea bed material to form the embankment and prepare appropriate foundation conditions for the overlying structure. The affected areas would need to be surveyed to determine the level of disturbance or loss of habitat.

In conclusion an EIA would need to show the extent of habitat loss or change associated with the development and the related impact on wildlife. Particular concerns for the Severn Estuary are habitat loss, waders and wildfowl, migratory fish, potential algal blooms, changes to sedimentation, increased flood risk and visual impact.

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3 Glossary

Glossary of technical terms

k	kilo 10^3
M	Mega 10^6
G	Giga 10^9
T	Tera 10^{12}
kWh	kilowatt-hour(s).
m	metre(s).
M	mega or million(s).
m/s	metre(s) per second.
m^3/s	cubic metre(s) per second.
MWHS	mean high water level of spring tides
MLWS	mean low water level of spring tides.
MW_e	Megawatts electrical output.
MWh	Megawatt-hour(s).
te	tonne(s); 1te = 1000kg.
kt	kilotonnes, 1,000 tonnes
1V:2H	A slope of 1 vertical to 2 horizontal.

Anadromous	Fish which migrate from the sea and ascend rivers to spawn for example salmon and lampreys. In contrast other migratory fish such as eels are Catadromous, they descend rivers as adults to spawn at sea.
Armouring	A construction technique used to protect an embankment either with rock or specially designed concrete units .
Availability	The availability of a power station is the ratio of the energy which it would produce if restricted only by plant faults and maintenance to that which it could produce if there were no limitations.
	A turbine where the axis is positioned in line with the direction of flow.
Axial-flow turbine	A turbine where the axis is positioned in line with the direction of flow.
Bathymetry	The measurement of the depth of seas, lakes and estuaries.
Blade pitch	The pitch of a turbine blade is the angle of the blade relative to its mounting on the hub of the rotor. The pitch is design to ensure that the angle of attack of the fluid passing over it is optimised to ensure maximum energy capture. In tidal conditions the pattern of fluid flow varies throughout the tidal cycle. Energy capture can be optimised throughout each tidal cycle by varying the pitch of the turbine blade.
Bulb turbine	A type of water turbine generator particularly suited to tidal energy. The generator is housed in a sealed steel bulb within the water passage, upstream of the turbine rotor.

Caisson	A large prefabricated steel or concrete structure which is floated into position and then sunk into place.
Capex	Capital cost for a project or scheme. The value should include all capital costs required to develop and build a scheme including design, management and environmental monitoring and impact assessment as well as capital outlay for materials, plant and labour.
Cavitation	Cavitation is the formation of vapour-filled cavities in the water, for example in the turbine passageway, as a result of a local drop in pressure. Their subsequent collapse in regions of higher pressure, for example adjacent to solid surfaces such as the turbine blades, can in time cause pitting and disintegration.
Chart datum (CD)	The datum for Admiralty chart depths of water, equal approximately to the level of a lowest astronomical tide (LAT).
Coefficient of performance, C_p	Power out/(1/2AρV^3) where A = swept are of blade, ρ = density of water and V = current velocity.
Discount rate	This is a rate expressed as a percentage, used in discounting all benefits and costs to present day values.
Discounting	This is a method of assessing the present worth of a stream of costs or benefits arising at various times in the future. The calculation is made in real terms and is not an allowance for inflation. It attempts to allow for the preference for money now rather than later.
Double regulated turbine	This is a type of turbine which enables two separate methods of regulating the water flow and hence power output, e.g. one with adjustable guide vanes (distributor) and runner blades.
Draft tube	A draft tube is the water passageway downstream of the turbine runner. It is designed to maximise the amount of energy which can be extracted from the water by ensuring a rapid flow past the turbine runner but a minimum discharge velocity.
Ebb generation	A mode of tidal power in which generation takes place as water passes through the turbines on the ebb tide, i.e. from the basin to the sea.
Embankment	A mound, bank, dam or dyke made from rock, sand and similar materials.
Flood generation	A mode of tidal power operation in which water passes through the turbines in the same direction as the flood tide, i.e. from the sea to the basin.
Flood pumping	A mode of tidal power operation in which the turbines are used to pump water from the sea into the basin at around the time of high water, to increase the volume of impounded water.
Food chain	The transfer of food energy from the source in plants through a series of organisms beginning with a herbivore. Each organism is successively dependent on the others for food.
Generator rating	The generator rating or rated electrical output is the normal maximum output.

Habitat	The area inhabited by a plant or by a plant community that has been colonised as a result of influential external factors.
Head of water	This is the difference in levels between the basin and the sea which drives a tidal power turbine.
Inter-tidal area	The zone between low water and high water.
Jack-up barge	A barge with retractable support legs that can be raised to allow the vessel to be floated and towed to different sites. Once in position the legs are lowered to provide a stable self supporting platform for drilling.
Horizontal-axis turbine	A turbine where the axis of the rotor and drive chain (turbine, gearbox and generator) are orientated along an horizontal axis
Kaplan turbine	A turbine similar to a propeller with upstream guide vanes.
Load factor	A ratio of the actual amount of energy produced by a power station to the maximum energy it would produce if running at full load all the time.
Low-head	A head of only a few metres, as in a tidal scheme. This may be compared with high heads of tens or hundreds of metres in hydroelectric and pumped storage schemes.
Macrobethos	Benthic organisms (animals or plants) whose shortest dimension is greater than or equal to 0.5 mm.
Mean neap tide	The average tidal range of tides with the lowest range in the spring-neap cycle. These tides occur when the sun's gravitational field is acting at right angles to that of the moon.
Mean spring tide	The average tidal range of tides with the greatest range in the spring-neap cycle. These tides occur at, or near, new and full moon when the solar and lunar gravitational fields reinforce each other.
Meiobethos	Benthic organisms (animals or plants) whose shortest dimension is less than 0.5 mm but greater than or equal to 0.1 mm.
Migratory fish	These are fish whose life cycle involves migration between river and sea. In the Severn Estuary the known migratory species are salmon, sea-trout, allis-shad, twaite-shad and eel. Sea and river lamprey also migrate.
Natura 2000	Natura 2000 is a European network of protected sites which represent areas of the highest value for natural habitats and species of plants and animals which are rare, endangered or vulnerable in the European Community. The term Natura 2000 comes from the 1992 EC Habitats Directive; it symbolises the conservation of precious natural resources for the year 2000 and beyond into the 21st century.
Neap peak velocity	The maximum velocity recorded during a neap tide.
Neap tides	The tides of lowest range in the spring-neap cycle. They occur when the sun's gravitational field is acting at right angles to that of the moon.

Net present value	This is the net amount of the discounted future costs and revenues expressed in real terms associated with a capital investment.
Numerical model	A computer-based simulation of a real situation. In the case of numerical hydrodynamic models, the equations of motion and continuity are usually solved in one or two dimensions.
Opex	Operation and maintenance costs required to run and maintain a project or scheme. This should include all costs associated with the project for example maintaining ground water levels and operation of ship locks as well as operation of the power plant. Opex should also include the cost of replacing major items of plant.
Ordnance Datum (OD)	Arbitrary zero height, assumed to be the mean sea level at Newlyn, Cornwall, and from which the heights above sea level of all official benchmarks in Britain are measured.
Power train	Combined turbine, gear box and generator combination which converts energy in a fluid flow into electrical energy.
Ramsar sites	Ramsar sites are wetlands of international importance designated under the Ramsar Convention
Rated Capacity	The capacity of a generator is the maximum energy output from the generator when it is operating at a specific optimum condition.
Rated velocity	The current velocity that is required to achieve the rated capacity for a turbine generator.
Runner	The rotating part of a turbine which converts the energy of flowing water into mechanical energy for driving a generator.
Sand-fill	Sand used as fill material, e.g. for the core of an embankment.
Sediment transport	The process of movement of sediment by air or water.
Significant Impact Factor	A condition when the extraction of kinetic energy from a natural system leads to leads to environmental changes in that system. For example, the deposition of sediment that would otherwise continue to move with the current. The amount of energy extracted when this condition occurs is expressed as a percentage of the maximum kinetic energy in the natural system.
Socket	A cylindrical hole drilled in the sea floor using a rotorary drill mounted on a jack-up barge to provide a firm foundation for a steel pile.
Spring peak velocity	The maximum velocity recorded during a spring tide.
Spring tides	Tides of greatest range in the spring-neap cycle. They occur at or near new and full moon when the solar and lunar gravitational fields reinforce each other.
Spring-neap cycle	The 14-day periodic cycle of tides. This is due to occurrence of maxima and minima in the combined effects of the sun's and moon's gravitational fields.
Tidal bulge	The increased volume of water over a specific area caused by the gravitational influence of the sun and moon.

Tidal current	A marine current caused by the moving gravitational fields of the sun and moon relative to the earth.
Tidal range	The difference in water levels between high water and low water.
Turbidity	A measure of the clarity of water from which the amount of suspended solids in the water may be inferred.
Two-way generation	A mode of tidal power generation on both the ebb and flood tides.
Wave height	For this assessment, taken as the significant wave height, which is the mean height of the 1/3rd largest waves.
Wave period	The time between successive wave crests.
Wave period	The time between successive wave crests.
Yaw	The angular rotation of an object about a fixed axis within a horizontal plane.
Yawing mechanism	The mechanical or hydraulic components of a turbine generator device which enable it to rotate about a fixed axis within a horizontal plane.

Appendix 1
Russell Lagoons

A1.1 Background

In 1978, a Severn Barrage Committee was set up under the chairmanship of Sir Hermann Bondi, former Chief Scientist at the then Department of Energy, to advise the Government on the feasibility of a barrage scheme. The principal objective of this broad investigation was to determine whether it was technically feasible to construct a large barrage and identify the most promising location before proceeding to a full-scale development study. In 1981 the committee published its conclusions and although the study favoured a single basin scheme between Lavernock Point near Cardiff and Brean Down near Weston-Super-Mare, it did evaluate a number of different technical options including the Russell Lagoons (A1.1, A1.2) (Figure A1.1).

Proponents of lagoons, including Russell, have argued that a large impounded basin can be created at relatively low cost by building embankments with dredged material. Lagoons can be built in comparatively shallow water on intertidal areas with sufficient tidal range. Turbines, generators and sluices housed in a section exposed to deeper water can be used to alternately fill and generate power on successive tides. By using more than one lagoon it is possible to generate on both the ebb and flood tide in adjacent basins providing predictable power over a greater proportion of the day. Russell also proposed lagoons that could be built out from the shore to limit the amount of material used. One of these lagoons would be built out from the south side of the Estuary in an area known as English Grounds. The other two lagoons would be built on the Welsh Grounds from the opposite shore.

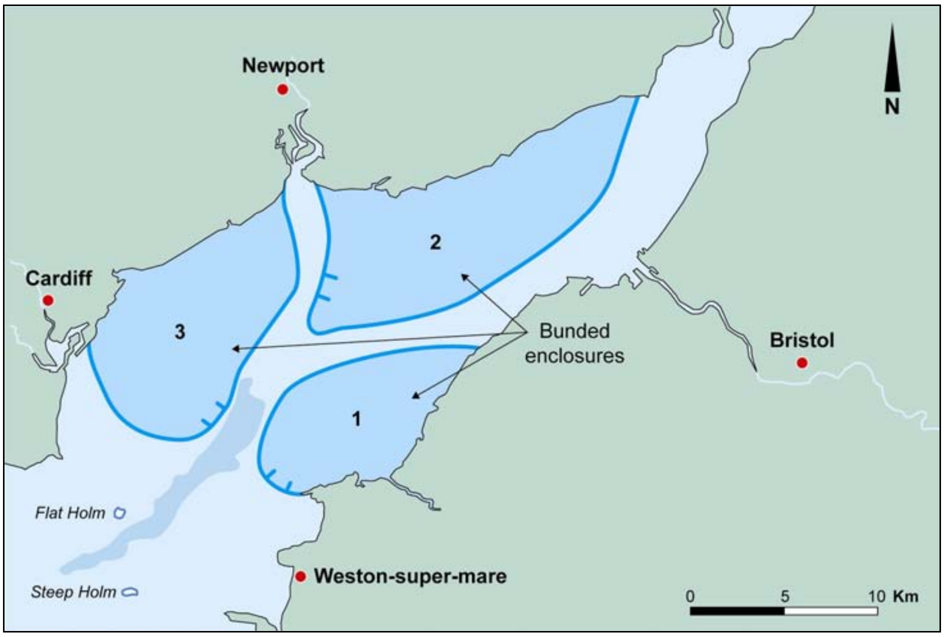


Figure A1.1 Proposed position of the three Russell Lagoons.

The 1981 review by the Severn Barrage Committee examined the energy capture potential, construction methods and cost of the English Grounds lagoons proposed by Russell. It did not examine the two lagoons proposed for the Welsh Grounds. The potential energy capture from these lagoons has consequently been inferred.

A1.2 Energy output

The energy output from a lagoon built on the English Grounds was estimated as part of the 1981 appraisal of the Severn Estuary's tidal energy potential. The study concluded that a lagoon with a combination of 21 9m diameter turbines and 24 12m^2 sluices could generate 2.16 TWh/year. In contrast to a barrage a lagoon would be more suitable for either generation on the incoming tide (flood generation) or on the out going tide (ebb generation). The artificial profile of a lagoon with comparatively steep sides means that there is a greater volume of water relative to the basin area and therefore the volume of water available for generation is broadly comparable on both the ebb and flood tides compared with a barrage. Barrages form an impoundment basin with more gradual natural slopes along either side of the estuary which means that there is a comparatively smaller volume of water relative to the basin area. This means that there is a greater discrepancy between the water available for generation on ebb and flood tides and therefore two way (ebb and flood) generation is less advantageous.

It is important to recognise that two way generation does not lead to an increase in power output by comparison with ebb generation. Two way generation would demand that a head of water is allowed to build on one side of the power plant prior to generation during both the ebb and flood tides. The volume and head of water available for generation which determines power output is constrained by the tidal cycle. With two way generation there is a lower head and volume of water prior to generation by comparison with generation in one direction only because the generation cycle limits the time available for impounding water. Consequently, it is not possible to increase power output with two way generation. Moreover, generation in one direction also enables the flow, and therefore the volume available for generation on the next high tide, to be maximised. The principle of ebb and flood generation is explained in more detail in Appendix 5.

For the English Grounds lagoon the energy output from flood generation would be about 95% of the energy produced by ebb generation. Under these circumstances it would be possible to generate on both the ebb and flood tide (two-way generation) providing a more even energy output from four blocks of energy instead of two (see Appendix 5). However, the necessity to regulate water levels on both sides of the power station means that the total amount of energy is no greater than the power output from ebb generation alone. Moreover, low head hydropower turbines, designed for operation in large volumes of water, are optimised for generation in one direction only. Experience from La Rance Barrage in France has shown that ebb generation is the most efficient method of operation partly because of the complexity of controlling two-way generation.

Two bunded enclosures built out from the Welsh shore could offer phased generation if one basin was operated in ebb generation mode and another in flood generation. The 1981 review did not assess the energy output from the two Welsh Lagoons. Given that they have larger surface areas and basin volumes it can be assumed that their energy capture potential would be at least as high as the English Grounds lagoon and possibly greater because of the larger lagoon areas. One significant limitation identified by the review is the restriction imposed by the necessity for deep water channels. Turbines need to be positioned so that there is a sufficient depth of water to avoid cavitation during generation and consequently must discharge into deep water channels. In the upper estuary these natural conduits are narrow, limiting the areas where turbines could be emplaced. The effect of periodic flows induced by discharge from turbines could also create adverse effects on shipping. As a consequence, the number and position of turbines that could be installed in each of the three power plants is likely to be restricted. For the purposes of this study it has been assumed that the energy output from the two Welsh Lagoons would be comparable to the lagoon built on the English Grounds.

A1.3 Lagoon construction and cost

Tidal energy lagoons would largely consist of embankment. Only the central section, housing turbines, generators and sluices would be built from prefabricated caissons. These structures could be built from either steel or concrete in a fabrication yard remote from the site. Large concrete caissons could be built in a protected dry dock. Upon completion the dock would be flooded and the caisson floated out. It would then be towed to the construction site and moored before being carefully winched into position. The structure would then be loaded with ballast to sink the caisson on to a prepared foundation.

The embankment would consist of a core of sand protected by rock debris and then covered with a protected layer to form a stable barrier. The protective layer can take different forms including concrete blocks, concrete slabs or stone filled mattresses. Building such structures in a hypertidal estuary with strong currents would be particularly challenging. Different construction techniques appropriate for embankments have been investigated for the Severn and other estuaries [A1.3, A1.4]. An embankment designed for long term stability in an exposed estuary must be capable of withstanding fluctuating water levels, wave attack and strong tidal currents both during and after construction. These factors are particularly pertinent to bunded lagoons in the upper Severn Estuary. Large lagoons on either side of the estuary would constrict the unobstructed flow in the deeper water between them, increasing the current velocity and erosive power. Furthermore, lagoons built on the Welsh Grounds extend over unconsolidated recent sediments vulnerable to erosion [A1.5]. In these circumstances the foot of the structure and the underlying sediment would need to be protected by a scour mattress to prevent instability adding to the cost and complexity of the construction. The detailed requirements that may be required under these circumstances have not been investigated in this study.

The design for an embankment proposed for the Severn Barrage would consist of a rock filled control structure comprised of quarry sourced material dumped from barges. This initial structure is designed to protect the larger volume of sand fill, locally supplied by dredged sediment. Large volumes of sand can be excavated using cutter-suction dredgers and pumped to the construction site. As this material is unconsolidated it must be protected by mounds of firmer material such as mine waste in a series of interleaved sections (see Figure 2.2). Once the structure is complete it is covered in a protective layer of rock amour. Sufficient space would be incorporated to allow for power cable gantries within the top of the structure for those sections where transmission cables would be required.

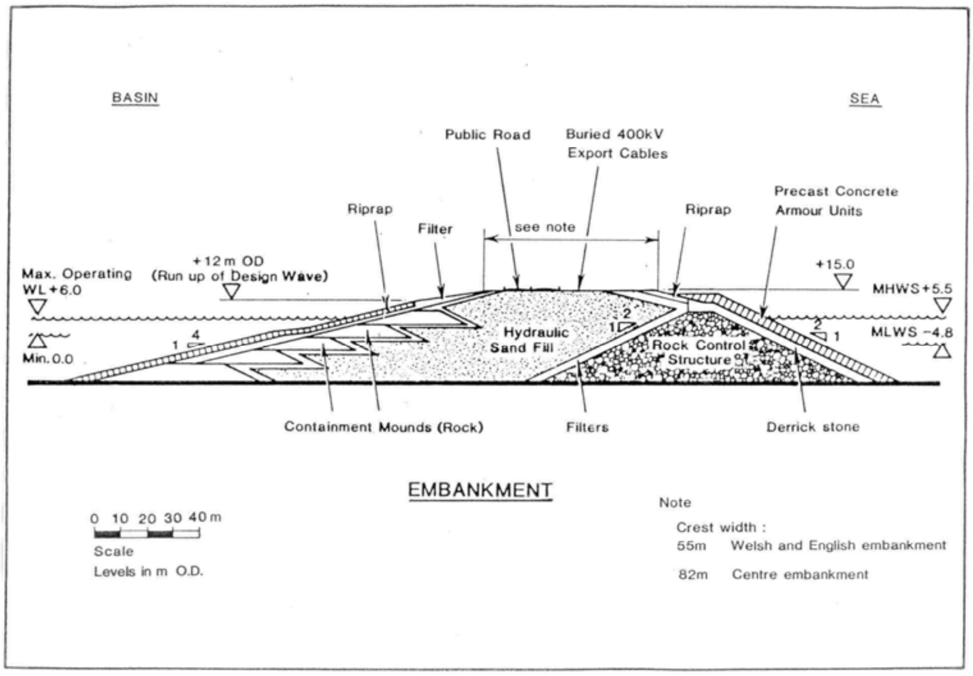


Figure A1.2 Cross section of embankment proposed for the Severn Barrage

Russell, the proponent of a lagoon system for the upper estuary, also proposed a novel construction method for constructing a sand filled embankment [A1.1]. A large temporary shield would be placed over one end of the embankment. It would be stabilised on either side by cables. Dredged sand would be pumped into the top of the shield filling the interior forming a protective mound. A series of progressive coarser materials such as gravels would be used to cover the sand fill via hoppers in the top of the shield. As the volume of material within the shield builds so does the interstitial pore pressure within the sand eventually pushing the front of the shield forward. The tension in the stablising cables on either side can be varied to change the direction of the shield. The 1981 review concluded that the technique was unlikely to be practical for barrage construction [A1.2].

For the purposes of this study the cost of the Russell Lagoon has been taken from the original estimate conducted as part of the Bondi appraisal of the Severn Estuary [A1.2]. The costs were only estimated for one of the three lagoons and have been inflated to 2006 prices using the All New Construction Price Index (COPI). The operation and maintenance cost for the scheme assume 0.5% of the total capital cost. The breakdown of costs presented in Table A1.1 has been taken directly from the source reference.

The costs for the turbine and sluice caissons are based on the numbers of turbines and sluices for the Russell Lagoon 1 estimated in the 1981 review. The scheme would have 21 9m diameter turbines each with an installed capacity of 45MW. It is assumed that there would be three turbines to each caisson. A total of 24 sluices were proposed with each caisson housing three sluices. These turbines are single regulated (they have variable pitch rotor blades but fixed pitch guide vanes) and do not require gear boxes.

Table A1.1 Breakdown of capital costs for Russell Lagoon 1

Russell Lagoons Components	**Lagoon 1 £M**
Caisson Construction	618
Embankment	622
10% contingency on civil costs	125
Sand shield (for embankment construction)	22
Total for Civils	**1,386**
Turbines & Generators	362
Transmission (connection to grid)	123
Total for Mechanical & Electrical	**484**
Non construction costs including preconstruction design consent & environmental studies	347
Site Engineering management costs	129
Total Scheme cost	**2,347**

A1.4 Electricity integration

As each lagoon scheme is assumed to have a rated capacity of 945 MW they would need to be connected directly into the national transmission system (i.e. 132 or 275 kV) at a suitable substation. For each lagoon the closest substation from the approximate position of the power house shown Figure A1.1 has been identified from the National Grid website [A1.6]. In the case of Lagoon 1 the power house would be connected to the 275 kV substation at Bridgewater, a distance of 31.4 km. The power house in Lagoon 2 is only 4.2 km from 275 kV substation Uskmouth. Lagoon 3 could be connected to a substation at Tremorfa a distance of 13.3 km [A1.6]. It has been assumed that in each case there would be no constraints imposed by a connection of this magnitude at any of these locations, but this may not necessarily be the case. It is assumed that these cables would be housed in concealed galleries along the top of each embankment partly to avoid corrosion but also to avoid visual intrusion. Lagoon 1 would require a new overland link to Bridgwater.

A1.5 Unit cost of generation

The unit cost of generation has been estimated using a discount cash flow analysis of each scheme (see Appendix 6). A constant annual energy output of 2,160 GWh has been assumed, although in reality this an average value which will fluctuate by as much as 10% depending on the astronomical configuration of the earth and moon relative to each other and the sun. A construction period of 7 years has been assumed for each lagoon with two years for preconstruction activities including detailed design and environmental assessment. The derivation of the total capital cost for the project is presented in Table A1.1. Operation and maintenance costs equivalent to 0.5% of total capital costs with complete turbine generator replacement at 40 year intervals have also been assumed. The unit cost of generation for a range of discount rates is presented in Table A1.2.

Table A1.2 Unit cost of generation for the Russell tidal energy lagoons.

Disc. Rate:	3.5%	8%	10%	15%
Lagoon 1 (p/kWh)	5.07	11.84	15.53	26.72

The unit cost of generation for the Russell scheme (lagoon 1) was approximately 40% higher than a barrage alignment slightly further downstream between Lavernock Point and Sand Point when these schemes were assessed as part of the Bondi study [A1.2]. By comparison the unit cost of energy for the Russell scheme 1, at 2006 prices is about 30% higher than the Cardiff Weston Barrage alignment which has recently been reassessed.

A1.6 Embedded carbon assessment

The length of each embankment was measured and the volume of the enclosed material estimated. The quantities of materials were then used to estimate the amount of embedded carbon and rock that would be required. The volume of concrete for each of these caissons is estimated to be 505,570 m^3 (Appendix 8).

Table A1.3 Embankment dimensions of the three Russell Lagoons

Lagoon Number	1	2	3
Maximum height of sand core (m)	12.75	12.75	12.75
Cross section area (assuming 1:2.5 slope) m^2	444.66	444.66	444.66
Length of embankment (km)	21	35	26.4
Length of sand core cross section (slopes + crest) (m)	71.66	71.66	71.66

As there is no definitive information on the size and structure of the power houses for the lagoons built on the Welsh Grounds it has been assumed that these lagoons would have the same configuration of caissons turbine, generators and sluices as the lagoon 1 on the opposite side of the estuary. The embedded carbon of each specific material has been calculated assuming the minimum and maximum carbon conversion factors as specified in Appendix 7. The amount of carbon saved from displacing fossil fuel emissions has assumed that each MWh generated would displace 430kgCO_2. The total carbon displaced assumes that each lagoon has a viable technical life of 120 years.

One lagoon has the potential to save about 111.5 Mt of CO_2 (Tables A1.4, A1.5). Some caution needs to be applied to this estimate. Each lagoon may not necessarily generate the same amount of energy. They may also be prone to sedimentation, depleting the volume of each impounded reservoir and therefore potential energy capture over time.

Table A1.4 Embedded carbon and carbon savings produced by the Russell tidal energy lagoons (minimum estimate)

Russell Lagoons	Lagoon 1	Lagoon 2	Lagoon 3
	Minimum estimated value of CO_2 (te)	Minimum estimated value of CO_2 (te)	Minimum estimated value of CO_2 (te)
Total volume of concrete (m3)	505,570	505,570	505,570
Total mass of steel (te)	141,259	141,259	141,259
Total mass of copper (te)	343	303	336
Pumping CO_2 (tonnes)	6,619	11,032	8,321
Estimated embedded CO_2 (tonnes)	338,553	342,898	340,244
Estimated carbon savings of technical life of 120 years (tonnes) and assuming 0.43kgCO_2/kWh	111,456,000	111,456,000	111,456,000
Carbon pay back period (months)	4.4	4.43	4.4

Table A1.5 Embedded carbon and carbon savings produced by the Russell tidal energy lagoons (maximum estimate)

Russell Lagoons	Lagoon 1	Lagoon 2	Lagoon 3
	Maximum estimated value of CO_2 (te)	Maximum estimated value of CO_2 (te)	Maximum estimated value of CO_2 (te)
Total volume of concrete (m3)	505,570	505,570	505,570
Total mass of steel (te)	141,259	141,259	141,259
Total mass of copper (te)	343	303	336
Pumping CO_2 (tonnes)	6,619	11,032	8,321
Estimated embedded CO_2 (tonnes)	443,473	447,819	445,164
Estimated carbon savings of technical life of 120 years (tonnes) and assuming 0.43kgCO_2/kWh	111,456,000	111,456,000	111,456,000
Carbon pay back period (months)	5.73	5.8	5.8

A1.7 Regional/social impacts and benefits

One of the benefits proposed for a system of lagoons in the upper estuary is that it allows access to ports located upstream of Cardiff without the necessity for locks. However, the construction of three lagoons would change the hydraulic flow patterns in the deep water channels. Firstly, flow that does not enter the lagoons will be constricted, leading to an increase in current velocity particularly during spring tides. Secondly, there will be localised changes to the flow patterns immediately downstream of each bank of turbines assuming each lagoon was operated as an ebb generation station. Flood generation could present severe difficulties for navigation. The tidal range downstream of the lagoons could also be affected possibly increasing the present upper limit of the current tidal range.

The extent to which hydraulic flow patterns and, as a result, navigation would be affected by tidal energy lagoons is difficult to predict without detailed modelling. A 2-D hydraulic model would need to be developed to model flow patterns through different tidal cycles. This would be necessary to predict power output, but it could be adapted to predict the tidal regime for different types of vessels entering or leaving ports in the upper Severn Estuary. This technique was developed for the Mersey Barrage [2.12] to provide some confidence for maritime operators using ports upstream of the barrage.

A1.7.1 Flood defence and land drainage.

The construction of tidal lagoons connected to the shore may offer some protection to low lying areas within the lagoon basin area. To be effective the embankments would need to exceed the highest spring tide levels. Building two lagoons in close proximity to each other could accentuate tide levels, effectively funnelling water towards the port of Newport. The flooding risk could be exacerbated if high tidal flows meet increased river discharges during periods of high rainfall. River flows on the Severn tributaries can be prevented from entering the estuary by high tidal flows moving in the opposite direction. The result could cause flooding inland as the river flood defences are breached [A1.8]. It would be essential therefore to model the post lagoon tidal levels to ensure adequate protection.

Large artificial structures built out from the coast would also affect the natural drainage of low lying land adjacent to the estuary. Water retained within a bunded reservoir will change the water levels and raise ground water levels in the land adjacent to the lagoon. Salinity levels are unlikely to increase in these areas. The low lying land on either side of the Severn Estuary currently relies on gravity flaps which allow drainage at low tide but close when the tide rises, a condition known as tide-locking [A1.8]. Areas protected by lagoons would need to allow the current drainage system to continue which might involve additional pumping to ensure adequate flow rates.

A1.7.2 Landscape/seascape

Lagoons built in the upper estuary would be predominantly adjacent to low lying areas. They would be most visible from elevated vantage points such as Penarth and Brean Down. The visual impact from these localities would be most prominent at low tide when the embankment would be fully exposed. At high tide these structures would appear as a narrow band extending into the distance.

The feasibility assessments of all the proposed barrage schemes, including the Severn, Mersey and the small-scale sites have concluded that transmission cables from the power plant to the shore would be concealed in conduits running the length of each structure. Visual intrusion is one reason for concealing the cables although corrosion of cables is also cited as a reason for preferring this option. If lagoons were built it is assumed that transmission cables would also be concealed, although this aspect was not considered in the 1980 review.

The Countryside Council for Wales have commented that for large scale developments such as the proposed Swansea Bay tidal energy lagoon highlights the necessity for developers to produce high quality photomontages from several different view points. These images would need to convey the impact of the structures from high visibility view points in different light conditions and at different states of the tide.

A1.7.3 Employment benefits

One of the principal benefits of large infrastructure projects is both direct and indirect employment. Assuming that building three large lagoons in the Severn Estuary was technically possible without serious deleterious environmental effects, it is possible that these schemes could be built in series. This would have the advantage of spreading the construction cost and generating income by completing one lagoon before progressing to the next one. This schedule would also allow the caisson construction to be concentrated at a single site. Direct comparison with the Severn Barrage project is therefore unreliable. However, previous assessments of employment for the Severn Barrage estimated that a single caisson fabrication yard in the Avon area might demand 1,500 workers. The smaller Mersey Barrage scheme (700 MW) would require an estimated 2,000 site workers at the peak of construction [2.12]. It is therefore not unreasonable to assume that a work force of at least 2,000 would be required to construct one lagoon with an installed capacity of 945 MW. Moreover, Avon would be a suitable location for caisson fabrication.

In addition to the Avon workforce a smaller number of skilled steel fabricators would be required possibly at Avonmouth but conceivably at other regional port facilities such as Barry, Newport or Port Talbot. Indirect employment for the Severn Barrage project estimated that it could amount to between a third and a half of those directly engaged in construction. This would equate to between 660 and 1,000 for each lagoon.

A1.8 Environmental issues

The Severn estuary is a largely urbanised inlet separating England and Wales. It extends from its limits of tidal influence in Gloucestershire to the coastlines around Weston-Super-Mare and Barry to the southwest where it meets the Bristol Channel. The Russell Lagoons would be prominent features along each side of the Severn Estuary between Cardiff and Avonmouth. Water depths are generally <5m, while a deeper channel of approximately 10-20m depth runs through the centre of the estuary upstream to Avonmouth. The two Holm islands lie in the western approaches to the estuary, while the smaller Denny Island lies centrally in the channel off the coast at Avonmouth. This review considers a study area approximately from the Barry and Bridgewater Bay to the upstream limit of the Severn Estuary Special Protection Area (SPA) (Figure A1.3).

The Severn is the second largest estuary in Britain, covering an area of 557km^2, including an intertidal area of 100km^2 dominated by mud flats and sand flats [A1.9]. The funnel shape and large tidal range of the estuary lead to strong tidal flows, causing highly mobile seabed sediments and large volumes of suspended sediment to be carried in the water column. These processes, along with considerable freshwater input and coastal effluent, dominate the ecology of the area. Large populations of water birds utilise the coastal and intertidal habitats, while the waters of the estuary provide a migration route for several important species of anadromous fish.

The specific impacts that the Russell Tidal energy lagoons might cause are highlighted in Table A1.7.1

The key impact that these lagoons would have is the change to the hydrodynamic regime within each impounded area but particularly in the remaining open estuary. This would not only affect the tidal range it could also lead to significant changes in sediment distribution. It is possible that given the high sediment load there could be preferential accumulation of fine sediment within each lagoon. There is also a potential risk of embedded contaminants becoming remobilised during construction.

The Severn and particularly the sub-estuaries of the Usk and Wye are designated Special Conservation Areas for a range of migratory fish including Allis, Twaite Shad, lamprey and salmon where the populations have declined in recent years. The Wye also has a designated conservation status for eels. Potential changes to water quality and changes to hydraulic flows both from and between lagoons may affect the behaviour of anadromous fish placing further pressure on their survival in these rivers. It should be noted that different species of migratory fish have different migratory patterns and responses to flow regimes.

The intertidal areas that would be displaced by these lagoons are important for waders and wildfowl. Displaced birds may find alternative locations but only if they are suitable and can support potential increases in population. Development of lagoons on this scale would require the establishment of comparable feeding areas under the Habitats Directive. The extent of the lagoons and the changes that they could induce could mean that it would not be possible to create sufficient habitat of comparable quality.

A1.8.1 Summary of the key environmental sensitivities/constraints

Table A1.7 – Summary of key environmental sensitivities/constraints

Feature	Summary	Potential adverse impacts of Russell tidal lagoon scheme
Seabed sediments and transport processes	• A mixture of sands and muds, with notable areas of gravel off the coast of Cardiff. Muds dominate on the north coast between the mouths of the rivers Taff and Usk, while patches of sandy gravel are also present throughout the estuary. Large areas of tide-swept hard substrata in the lower estuary [A1.10, A1.11]. • Widespread active sandwaves and megaripples, generally orientated northwest to southeast [A1.10]. • Strong tidal flows suspend, or retain in suspension, large amounts of sediment [A1.12].	• Physical disruption to tidal flows may affect sediment transport. • Alteration of estuary profile.
Hydrology	• The estuary exhibits a large tidal range of over 12m on spring tides, peaking at 14.8m at Avonmouth, with peak spring tidal flows of 2-4m/s in deeper channels [A1.13, A1.14]. • High levels of vertical mixing, suspended sediment and subsequently poor light penetration are experienced [A1.9]. • There is considerable freshwater input from the River Severn and several other rivers. • Salinities vary from approximately marine in the southwest to upper estuarine in the northeast [A1.11].	• Disruption of tidal flows, levels of vertical mixing and light penetration, salinity. • Alteration of tidal prism. • Alteration of terrestrial drainage patterns • Change in wave exposure
Water and sediment quality	• Water quality is generally good in the inner estuary and fair in the middle and outer estuary [A1.13]. • Much of the area is heavily developed, and has historically received considerable inputs of industrial and urban waste. Contaminant and nutrient concentrations are higher around urban/industrial outfalls, sub-estuaries and the inner estuary [A1.9]. • There is little evidence to suggest modifications to biota due to contaminants [A1.9]. • In recent years, monitored discharges have very rarely failed to meet environmental quality standards (EQS) [A1.9].	• Contamination. • Re-suspension of contaminated sediments. • Disruption of tidal flows may allow accumulation of contaminants.
Landscape/ Seascape	• The coastal landscape is predominantly low-lying with large areas of intertidal mudflats and sandflats at low tide. • Largely agricultural and rural, although some parts of the coast are heavily urbanised. • Relevant landscapes of outstanding historic interest include the Gwent Levels and the Lower Wye Valley.	• Visual intrusion. • Habitat loss. • Change in landscape character. • Increased coastal traffic. • Direct physical impact on landscapes of outstanding interest.
Coastal habitats	• The inner estuary includes extensive areas of saltmarsh, progressing inland to pasture [A1.9]. • Priority coastal habitats listed on relevant LBAPs include neutral grassland, coastal and floodplain grazing marsh, rivers and streams, coastal saltmarsh, reedbeds, coastal sand dunes, coastal vegetated shingle, maritime cliffs and slopes and saline lagoons (UK BAP website).	• Physical disturbance. • Habitat loss. • Habitat change. • Loss of existing flood protection value of natural features such as saltmarshes.

Feature	Summary	Potential adverse impacts of Russell tidal lagoon scheme
Intertidal and subtidal habitats and communities	• Highly mobile subtidal and intertidal muds support very little infauna [A1.15]. • Less mobile intertidal muds and sands support a low diversity but high abundance of a few bivalve, polychaete and small crustacean species [A1.11]. These provide an important food source for water birds. • Typical rocky shore communities present near the mouth of the estuary, and at several small sites further upstream [A1.11] • The subtidal benthic fauna is generally species-poor due to scouring and the mobility of substrata. The reef-building worm *Sabellaria alveolata* dominates tide-swept hard substrata in the lower estuary, forming reefs unique to this location in the UK [A1.11, A1.12].	• Physical disturbance. • Habitat loss. • Habitat change.
Plankton	• Phytoplankton abundance is generally low, with limited seasonal variation. Greater abundance occurs in the inner estuary [A1.9]. • Zooplankton is dominated by copepods and mysids in the inner and outer estuary respectively [A1.16, A1.17]. • These plankton provide a key food source to higher trophic levels	• Changes in the plankton community. • Harmful algal blooms.
Fish and shellfish	• The estuary provides nursery areas for whiting, plaice and sole [A1.18]. • Cod, whiting, bass, sole, plaice, flounder, dab, rays, salmon, sea trout, elvers and mullet are exploited in the region [A1.19]. • Important and vulnerable populations of several species of anadromous fish migrate to rivers entering the estuary. These fish use estuary waters for passage and feeding [A1.20]. • The burrowing brown shrimp *Crangon crangon* is abundant in many soft sediments, and is the main exploited shellfish species in the area [A1.19].	• Physical disturbance, particularly to migration routes. • Electromagnetic field (EMF) disturbance. • Habitat loss • Collision risk. • Noise.
Birds	• Supports internationally important populations of waders and wildfowl over-winter (94,000 individuals) and, to a lesser extent, waders on passage during the autumn and spring. • Waders feed on high densities of burrowing invertebrates in intertidal mudflats and sandflats. • Seabird vulnerability to surface pollution is generally classified as low [A1.21].	• Physical disturbance. • Habitat loss. • Noise.
Marine Mammals	• Harbour porpoise are commonly sighted throughout the area, and three species of dolphin are occasionally sighted in the Bristol Channel [A1.22]. • There are no known important haul-out or breeding sites for seals in the estuary [A1.23].	• Physical disturbance. • Habitat loss. • Noise.
Riverine Mammals	• Otters are present in the Usk and Wye rivers	• Dependence on fish including migratory species such as eels.

A1.8.2 Conservation sites and other key environmental sensitivities

The Severn estuary is designated a Special Protection Area (SPA) for avian features under the EC Birds Directive[1] and a possible Special Area of Conservation (SAC) for habitat and

[1] *Council Directive 79/409/EEC on the conservation of wild birds*

species features under the EC Habitats Directive[2] (Table A1.8). The estuary is also identified as a Ramsar site under the Ramsar Convention[3], and an Important Bird Area (IBA) – a non-statutory site recognised as supporting internationally or nationally important numbers of birds (BirdLife International website) (Figure A1.3).

A Coastal Habitat Management Plan (CHaMP) is currently being developed for the Severn estuary to address the issue of changes (adverse or otherwise) to sites designated under the Ramsar Convention and Habitats and Birds Directives due to natural or quasi-natural changes to the shoreline. Preliminary outputs from the draft CHaMP identify the sensitivity of coastal, intertidal and subtidal habitats to changes in sea level (personal communication with Howell R).

Table 2.8 – International conservations sites

Map ref	Site	Area (ha)	Key Features
A	Severn Estuary SPA/Ramsar/IBA	24,701 (SPA)	*Over winter*: Bewick's swan *Cygnus columbianus bewickii*, curlew *Numenius arquata*, dunlin *Calidris alpina alpina*, pintail *Anas acuta*, redshank *Tringa totanus*, shelduck *Tadorna tadorna* *On passage*: Ringed plover *Charadrius hiaticula* *Assemblage qualification*: Regularly supports 94,000 waterfowl over winter *Non-bird Ramsar features:* Habitats affected by immense tidal range, unusual estuarine communities with reduced diversity and high productivity, diverse fish community including seven species of migratory fish, feeding and nursery grounds for many species of fish
B	Severn Estuary pSAC	73,488	Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*), mudflats and sandflats not covered by seawater at low tide, sandbanks which are slightly covered by sea water all the time, estuaries, estuaries, reefs, allis shad, twaite shad, sea lamprey, river lamprey
C	River Usk SAC	1,008	Water courses of plain to montane levels with the *Ranunculion fluitantis* and *Callitricho-Batrachion* vegetation, sea lamprey, brook lamprey, river lamprey, twaite shad, Atlantic salmon, bullhead, otter, allis shad
D	River Wye SAC	2,235	Water courses of plain to montane levels with the *Ranunculion fluitantis* and *Callitricho-Batrachion* vegetation, transition mires and quaking bogs, white-clawed crayfish, sea lamprey, brook lamprey, river lamprey, twaite shad, Atlantic salmon, bullhead, otter, allis shad
E	Mendip Limestone Grasslands SAC*	417	Semi-natural dry grasslands and scrubland facies: on calcareous substrates (*Festuco-Brometalia*), European dry heaths, caves not open to the public, *Tilio-Acerion* forests of slopes, screes and ravines, greater horseshoe bat

Source: JNCC website.

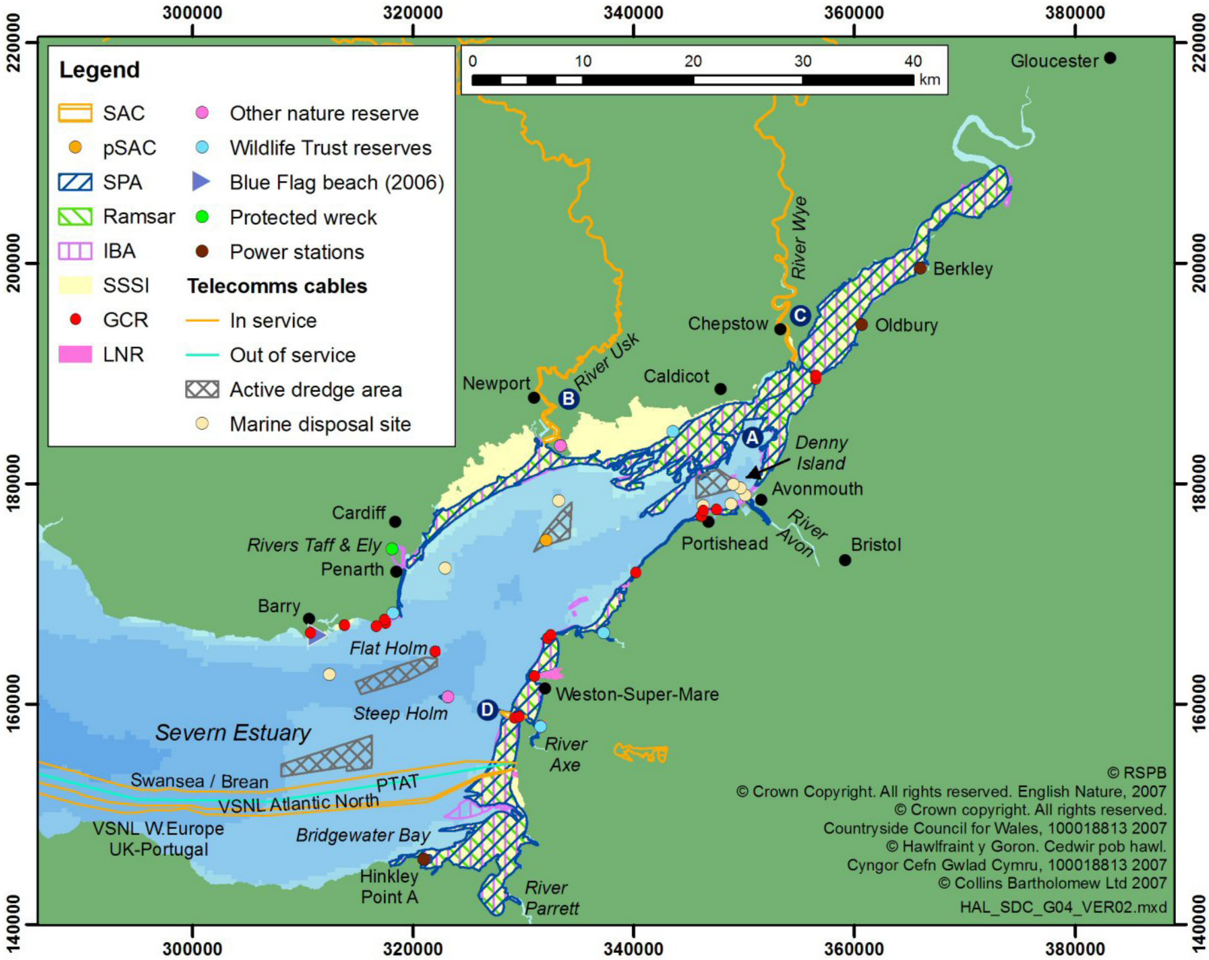
*Note: *Only a small proportion of the Mendip Limestone Grasslands are coastal*

[2] *Council Directive 92/43/EEC on the conservation of natural habitats of wild flora and fauna*
[3] *The Convention on Wetlands of International Importance, especially as Waterfowl Habitat*

Coastal national and local conservation sites in the area include 26 Sites of Special Scientific Interest (SSSIs), 1 National Nature Reserve (NNR), 8 Local Nature Reserves (LNRs), 1 Historic Landscape and 4 Wildlife Trust reserves and 1 other non-statutory reserve (Figure A1.3). These sites are designated for coastal/estuarine habitats and plant species, and geological and avian features. Most sites overlap with international conservation sites.

The coastline of the estuary is covered by many Local Biodiversity Action Plans (LBAPs) which work towards delivering the national Biodiversity Action Plans[4] (BAPs) for a variety of habitats and species of conservation interest. These include a variety of intertidal, coastal and riverine/estuarine habitats, along with species such as otter, allis and twaite shad and many species of water bird (UK BAP website).

Figure A1.3 – Conservation sites and other key features



Notes: Gwent Levels Historic Landscape follows boundary of Gwent Levels SSSIs, east and west of River Usk. Central location only of Severn Estuary pSAC shown, proposed boundary covers estuary waters to western limit of Severn Estuary SPA.

A1.9 Other uses/users

Land use around the estuary is varied, with extensive areas used for agriculture, along with several large conurbations and industrial areas, particularly between Cardiff and Newport,

[4] The UK Biodiversity Action Plan is the UK's response to the *Convention of Biological Diversity*

and around Avonmouth [A1.24]. Industrial activities along the coast include power stations (nuclear and hydrocarbon), water treatment works, and processing facilities for paper, steel and chemicals. Industrial and sewage effluents from these areas are considerable, but are highly regulated to minimise environmental implications [A1.24].

There are no pipelines, communications cables or oil/gas infrastructure in the Severn estuary [A1.25]. Four telecommunications cables extend west from the coastline southwest of Weston-Super-Mare (Kingfisher Cable Awareness Charts 2005). The estuary overlaps with several airspace control areas (non-authoritative). There is a small MOD rifle range off the coast near Caldicot, and a MOD underwater explosion trials area extends several kilometres offshore of the mouth of the River Axe. A Royal Navy firing and bombing range is situated to the west of Bridgewater Bay [A1.26].

The estuary is an important shipping route, and a variety of cargo is transported to the region's several ports by vessels of up to 300m in length [A1.24]. When considering the level of shipping activity and sensitivity of the environment, DfT [A1.27] identified the outer Severn estuary as a very low risk area. Strong tides limit commercial fishing opportunities. Salmon, elvers (young eels) and sea trout are seasonally caught to a limited extent by static and hand nets, particularly from the Wye, Parrett and inner Severn estuaries [A1.19]. Approximately 40 small vessels (under 10m length), most of which are part-time, operate in the outer estuary and eastern Bristol Channel out of harbours along the north coast from Newport to Port Talbot [A1.19]. These use a combination of otter trawls, beam trawls and long lines to target flatfish, cod, bass, whiting, rays and brown shrimp.

Dredging of sand and gravel takes place at a number of sites in the outer Severn estuary, with some of the largest sites off the coast of Avonmouth and immediately west of Flat Holm [A1.10, A1.24]. Additionally, 486,000 tonnes of dredged material from rivers, harbours and estuaries was deposited amongst eight different sites within the Severn estuary in 2004 [A1.28]. The majority of this material was deposited at one large site several kilometres off the coast of Cardiff, and several smaller sites near the mouth of the River Avon.

Although relatively understudied, the Severn estuary is regarded as an area of high archaeological importance, particularly due to the excellent preservation potential of waterlogged alluvial sediments, with finds dating back to the Palaeolithic period [A1.24, A1.29]. Many Scheduled Ancient Monuments and other sites of archaeological interest listed on the National Monuments Record occur along the coastline, including several wrecks around the islands of Flat Holm and Steep Holm [A1.30].

Tourism is one of the largest employment sectors in the area, and is focussed around traditional seaside resorts, small historic coastal towns and landscape features. Shore- and boat-based recreational angling are popular, and provide an important contribution to the economy of the area [A1.24]. Other activities include wildlife watching, walking, sailing and other watersports.

There may also be some indirect effects caused by potential reductions in commercially important fish species such as salmon and eels. Both inshore and recreational fishing are important to the local economy particularly areas along the subestuaries of the Severn.

A1.10 Indirect Impacts

The construction of all three lagoons at this scale would require an estimated 15.8 million tonnes of rock and 3.43 million tonnes of aggregate. The aggregate could be locally sourced from the Severn Estuary however the crushed rock would probably need to imported from other regions of the UK or Europe. The total quantity of rock is equivalent over 11% of UK production of this material in 2005 which could place a substantial burden on domestic supplies although demand would be spread over a number of years. The estimated amount of aggregate represents about 3.6% of UK production in the same year. The derivation of these estimates is explained in Appendix 9.

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Appendix 2
Swansea Bay Lagoon

A2.1 Background

Since 1978, most proposals for exploiting tidal energy from the Severn Estuary have concentrated on different barrage alignments or lagoons either as separate bunded enclosures built from the shore or as secondary basins linked to barrages. More recently, an American owned company Tidal Electric Limited (TEL) [3.1] have proposed a lagoon system for Swansea Bay. This scheme would be built entirely on the intertidal area in the Bay as depicted in Figure A2.1 [A2.1]. TEL's current design proposal for Swansea Bay is for a $60MW_e$ scheme which would rely on both ebb and flood generation. The artificial lagoon would have a 9km embankment enclosing a $5km^2$ basin. TEL have proposed a design based on a conventional embankment created by using sand and rock dumped on the sea-bed. The crest of the impoundment proposed for this scheme would be kept to a level only slightly above Mean High Water Springs (MHWS) to reduce material costs and to reduce the visual impact. Thus in periods of storm surge, high wave action and with rising sea levels over the life of the structure, the embankment is to be allowed to be overtopped by waves at high tide.

This scheme has been assessed by consultants contracted by the DTI and WDA in 2006 [A2.2]. The objective of this review was to provide this Government Department and Regional Development Agency with an authoritative independent review of the scheme by experienced civil engineers. The curriculum vitea of the two reviewers is published in an appendix to the DTI/WDA review. This case study considers both designs and compares the costs, energy output and unit cost of generation. Because of the difference of opinion, Professor Mike Forde, Carillion Professor of the Institute for Infrastructure and Environment, at the University of Edinburgh was consulted for his opinion of the assumptions used in the construction of the embankment.

Since publication of the DTI/WDA review, the developers TEL has published a rebuttal refuting many of the conclusions drawn by the DTI/WDA review [A2.3]. TEL commissioned a report by the engineering and environmental consultancy W S Atkins which forms the basis of the design and cost estimate of the proposed lagoon. Only a summary of this report has been published and it is not therefore possible to discuss the contents of the main study.

The lagoon concept has also been reviewed by Friends of the Earth Cymru in a briefing which compares the concept with a Severn Barrage [A2.5]. This review claims that lagoons could generate proportionately more energy then a large barrage if they were built in a series of optimum sites. The review also claims that lagoons would occupy less area by comparison with the area impounded by the Severn Barrage. One reason proposed in this review for the difference in energy output is that lagoons could operate on both the ebb and flood tides, whereas a barrage would only operate on an ebb tide. As previously explained in Section A1.2 tidal energy generated from either type of impoundment can be operated in either of these modes, however because of constraints imposed by the tidal cycle two way generation does not necessarily result in significantly greater energy capture. The two types of tidal generation are explained in Appendix 5. The amount of energy from either system is directly proportionate to the area of impoundment and the tidal range. Consequently, lagoons built in areas with a lower tidal range than the Severn Estuary would generate less energy compared with an impounded area in the Severn Estuary of the same size. The Friends of the Earth review asserts that lagoons would not necessarily impound inter-tidal areas of ecological value, however, most inter-tidal areas have some ecological value.

Moreover, large-scale development of lagoons would not only affect impounded areas but also adjacent estuary or coastline.

The use of lagoons for retiming and pump storage has been recently proposed as a further benefit [A2.5]. Additional energy can be gained by pumping water into an impounded basin at or close to high water, particularly on neap tides. The increase in the head of water will enable a power generation system to gain up to 10% more energy during generation on the succeeding ebb tide. This phenomenon has been previously studied in some depth by other companies with interests in tidal energy [2.11, 2.12].

The unit cost of energy that a pump storage system would generate is not apparent from the recent analysis. The paper also acknowledges that it has not examined the true dependence of generation and pumping efficiency on the head of water [A2.5].

A2.2 Lagoon construction and cost

Constructing an embankment with a central sand fill core in an exposed location will demand a technique that can provide adequate protection to the core during construction. Previous feasibility assessments have proposed a system where a containment rock bund would be used along the seaward edge of the structure to protect the sand filled core [A2.2]. The core would be protected on the inner, basin side by using a succession of interleaved rock as depicted in Figure A2.2. These layers only afford temporary protection during construction. Once the embankment is built it would need to be covered in rock amour to dissipate wave attack and sustain the integrity of the structure.

The proposed power station would extend from the seaward side of the lagoon as a salient extension. The power house would be housed in six concrete caisson structures each 40m long by 30m wide set in deeper water (~7m below Mean Low Water Springs (MLWS)). The power station would house 24, 2.5MW low-head hydroturbine and generator sets to produce the required 60MW rating. The proponents of the scheme claim that it would generate on both the ebb tide and flood tides.

It is assumed that the caissons would be fabricated elsewhere and towed to the site then winched into position, which is the procedure that would be adopted for most other tidal barrages or lagoons. As each caisson is winched into position the residual gap is progressively reduced until complete closure is achieved. The technique has been examined in some detail for the Severn and Mersey barrages. As the gap is gradually reduced the current in the residual gap will increase making the operation harder.

Previous technical assessments of this construction technique concluded that the current in the remaining gap could be minimised by leaving the sluices in the partially complete barrage open to maximise the flow in and out of the estuary. Whilst this is possible for a structure with large numbers of sluices extending across an estuary it is not clear how the residual current can be minimised so effectively for the Swansea Bay scheme because the design does not include sluices. It is also assumed that the power house caisson would require either a plain caisson or some other structure to connect the power house caisson with the embankment. However, details related to the construction of this scheme have not been published and it is not possible to comment on the proposed construction technique.

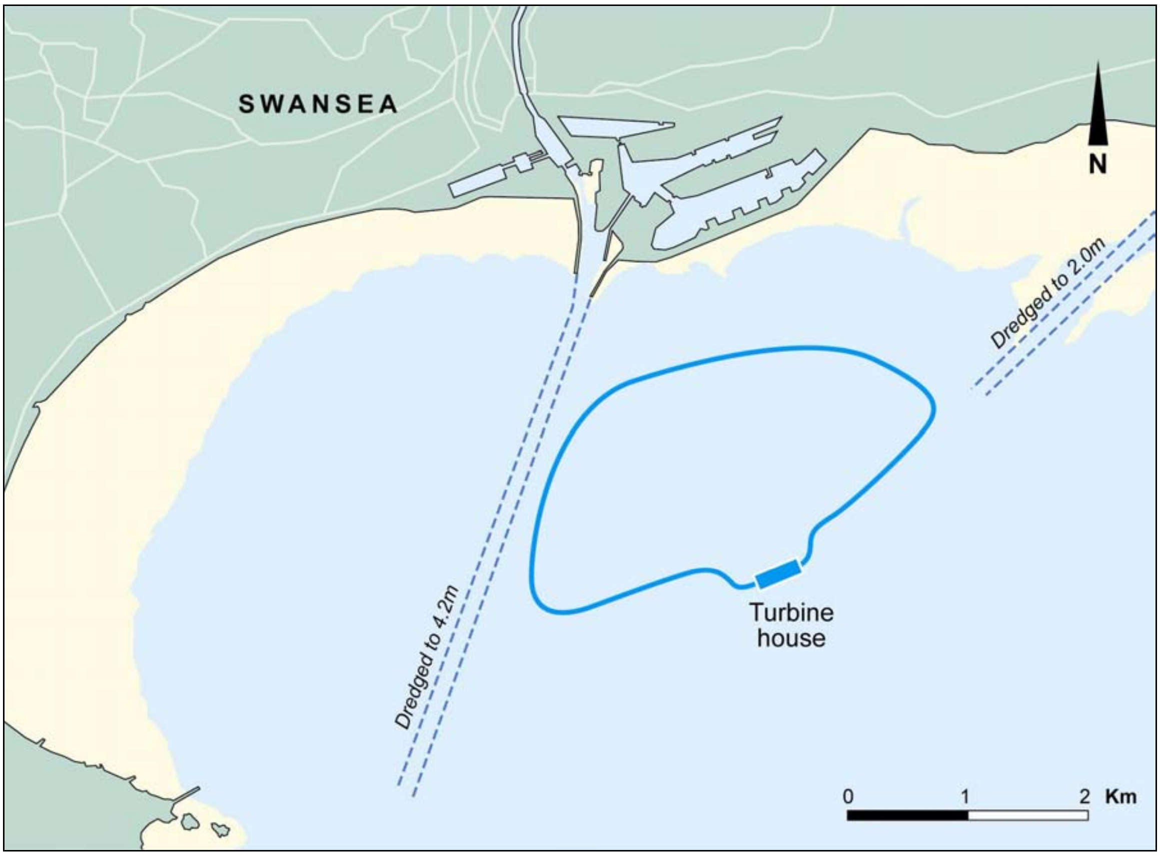


Figure A2.1 Proposed position for the Swansea Bay tidal energy lagoon

TEL has proposed a design which could offer significantly lower costs in proportion to generation capacity by comparison with assessments for other barrage schemes. They have proposed an embankment with a lower profile and with steeper slopes which could be overtopped at high water. Figure A2.2 compares the slope profile for the embankment proposed by TEL and the embankment profile proposed by the independent consultants. The DTI/WDA review not only proposed a crest height 3.0 m higher than TEL but significantly a gradient of 1:2.5 for the inner slope compared with a gradient of 1:1.5 for TEL's design. The principal reason for the difference in these profiles is that the DTI/WDA review concluded that a slope gradient of less than 1:2.5 would compromise the stability of the embankment structure. The resultant profile of a structure with symmetrical gradients of 1:2.5 increases the volume of material including the rock amour. The DTI/WDA review also advocated a structure which could resist waves up to 5m in height compared with TEL's assumed wave height of 4.0m. The height advocated for the structure was based on the probability of 1 in 100 extreme event in any single year sometimes referred to a 100-year storm. Studies for the Swansea Bay Shoreline Management Plan suggest using a mean of the wave height derived for Mumbles Head +2m CD contour and Port Talbot +5m CD contour. This value is 5.73m for a 1:100 year storm [A2.6].

Professor Forde has also concluded that in view of rising sea levels and the probability of increasing storm frequency the embankment profile proposed by TEL is too low. As a basic minimum the crest width should at least comply with CIRIA SP 83. This is an accepted industry standard. Overtopping of the structure would potentially expose the inner face of the embankment to erosion unless larger rock armour sizes were used. He also stressed that flows over or through a water retaining embankment should be minimised to retain stability. Moreover, an embankment at or close to high water would be inaccessible for maintenance except at low tide [A2.2]. Sea level rise and increased storm frequency as a result of climate change would also increase the potential impact of wave action on the structure.

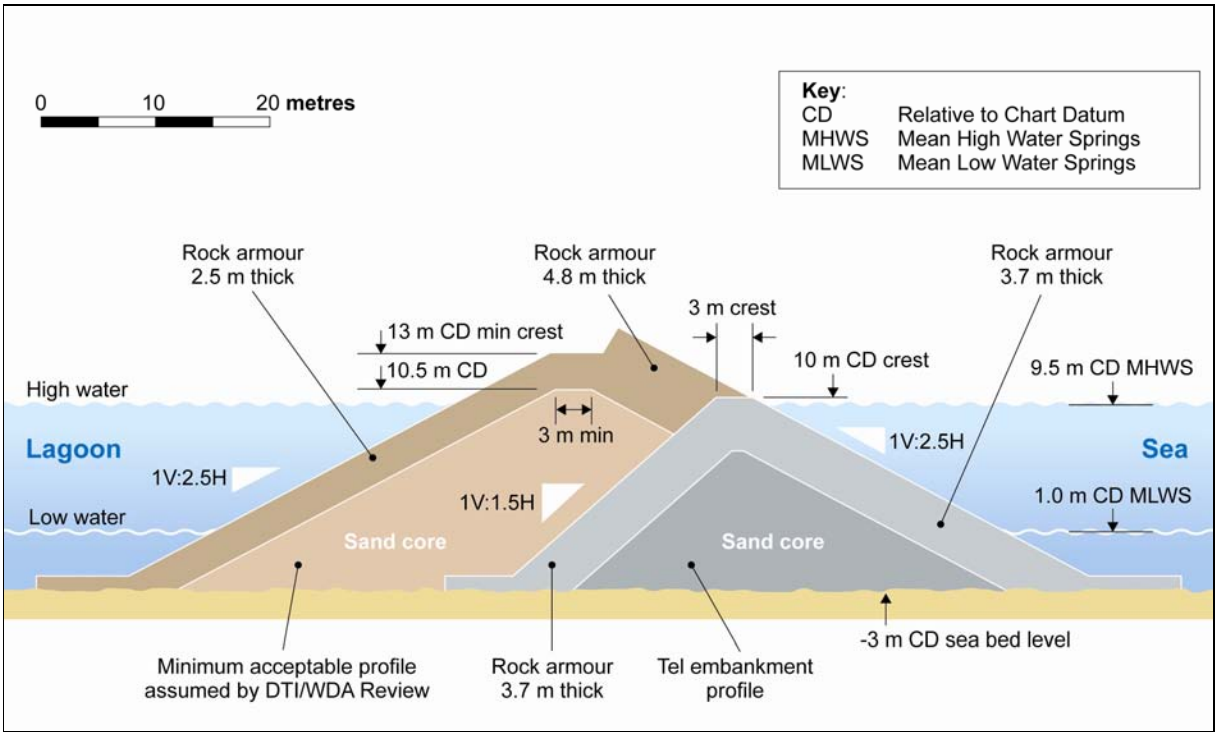


Figure A2.2 Comparison of the embankment profiles proposed for the Swansea Bay Tidal energy Lagoon

The rationale for the two different slope profiles was reviewed by Professor Forde. On the basis of the information provided he concluded that the slope profile of 1:1.5, for an embankment constructed from unconsolidated sediment, would be unstable and could possibly fail during construction. However, an embankment could be built with steeper gradients if more stable foundation conditions were evident. Without any detailed information on the foundation conditions it is not possible to draw definitive conclusions on the embankment profile or cost. Professor Forde agreed with the conclusion drawn by the DTI/WDA review that the height of the structure is reasonable based on the wave height at the proposed location. He also confirmed that the choice of rock armour favoured by the reviewers was comparable to the Cardiff Bay Barrage and based on the specifications stipulated by CIRIA [A2.7].

The independent review commissioned by DTI/WDA estimated that settlement due to compaction from the weight of this structure could be as much as 2.3m. Consequently the reviewers estimated that cost of the embankment could rise by 5% to allow for settlement whereas TEL have based their cost contingency on a more optimistic settlement of 0.3m. In view of the uncertainty of these estimates the TEL cost needs to be regarded as optimistic and the estimate from the DTI/WDA review should be viewed as conservative.

Table A2.1 Comparison of embankment design criteria for Swansea Bay tidal energy lagoon

Design criteria for embankment	TEL	Independent review
Weight wave	4m	5m
Post construction settlement	0.3m	1.3
Height of water-retaining core	+7.0m CD	+10.5m CD
Slope gradient for the inner face	1V:1.5H	1V:2.5H
Crest width	3m	5m
Median weight of rock armour	4 tonnes	11 – 15 tonnes

Table A2.2 Comparison of embankment costs for the Swansea Bay tidal energy lagoon

	TEL cost (£millions)	Review cost assessment (£millions)
Capital cost		
Embankment cost	48.5	114
Design risk contingencies	0	23
Powerhouse structure	11.55	42
Design & construction contingencies for the power house structure.	1.15	4
Turbine plant and equipment	14.1	33
Construction contingency for the embankment.	0	3
Connection to network and other costs not assessed in review	3.7	3.7
Sub-total	**79**	**222.7**
Contingencies allowance 10%	-	22.3
Sub-total		245
Other costs		
Consent, detailed design, supervision of construction	2.5	10.1**
Relocation or extension of the water utility's long sea outfall.	0	0***
Total cost	**81.5**	**255**

A2.3 Electrical integration

Power would be generated at 11kV and stepped up locally to 132kV for dispatch to shore via sub-sea cable. On shore, an overhead line would connect to the local power company's distribution network at 132kV.

A2.4 Energy output

TEL has predicted a mean energy output of 187 GWh/year. The underlying methodology which was used to derive this estimate has not been made public. The DTI/WDA review of the scheme included a separate evaluation of the energy output. The reviewers developed a spreadsheet model for the site and applied a series of assumptions, although the model assumed the same turbine runner diameter (3.3m) as TEL's proposed design. Although the scheme can be operated in two different directions the Kaplan turbines that would be used are designed for optimised use in one direction. These turbines have a set of guide vanes upstream of the turbine runner which impart a swirl to the flow as it approaches the runner blades to maximise efficiency. In reverse operation the guide vanes are downstream of the runner. Not only are the runner blades operating less efficiently but the blades obstruct the flow further reducing overall efficiency. The DTI/WDA concluded that this phenomenon would reduce the overall scheme efficiency (operation in both directions) by 7.5% compared with TEL's estimate of 2%.

TEL propose that two way generation on both the ebb and flood tide would offer greater energy output. As previously discussed in Section A1.2 it is unlikely that two way generation would offer significantly greater energy capture. This mode of operation has been discounted for other tidal energy schemes, notably the Severn Cardiff-Weston Barrage [2.8] and the Mersey [2.12]. These developers concluded that the most economic method of operation that would yield the most energy capture is ebb generation with additional food pumping on some tides. At or close to high water the turbines are operated in reverse as pumps to increase the volume of impounded water. Generation then proceeds on the ebb tide once there is a sufficient head. Although ebb generation can only occur over a shorter period, more energy capture can be achieved compared with two way generation. Experience from La Rance shows that the predominant mode of operation is a combination of flood pumping and ebb generation, although some flood generation also takes place.

A spreadsheet model to estimate the power output from the Swansea Bay scheme was developed for the DTI/WDA commissioned review. Power output was estimated on a mean spring tide, a mean tide and a mean neap tide. By extrapolating between these values and the turbine performance at the minimum possible operational head it is possible to calculate the energy output within a given tidal range. TEL supplied data on the tidal ranges at the site which enabled the reviewers to estimate the energy output for 705 tides during 2003. It should be stressed that energy output from tidal energy schemes will vary over an 18.6 year cycle because of the astronomical configurations of the Earth and Moon as they orbit the Sun. 2003 is close to the annual average for this site over this time scale. The energy output for the scheme using the spreadsheet model was 124 GWh/year. The estimate takes account of friction losses.

A2.5 Unit cost of energy

The unit cost of energy for the Swansea Bay tidal energy lagoon is presented in Table A2.3. The unit costs have been calculated using a discounted cash flow analysis over a technical life of 120 years, with major turbine generator refurbishment at 40 year intervals. In each example a construction period of 2 years has been assumed preceded by one year for detailed design and mobilisation. TEL estimate that the initial year would require 3% of the overall capital cost compared with 4% for the independent reviewers. Operation and maintenance costs have been assumed to be 0.5% of the total capital cost for each year of operation. The marked difference in the values is due to the lower capital cost and higher energy output estimated by TEL compared with the DTI/WDA review.

Table A2.3 Comparison of embankment costs for the Swansea Bay Tidal energy lagoon

Disc. Rate:	3.5	8	10	15	GWH/y
Swansea Bay unit cost p/kWh (independent review)	8.7	18.39	22.91	34.63	124
Swansea Bay unit cost p/kWh (TEL)	2.05	4.15	5.13	7.67	187

The projected unit cost of generation up to 2020 for tidal energy lagoons has also been assessed by Ofgem [A2.3]. The report commissioned by Ofgem concluded that unit generation costs would fall from 6 p/kWh to 5 p/kWh. However, the basis for this assessment was based on results presented in the Atkins report. The reported commissioned by Ofgem assumed the same load factor (36%) and capital costs as the Atkins report and then applied a sensitivity to these data.

In addition, TEL cites two other reports in support of the lagoon concept. These reports are not available publicly and have not therefore been reviewed. TEL states that a Rothschild report by its financial advisors concludes that lagoons could be competitive with offshore wind. TEL also refers on its website to a 2002 report *Swansea Tidal Schemes* by authored by T W Thorpe, AEA Technology although the information provided on the website does not include any costs from this report.

http://www.publications.parliament.uk/pa/cm200506/cmselect/cmwelaf/876/6032803.htm

http://www.tidalelectric.com /News%20AEA.htm

A2.6 Embedded carbon emissions

The embedded carbon emissions for the Swansea Bay tidal Lagoon are summarised in Table A2.4. The embedded carbon has been estimated from the quantities of key materials used in the construction of the caisson. The methodology used to estimate the quantity of embedded carbon is explained in Appendix 7. The volume of concrete was supplied by TEL. The quantities of steel for turbine and generators have been estimated by comparing the quantities for these items of equipment with the Mersey Barrage. The estimates are based on the weight per MW of installed turbine. The embedded carbon related to the switch gear cables has been estimated from the length of cable to the shore.

Table A2.4 Swansea Bay tidal energy lagoon embedded carbon

Material	Embedded carbon (DTI/WDA) Review	Embedded carbon TEL
Total volume of concrete (m^3)	67,100	67,100
Total mass of steel (te)	16,115	16,115
Total mass of copper (te	21	21
Estimated embedded CO_2 (tonnes)		
Minimum	42,263	42,263
Maximum	55,872	55,872
GWh/y	124	187
CO2/year displaced (te/GWh)	53,320	80410
CO2 saved over life of the scheme (te)	6,398,400	9,649,200
Carbon payback minimum (months)	9.5	6
Carbon payback maximum (months)	12	8.3

A2.7 Decommissioning

TEL has suggested that only the mechanical and electrical components and the power house structure would be removed from the structure. The remaining civil works would be left in place to form an offshore reef. However, leaving residual structures would lead to residual liabilities for third parties. It is possible that a more detailed decommissioning programme may be necessary to gain consent which could involve complete removal of the rock armour and protective layers. The sand core would then be exposed to wave attack and distribution by currents. The independent review completed in 2006 noted that the Crown Estate requires developers to submit detailed proposals for decommissioning which include a funding mechanism such as a bond. An environmental impact assessment of the proposed decommissioning programme would also be required.

The DTI/WDA review concluded that decommissioning costs could be as high as the original construction costs but they did not give a firm cost. Professor Forde reiterated this view but believed that this value represents the maximum cost.

A2.8 Regional impacts

A2.8.1 Visual Impact

The Swansea Bay lagoon would be built in close proximity to the shore. Consequently it would appear as a prominent feature from the shore, particularly at low tide when the full height of the embankment becomes evident. At high tide only 3m would be visible assuming that the design included an embankment that could not be overtopped. The uppermost part of the lagoon boundary would be visible. The review of the Swansea Bay lagoon recommended that sophisticated simulated visual images would be necessary to support a full environmental impact assessment.

A2.8.2 Shipping

Vessels up to 30,000 dwt use Swansea docks. The area is also popular for sailing and other leisure craft. The operators of a tidal energy lagoon would need to ensure that alterations to current flows, particularly in the main navigation channel were acceptable to shipping. The Mersey Barrage Company used complex hydrodynamic models to predict the effect of different types of vessels as they approached the barrage and its ship locks. Although the likely effects will be different in Swansea Bay, ship operators will need some confidence that vessels can operate safely. The lagoon operators would also need to implement a large exclusion zone in front of the power house because of the potential hazard caused by turbulent flows during generation. La Rance has a large exclusion zone on either side of the barrage for this reason.

A2.8.3 Existing wastewater outfall

The development of the proposed lagoon would enclose a long sea sewage outfall (as shown on the Admiralty chart for Swansea Bay). The development cost would have to include alterations to this outfall and the effects on effluent dispersion from the modified discharge point. The potential impacts of these alterations to the long sea outfall would have to be analysed in any environmental impact assessment.

A2.9 Environmental issues

Swansea Bay is an industrialised shallow embayment situated along the northern coastline of the Bristol Channel. The current study area is defined as the area between Worms Head on the Gower Peninsula and Lavernock Point (Figure A2.3), as described in the Swansea Bay shoreline management plan [A2.9].

The physical and biological characteristics of Swansea Bay are determined principally by its large tidal range (8-10m) and exposure to waves from the south west. Tidal currents are quite strong within the Bay although stronger flows are present offshore. The industrial nature of much of the shoreline has resulted in significant historical contamination of sediments and water within the Bay although present levels are much reduced.

The coastline of the Bay is varied, with significant lengths of defended coastline particularly in the region of Swansea and Port Talbot docks. These areas are fronted by expanses of intertidal sand and mud, becoming sand and shingle towards the Mumbles. Rocky shoreline and cliffs punctuated by sandy beaches and dune systems characterise much of the remaining coastline, although defended sections are common. Estuarine habitats including mudflats are present at the outflow of the rivers Tawe and Nedd with saltmarsh concentrated at Neath and Crymlyn Burrows. The sand dunes at Crymlyn are the remnants of the once extensive system that fringed the whole bay and there are also dunes at Baglan, Kenfig and Merthyr Mawr. Merthyr Mawr, Kenfig and Margam Burrows are two discrete, but extensive areas of littoral, wind blown sand dunes containing buried remains of archaeological and historic potential from the prehistoric, Roman and medieval periods.

There are a variety of other users including shipping, dredging, marine disposal, fishing, tourism and outdoor recreational activities.

The potential environmental impacts of the Swansea Bay scheme are highlighted in Table A2.5. The predominant impact that this scheme would have is the change to the hydrodynamic regime and the concomitant change in sediment distribution. There may be subsequent changes to coastal processes around Swansea Bay which will need careful evaluation. Historic contaminants might also become mobilised during construction.

A2.9.1 Summary of the key environmental sensitivities/constraints

Table A2.5 – Summary of key environmental sensitivities/constraints

Feature	Summary	Potential adverse factors
Seabed sediments and transport processes	• Extensive area of muddy sand with sands, gravels and hard substrates in more exposed areas and offshore [A2.10]. • Strong tidal flows and waves cause high turbidity and generate a range of sand bedforms. • The bay is an open system, receiving sediment inputs from either the eastern Bristol Channel or an unspecified source to the west, and outputting this material around the southern Gower and Helwick area to the west [A2.11]. • Models suggest complex sediment transport between coastal beaches and offshore banks [A2.11]. • Concerns over coastal erosion at beaches in the area including Blackpill, Swansea SSSI, Crymlyn Burrows SSSI, Kenfig SAC, and the south Gower beaches, at Aberavon seafront, Margam Sands, Kenfig Sands and Rest Bay (CCW communication).	• Physical disruption to tidal flows may affect sediment transport.
Hydrology	• Water depths range between 5-8m with deeper water (20-30m) offshore. • Mean spring tidal range is 8-10m [A2.12]. Water levels may exceed this in periods of storms.	• Disruption of tidal flows, levels of vertical mixing and light penetration,

Feature	Summary	Potential adverse factors
	• Peak flow for a mean spring tide varies from 1-2m/s in offshore areas to 0.25-0.5m/s nearshore [A2.12]. • Models suggest anticlockwise residual tidal currents to occur north and west of Port Talbot, with clockwise movement to the south-east [A2.11]. • Exposed to prevailing SW wind and resultant wave action. Annual mean significant wave height is 1-1.2m [A2.12].	salinity.
Water and sediment quality	• Water quality generally good to excellent although bathing water at Port Talbot classified as poor in 2006 [A2.13]. • Contamination of sediments due largely to historic industrial and urban discharges.	• Contamination. • Re-suspension of contaminated sediments. • Disruption of tidal flows may allow accumulation of contaminants.
Landscape/ seascape	• Landscape characterised by rocky cliffs, sand dunes and beaches with seaside villages and industrial/port frontage. • Seascape units include: Mumbles Head to West Pier, Swansea Docks and environs, Neath Estuary, Port Talbot West and Aberavon Sands, Port Talbot East and Steel Works [A2.14]. • Designated landscapes include the Gower AONB and the Gower and Glamorgan Coast Heritage Coasts. • Relevant landscapes of outstanding historic/special interest include the Gower, Cefn Bryn Common, Margam Mountain, Merthyr Mawr, Kenfig and Margam Burrows.	• Visual intrusion. • Habitat loss. • Change to landscape character. • Increased coastal traffic. • Direct physical impact on landscapes of outstanding interest.
Coastal habitats	• Priority BAP habitats include coastal saltmarsh, sand dunes, vegetated shingle, maritime cliffs and slopes, and coastal and floodplain grazing marsh [A2.15].	• Habitat change due to changes in wave exposure. • Loss of existing flood protection value of natural features such as saltmarshes.

Intertidal and subtidal habitats and communities	• Range of shoreline types from moderately exposed to sheltered shores, and substrates ranging from rocky shores to sand and mud (CCW communication).
	• Extensive *Sabellaria alveolata* reefs between Mumbles and Swansea. These are listed as a priority habitat in the Swansea LBAP with intertidal and subtidal piddocks in peat and clay listed as a local habitat.
	• Other priority habitats present include mudflats, seagrass beds, subtidal sands and gravels, and sheltered muddy gravels [A2.15].
	• Mackie *et al.* (2006) [A2.16] described benthic communities present in the outer Bristol Channel. Those which may be present in the area include:
	  • *Abra alba* and *Nucula nitidosa* in circalittoral muddy sand or slightly mixed sediment.
	  • *Fabulina fabula* and *Magelona mirabilis* with venerid bivalves and amphipods in infralittoral compacted fine muddy sand.
	  • *Nephtys cirrosa* and *Bathyporeia* spp. in infralittoral sand.
	  • *Hesionura elongata* and *Microphthalmus similis* with other interstitial polychaetes in infralittoral mobile coarse sand.
	  • Infralittoral mobile clean sand with sparse fauna.
	  • Epifauna varies according to availability of suitable attachment surfaces (e.g. gravel, cobbles, rock) and the mobility of any surface sand [A2.16].
		• Physical disturbance.
		• Habitat loss.
		• Habitat change due to changes in wave exposure.

Plankton	• Phytoplankton growth limited by the high turbidity of the water	• Harmful algal

Feature	Summary	Potential adverse factors
	column [A2.17]. Spring growth dominated by diatoms in April and May, followed by dinoflagellates. • Calanoid copepods dominate the zooplankton assemblage which varies with salinity [A2.18].	blooms.
Fish and shellfish	• Sandy areas typified by large numbers of juvenile flatfish and sand-eels, with seasonal influxes of sprat, herring, juvenile gadoids, mullet and bass [A2.18]. Nursery area for plaice, sole and whiting [A2.19]. • Rocky shore fish assemblages dominated by small species such as wrasses, gobies and blennies. • Relatively diverse elasmobranch fauna with important egg case deposition sites and nursery areas recorded (e.g. thornback rays) (CCW communication). • Fish of conservation importance including migratory shads, lampreys, salmon and sea trout may be present [A2.20]. • BAP species present include allis and twaite shads, basking shark, flatfish, hake and cod, other sharks and monkfish. • Native oyster beds present although much reduced [A2.21]. Other exploited species include cockles, mussels, crabs and lobsters [A2.22].	• Physical disturbance, particularly to migration routes. • Electromagnetic field (EMF) disturbance. • Habitat loss • Collision risk. • Noise.
Birds	• Provides an important over-wintering and passage site for a large number of waders [A2.23]. • Large numbers of oystercatchers, sanderling (both in nationally important numbers), ringed plover and dunlin present with smaller numbers of redshank, turnstone, bar-tailed godwit and grey plover. • Network of sites (including Crymlyn Burrows SSSI, Eglwys Nunydd Reservoir SSSI and Kenfig Pool and Dunes SSSI) supports nationally important wader populations. Highest concentrations at Blackpill, Swansea SSSI. • Large numbers of black-headed gull, herring gull and common gull with lesser and great-black backed gulls also present [A2.24]. • Overall sensitivity to surface pollution is low [A2.25].	• Physical disturbance. • Habitat loss. • Noise.
Marine mammals	• Mumbles Head, Port Eynon Head and Worm's Head important locally for harbour porpoise. Low numbers of common dolphin also recorded [A2.26]. • No known haul-out or breeding sites for seals although seals may forage within the region [A2.25]. • BAP species include otters, harbour porpoise, small dolphins, grouped plans for baleen whales and toothed whales.	• Physical disturbance. • Habitat loss. • Noise.

A2.9.2 Conservation sites and other key environmental sensitivities

Within the Swansea Bay area there are a number of Special Areas of Conservation (SAC) designated under the Habitats Directive[5] as well as an Important Bird Area[6] (IBA) at Swansea Bay-Blackpill (Figure A2.3).

Table A2.6 – Nature conservation sites of international importance

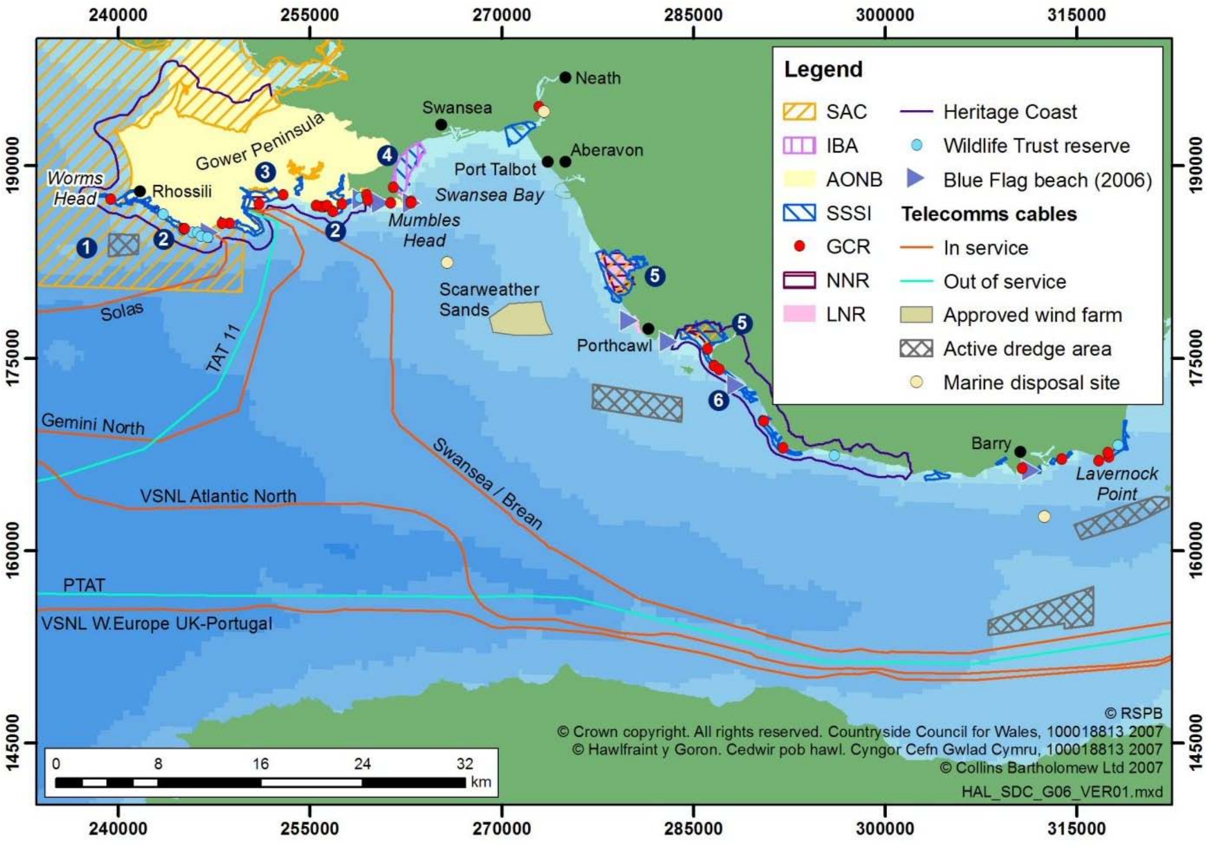
Map ref	Site	Area (ha)	Key features

[5] *Council Directive 92/43/EEC on the conservation of natural habitats of wild flora and fauna.*
[6] *Important Bird Areas (IBA) Programme of Birdlife International is a worldwide initiative aimed at identifying and protecting a network of non-statutory sites important for the long-term viability of bird populations.*

1	Carmarthen Bay and Estuaries SAC	66,100.9	Sandbanks which are slightly covered by sea water all the time, estuaries, mudflats and sandflats not covered by seawater at low tide, large shallow inlets and bays, *Salicornia* and other annuals colonising mud and sand, Atlantic salt meadows (Glauco-Puccinellietalia maritimae), twaite shad, sea lamprey, river lamprey, allis shad, otter.
2	Limestone Coast of South West Wales SAC	1,594.5	Vegetated sea cliffs of the Atlantic and Baltic coasts, fixed dunes with herbaceous vegetation ("grey dunes"), submerged or partially submerged sea caves.
3	Gower Ash Woods SAC	233.2	Tilio-Acerion forests of slopes, screes and ravines, alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior.*
4	Swansea Bay-Blackpill IBA	490	*Non-breeding:* Ringed plover *Charadrius hiaticula*, sanderling *Calidris alba.*
5	Kenfig SAC	1,191.7	Fixed dunes with herbaceous vegetation ("grey dunes"), dunes with *Salix repens* spp. *argentea* (Salicion arenariae), humid dune slacks, Atlantic salt meadows (Glauco-Puccinellietalia maritimae).
6	Dunraven Bay SAC	6.47	Shoredock.

Source: JNCC website.

Figure A2.3 – Conservation sites and other key features



National and local nature conservation designations in the area include 21 Sites of Special Scientific Interest (SSSI), 4 National Nature Reserves (NNR) and 6 Local Nature Reserves [A2.23]. The sites are designated to protect a wide variety of interest features including geological exposures, coastal habitats and species including sand dunes (e.g. Kenfig which supports LNR, NNR and SSSI designations), and important bird sites (e.g. Blackpill, Swansea SSSI). The Wildlife Trust of South and West Wales have reserves at South Gower Cliffs and Cwm Colhuw [A2.27].

Thirty five Geological Conservation Review sites [A2.28] are present along the Swansea Bay coast, which also supports the Gower and Glamorgan Coast Heritage Coasts. The Gower Area of Outstanding Natural Beauty was the first AONB designated in England and Wales in 1956 and includes the dramatic limestone cliffs and sandy beaches of the southern Gower coastline.

A2.10 Other uses/users

The Swansea Bay tidal lagoon scheme would lie between two navigation channels serving the Port of Neath and the larger docks at Swansea. These channels are dredged regularly and in 2004, 949,633 tonnes of dredge spoil was disposed of at a site at the mouth of the Bay [A2.29]. There are also two active dredge areas for marine aggregates in the region, one off Worms Head and the other off Porthcawl [A2.30]. Both ports primarily service the steel industry with large vessels passing through the Bay. A ferry service to Cork also uses Swansea Docks [A2.2].

Strong tides within the region limit commercial fishing opportunities, but valuable potting grounds are found around the Gower Peninsula and mollusc fisheries take place in some estuaries and bays. In 2005, two areas of the Bay, Southern beds (mussels) and Swansea Bank (native oyster), were classified as shellfish production areas [A2.31]. Fishing vessels target plaice, turbot, whiting and rays along the sandbanks from spring through autumn, with monkfish and lemon sole taken over rougher ground. In winter, cod, whiting, plaice, rays and dogfish predominate in landings. Gill nets and drift nets are used for cod, bass and herring in season and tangle nets are set from spring onwards for turbot, rays and brill. Recreational fishing is also popular (CCW communication).

Other recreational activities of relevance include boating, sailing, swimming, surfing, and SCUBA diving. There are numerous bathing beaches some of which were awarded Blue Flag status in 2006, including Bracelet Bay, Caswell Bay, Langland Bay and Port Eynon [A2.32]. The numerous small coastal towns and villages are popular with tourists (e.g. Mumbles) with coastal paths for walkers and cyclists.

A telecommunication cable skirts the Bay before making landfall on the Gower peninsula. A large offshore windfarm (30 turbines) has been approved for Scarweather Sands, a seabed shoal about 5.5km off the Porthcawl coast [A2.33].

The region supports a rich archaeological resource dating back to the Mesolithic with a large number of National Monuments present along the coast and in Swansea Bay [A2.34]. These include the internationally important Gower bone-caves, the Paviland caves (the earliest scientifically excavated cave site in Britain), Bronze Age burial sites, Iron Age hillforts and Medieval buildings [A2.35]. The large numbers of shipwrecks present within the Bay and surrounding waters [3.33] is testament to the important role the region has played in marine trade and industry from Roman times through to present.

A2.11 Indirect Environmental Impacts

The construction of a lagoon at this scale would require 1,688,000 tonnes of rock and 151,870 tonnes of aggregate. The aggregate could be locally sourced from the Severn Estuary however the crushed rock may need to imported from other regions of the UK or

Europe. The quantity of rock is equivalent to 1.2% of UK production in 2005. The estimated amount of aggregate represents about 0.16% of UK production in the same year. The derivation of these estimates is explained in Appendix 9.

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Appendix 3
Severn Estuary tidal current array

A3.1 Background

Tidal current energy using submerged turbines is the direct extraction of energy from naturally occurring tidal currents. In many respects the technology employed and physical response of the system is analogous with the wind energy industry, which uses wind turbines to harvest energy from the wind. One of the major advantages of tidal current energy in comparison with the wind industry is the long term predictability of the available resource and therefore energy harvest, once suitable in-situ measurements have been obtained.

In terms of energy harvesting, the UK is blessed with a disproportionate number of sites exhibiting extreme tidal currents. These extreme tidal currents are expected to be targeted for exploitation by first generation tidal current energy converter (TEC) device technologies. Occurrences of such extreme tidal currents are due to very specific circumstances relating to the topography, bathymetry and propagation of tidal energy from the deep oceans onto shallower continental shelf regions [A3.1].

A number of different TEC device technology concepts have been proposed in recent years. With a few exceptions the majority are variations on the theme of a horizontal-axis turbine. The major differences between concepts relate to the method of securing the turbine in place, the number of blades and rotors and how the pitch of the blades is controlled. One of the most advanced tidal current generator concepts, in the sense that it has been under development for the longest period of time, is the pile-mounted device being developed by Marine Current Turbines Ltd (MCT). The first version of this horizontal-axis device, the “Seaflow”, was installed in the Bristol Channel off Lynmouth in 2003 [A3.2]. The second version, the “Seagen” is planned to be installed in Strangford Narrows in Northern Ireland during 2007. For the purposes of this hypothetical case study investigating the development of a Severn Estuary tidal array, an extrapolation has been based on a concept similar to MCT’s Seagen type of technology. The Bristol Channel is the home of the first full-scale TEC device in the UK, and is one of the potential sites for an array of tidal current devices [A3.3, A3.4].

This hypothetical case study will be based on what are considered to be reasonable assumptions concerning technology development, number, size, location and configuration of a likely array of tidal current turbines in the Severn Estuary. A hypothetical case study based on an array of devices provides an indication of the energy output, economic value and potential environmental impact of this technology assuming mass deployment.

It is also important to acknowledge that much of this case study is based upon time-restricted desk-based study. If commercially proven

Box 1: Couch & Bryden have characterised the three mechanisms that can give rise to extreme tidal current regimes[1]:

Tidal streaming: Is the physical response of the tidal system to maintenance of the continuity equation; when a current is forced through a constriction, the flow must accelerate.

Hydraulic current: If two adjoining bodies of water are out of phase, or have different tidal ranges, a hydraulic current is set-up in response to the pressure gradient created by the difference in water level between the two bodies. In regions with medium to high tidal ranges, resulting hydraulic current between the adjoining regions can become very large.

Resonant system: Resonant systems occur as a consequence of a standing wave being established. A standing wave arises when the incoming tidal wave and a reflected tidal wave constructively interfere. The interaction of the waves can create very large tidal amplitudes and associated tidal currents.

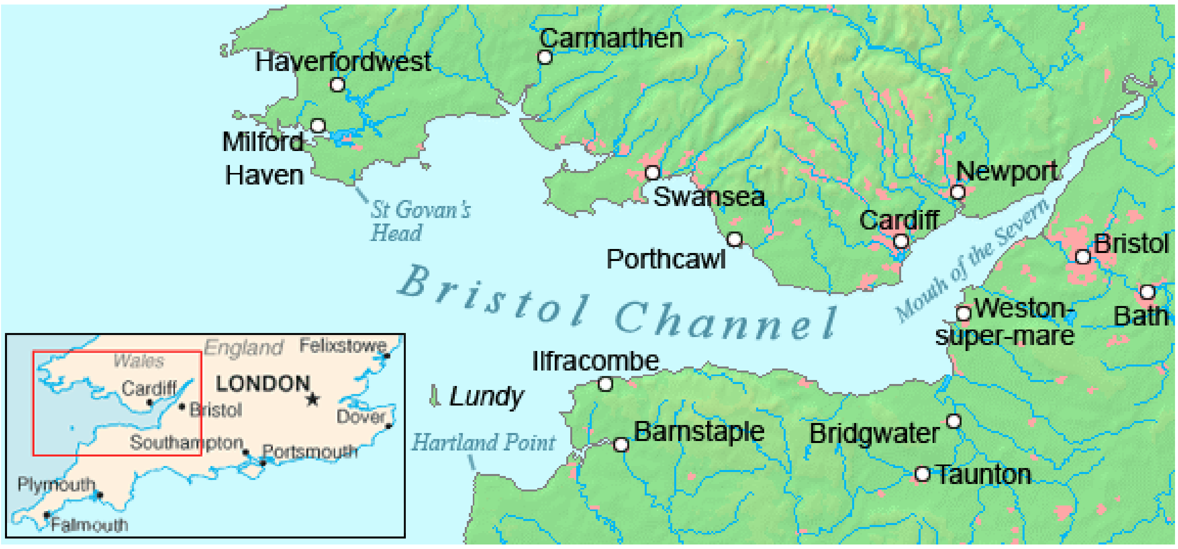
technology was on the market, and serious consideration of harvesting significant energy from a location was an immediate consideration, the level of understanding of (i) the existing hydrodynamic resource, and (ii) the impact of any developments on this underlying resource would be comparable to any other large offshore renewable scheme such as a wind farm. The development would also be required to meet detailed design and permit requirements comparable to other major coastal infrastructure projects (e.g. the Cardiff Bay Barrage, which required the development of bespoke numerical models and the construction of a 1:250 scale physical model in order to properly inform the project design and implementation [A3.5]). The case study presented here is therefore very much at the comparative level of a scoping study.

The physics of the exploitation of tidal currents are not yet fully understood and this is a rapidly developing area of active fundamental research. Because of this, there is great uncertainty surrounding the size of the resource and the amount of energy that can be extracted from it. This is especially true when large arrays are considered that attempt to extract a significant proportion of the energy available in a current. Numerical results quoted in this case study should therefore be regarded as first approximations.

A3.2 The location

The Severn Estuary-Bristol Channel tidal system is renowned as having one of the highest tidal ranges anywhere in the World. The location separates south Wales from south-west England (Figure A3.1). Large areas of intertidal zone occur, exposed by the extreme tidal range. Even in non-intertidal areas, the upper half of the system is fairly shallow, and depths of not much more than 20-30 metres predominate in the lower half of the system.

Figure A3.1 Severn-Estuary-Bristol Channel (source: http://en.wikipedia.org/wiki/Image:Bristol_channel_detailed_map.png).



The dominant tidal regime in the Severn Estuary-Bristol Channel is a resonant system, although tidal streaming also contributes [A3.6] (see Box 1). These two mechanisms combine to generate the extreme tidal ranges occurring in the Channel. This variation of tidal range across a semi-diurnal (12.4 hour) period leads to significant pressure gradients occurring across fairly short length scales of a few hours. These pressure gradients produce strong tidal currents across large extents of the region of between 1.5-2.5 m/s during spring peak tide conditions. The tidal currents in the Severn Estuary exceed 2.5 m/s on spring tides but the velocity falls below this value further west in the deeper water of the Bristol Channel. So although there is a tidal current resource in this region (as defined by depth of water and current velocity) it is comparatively small by comparison with other coastal regions around the UK where higher current velocities occur in similar water depths.

Tidal currents through the channel tend to follow topographic contours. This ensures that in large extents of the Channel, current velocities are rectilinear through the tidal cycle; the current is directed toward one of two opposite directions (flood and ebb tide), except during slack periods when the current is at or near zero. Some of the headlands in the region are however known to generate small eddy structures which do not exhibit rectilinear flow conditions. It is not possible to determine the current structure in these eddy regions without recourse to involved development of a bespoke hydrodynamic model of the region. Avoidance of installing devices in areas known to be subject to eddy generation is therefore advised.

A3.2.1 Site selection

A number of publications provide guidelines towards conducting site selection [A3.1, A3.7 – A3.9]. At the heart of these guidelines is analysis of the tidal current resource and consequent 'raw' energy available for exploitation. Then technology constraints and practical restraints are considered in order to determine the suitability of the site. For this analysis the following criteria were identified as being key to identifying a suitable site within the constraints of the available resource:

1. Spring tidal peak velocity greater than 2.25 m/s, which relates to the *theoretically available resource.*
2. Area of bathymetry suitable for locating an array circa 30MW installed (acceptable depth range 25-45 metres), which relates to the *technically available resource*.
3. Consideration of potential impact on shipping lanes and general navigation. This impacts on the *practically available resource*.

The usual guidelines identified in the literature for site selection require a spring tide peak velocity greater than 2.5-3.0 m/s. Unfortunately, the first criterion has to be relaxed for this analysis as there is no suitable location where a substantial area in the Channel exhibits this characteristic from analysis of the relevant data [A3.10 – A3.13]. The second criterion rules out all locations within the Severn Estuary, therefore the analysis concentrates on the Bristol Channel. A combination of the first two criteria identifies only two preferred sites; one off of Foreland Point near Lynmouth; the other off the port of Barry. The third criterion rules out the Barry location as it lies astride the Pilot Boarding Area for major ships bound for Barry, Cardiff, Newport, Avonmouth, Bristol, Sharpness and Gloucester [A3.13]. The Foreland Point location (see Figure A3.4) is therefore selected as the preferred candidate for analysis as part of this hypothetical case study. One benefit of selection of this location is that it does not clash with any of the major barrage or lagoon options that are also being considered within this report. The site selected is characterised by maximum spring and neap tidal velocities of 2.4 m/s and 1.45 m/s respectively. It is interesting to note that MCT and its partners have independently identified the exact same location as the preferred Bristol Channel site for potential future development of an array of TEC devices [A3.3, A3.4].

Box 2: Meaningful resource assessment needs to be considered in three distinct phases:

Theoretical resource: A top level statement of the energy contained in the entire tidal resource.
Technical resource: The proportion of the theoretical resource that can be exploited using existing technology options.
Practical resource: The proportion of the technical resource that can be exploited after consideration of external constraints (e.g. grid accessibility, competing use (MOD, shipping lanes, etc.), environmental sensitivity).

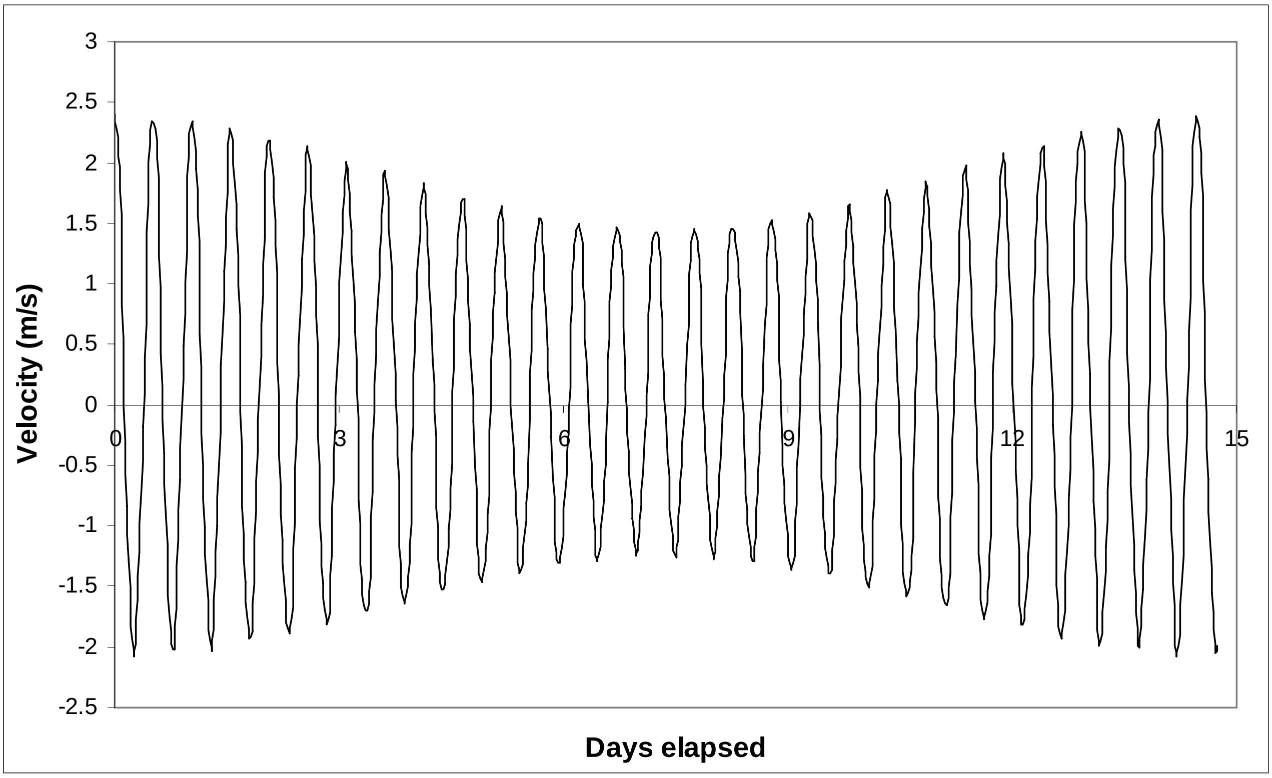
A3.2.2 Resource analysis

Fully fledged resource analysis would require an extensive in-situ marine survey program and subsequent analysis of the data gathered. The University of Edinburgh under contract to AEA Technology is developing a protocol for the DTI's Marine Renewable Deployment Fund program which incorporates a methodology for such analysis [A3.14, A3.15]. However, in this case, no site-specific data is available, and therefore it is necessary to rely on information that lies in the public domain to populate the resource analysis. Without detailed specific data it is also not possible to conduct an exhaustive resource analysis. Therefore the variation of the tidal current resource through a spring-neap cycle at the chosen site off of Foreland Point has been modelled using a simple bi-sinusoidal formula operating on the parameters shown in Table A3.1 obtained from three corroborating sources [A3.10 – A3.12] (see Figure A3.2). The data available in the referenced material supports the application of a bi-sinusoidal analysis technique. Nonetheless, this is a simplified approach and should only be taken as indicative of the variation over a typical Spring-Neap cycle.

Table A3.1 Key parameters characterising the Foreland Point site tidal current resource

Mean max Spring velocity	Mean max Neap velocity	Ratio Neap to Spring	Ratio Ebb to Flood
2.40 m/s	**1.45 m/s**	**0.604**	**0.87**

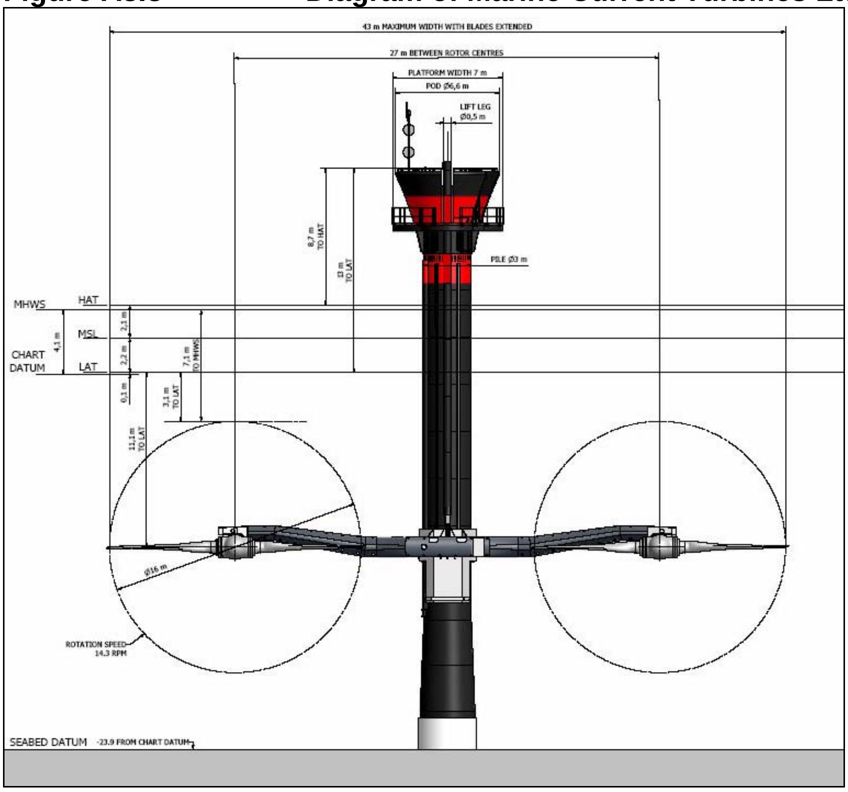
Figure 4.2 Velocity variation for a typical Spring-Neap cycle from a bi-sinusoidal simulation at the chosen site off of Foreland Point.



A3.3 The technology

We have chosen to base this case study on a concept similar to Marine Current Turbine Ltd's "Seagen" machine. A prototype is currently under development and is scheduled for deployment in Strangford Narrows [A3.16]. This is currently the furthest developed tidal-current device-concept. Figure A3.3 below shows a diagram of this technology. This pile mounted concept is best suited to sites where the water depth is approximately twice the turbine diameter. This is necessary to ensure that the turbine blades are located appropriately in the water column. Energy density near the sea-bed tends to be insignificant and is therefore not of interest for energy harvesting. Furthermore, appropriate turbine clearance above the sea-bed ensures that any significant physical debris moved around the sea-bed by the extreme tidal currents of any potential farm location do not interact with, and so damage, the turbine blades. It is also necessary to ensure sufficient clearance between the turbine blades and sea surface. This requires careful consideration of the worst combination of potential factors such as the lowest astronomical tide, largest wave amplitude and extremes of atmospheric pressure. Limiting the potential depth of installation of TEC devices are the cost, loadings and installation process required at greater depths [A3.7].

Figure A3.3 Diagram of Marine Current Turbines Ltd's "Seagen" machine



The hypothetical device selected for this case study has two 16m diameter two-bladed rotors attached to the ends of a horizontal cross beam supported on a vertical pile. The pile is a steel tube 3m in diameter, 55m long and weighing 270 tonnes. It is cemented into a 21m deep socket drilled into the seabed.

The rotors always point in the same direction but can be changed from flood tide to ebb tide operation by changing the pitch of the blades through 180°. The ability to pitch the blades also enables the blade angle to be altered to optimise device efficiency for a given tidal current, and similarly to limit the maximum power generated. This method of controlling TEC device performance is known as pitch control, which is also a popular control mechanism for wind turbines.

The distance between the centres of the two rotors is 27m. This means that there is an 11m gap between the edges of the disks swept out by the two rotors. This will prevent the wake of the pile impinging on the rotors when they are downstream of the pile.

The clearance between the rotor disk and the seabed is designed such that at low tide the rotors occupy two thirds of the height of the water column.

The twin powertrains (rotors, gearboxes and generators) are mounted on either end of the cross beam, which is attached to a collar that can slide up and down the pile. Using this, the crossbeam and rotors can be lifted out of the water for inspection and maintenance. Apart from the powertrains, all the other systems are housed in a 'pod' on the top of the pile.

The machine is designed to produce 1MW of electricity when the water velocity is 2.8m/s. At lower water speeds it will produce correspondingly less electricity, roughly in proportion to the cube of the current velocity.

A further report conducted as part of scoping studies based upon the Seagen concept focussed on the potential future development of an array of tidal devices in Strangford Narrows provides further details of scaled up device performance [A3.17]. This has proved useful in enabling this study to perform similar operations as detailed in the following section. **It must be stressed that MCT have no plans for commercial development of their tidal current technology in the Strangford Narrows, and the Strangford cases study was included because of the requirement to include at least once case study for Northern Ireland, and to illustrate the range of potential environmental impacts.**

A3.4 The proposed array

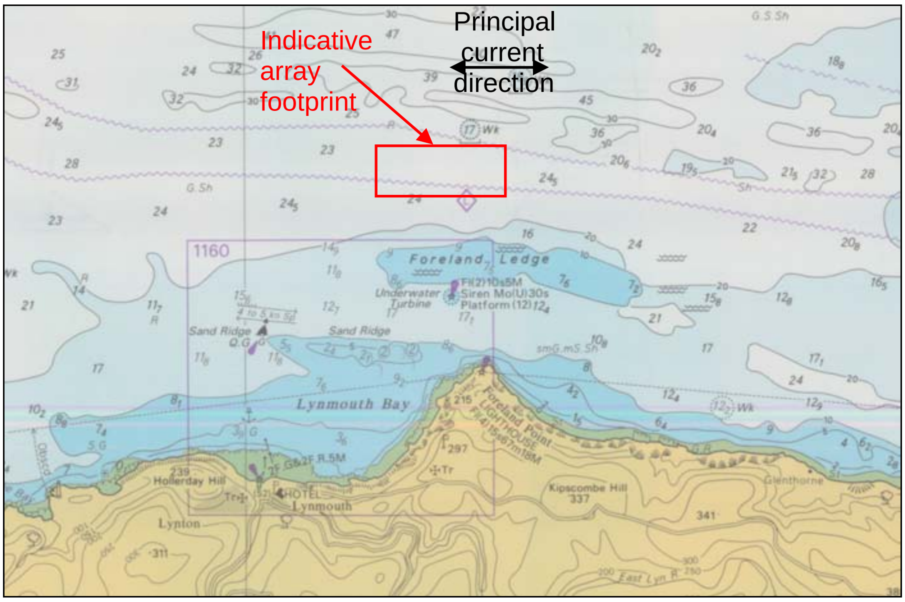
Given the lack of knowledge of the underlying tidal current resource it was considered prudent to select a comparatively small array size of 30MW. The size of the array is entirely arbitrary and should not be regarded as an upper limit.

This example of a tidal current array can provide an indicative measure of the energy capture and its cost. It can also be used to provide a general indication of this technology's energy density in the Bristol Channel (i.e. the kinetic energy generated per square kilometre).

The preferred site identified lies to the north of Foreland Point. Examination of the DTI Atlas of UK Marine Renewable Energy Resources: Atlas Pages [A3.11] informed exact placement of the array in the region.

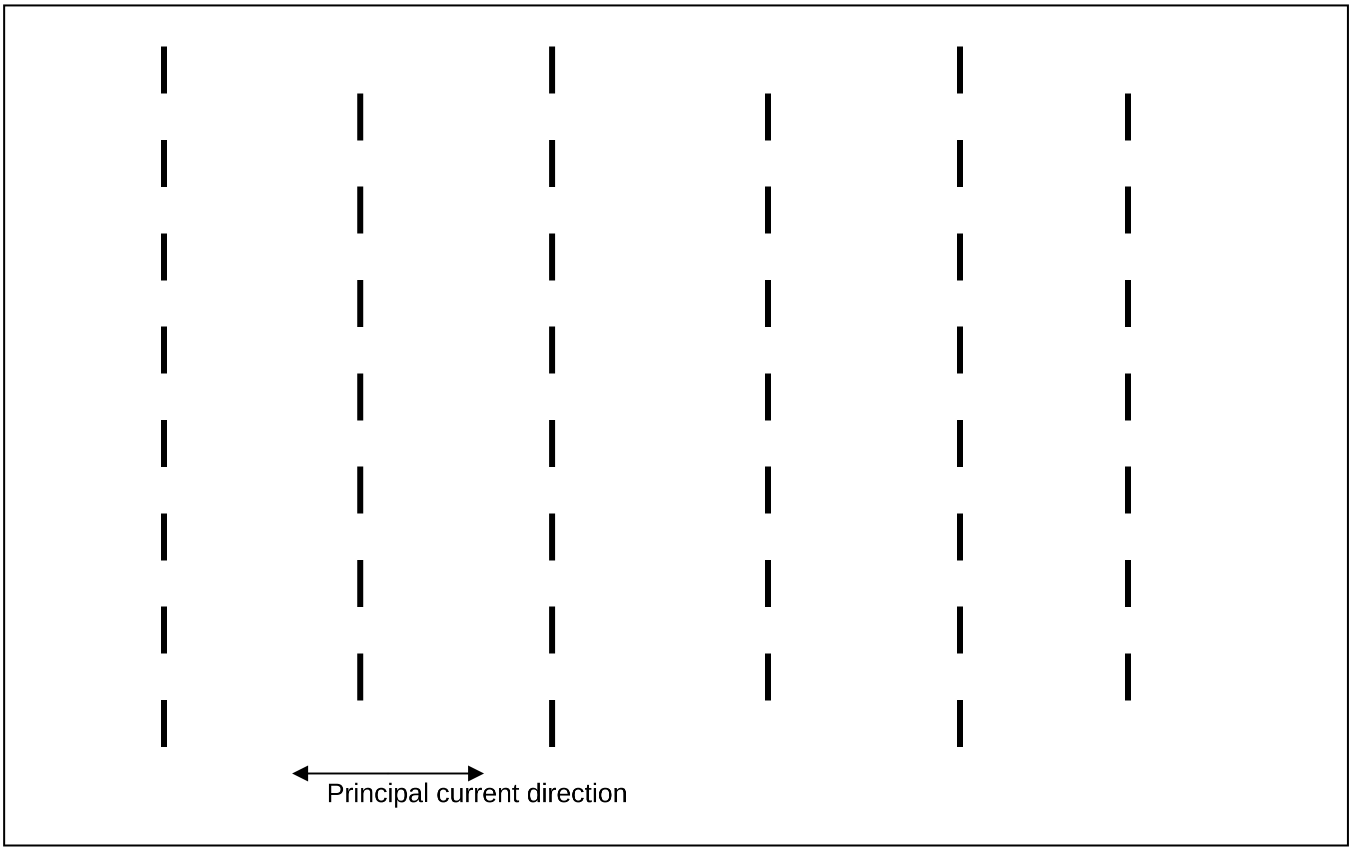
The array footprint is indicated on Figure A3.4. The shape of the footprint is constrained by the area of shallow water to the south known as the Foreland Ledge and a chasm to the north where the sea bed rapidly shelves away. A detailed bathymetric survey would be a pre-requisite of a more detailed analysis of the potential of the site for development as a TEC array location. The downstream extent of the array assumed that it would have an installed capacity of 30MW. The resource analysis in section A3.4.1 suggests the potential for a larger array by extension downstream. Achieving an effective balance between the increased energy production of each additional device in the array with the cumulative impact of energy extraction on the local resource would help to optimize the size of the array.

Figure A3.4 Foreland Point site (source: Admiralty Chart 1165, scale 1:75,000)



The width of a TEC device in this case study is taken as being 43 metres. The spacing between devices orientated in the direction of the flow is selected as one device width laterally and eight device widths in the downstream direction (344 metres). The devices are ‘staggered’, so the effective length between one device and the next device directly behind it is twelve device widths (688 metres). The preferred orientation of an array to maximise energy capture and minimise wake interactions is in a long line perpendicular to the dominant flow direction. However, this orientation is less economically efficient, as connecting all the devices to the local substation becomes more expensive. Work conducted at the Robert Gordon University has suggested that when there are more than 10 devices in the array, in terms of cable expense, it is advisable to group the devices in a rectangular area no more than 10 devices wide (private communication). At the Foreland Point site, the width of the array is constrained by the available region of suitable installation depths surrounding the identified primary location. The relative position of devices in the array is therefore as indicated in Figure A3.5, with three rows of eight devices interspersed with three rows of seven devices for a total of 45 installed Seagen-type devices. The length of the array is therefore 1,720 metres. It has been an iterative process to reach this conclusion, as the number of devices in the array required with an installed capacity of 30MW is dependent upon the installed capacity of the device, as determined in section A3.5. The lowest astronomical tide (LAT) in the region is + 0.9 metres above Chart Datum. Assuming a minimum clearance of 5 metres between the sea-bed and turbine swept area, for the purposes of this case study it will be assumed that the minimum acceptable depth of deployment for a 16 metre turbine is 24.5 metres. This provides 4.4 metres of clearance between the sea surface at LAT and turbine swept area.

Figure A3.5 Relative positions of the 45 666.1kW rated Seagen devices in the proposed array .



A3.4.1 Array effects

It is well understood that extracting energy from the tidal system will have some effect on the local flow conditions [A3.18, A3.19]. Understanding of these effects remains the subject of ongoing academic research and is as yet far from being fully developed, particularly the consideration of realistic array configurations. In order to provide some insight into the potential significance of array effects on the available resource, some simple generic numerical model experiments of a spring tide conditions were conducted. It is important to acknowledge the limitations of this idealised analysis, and to advise that the results are taken only as being indicative rather than definitive. Similar techniques used in the research reported in A3.18 and A3.19 are used to produce these idealised simulations. Output from the analysis is presented in Figures A3.6, A3.7 and A3.8. Figure A3.6 indicates the impact of array operation as observed at the centre of the array. Limited measurable impact is observed on surface elevations across the tidal cycle (less than 1 centimetre difference, and therefore not shown). Depth-averaged velocities however are measurably reduced by energy extraction from the array. Velocities at peak flood and ebb at the extraction location, in the middle of the array are reduced by about 6%. Although the reduction in available energy implied by Figure A3.6 is significant given the cubic relationship between velocity and kinetic energy, the impact on power production is less significant than may first be thought when considering the operational envelope of the extraction device in operation. For example, this case study is considering a device with a rated velocity of 2.0 m/s. In terms of energy harvested in this case, the reduction due to clipping of peak velocities by array performance would likely be of a similar magnitude to the velocity deficit.

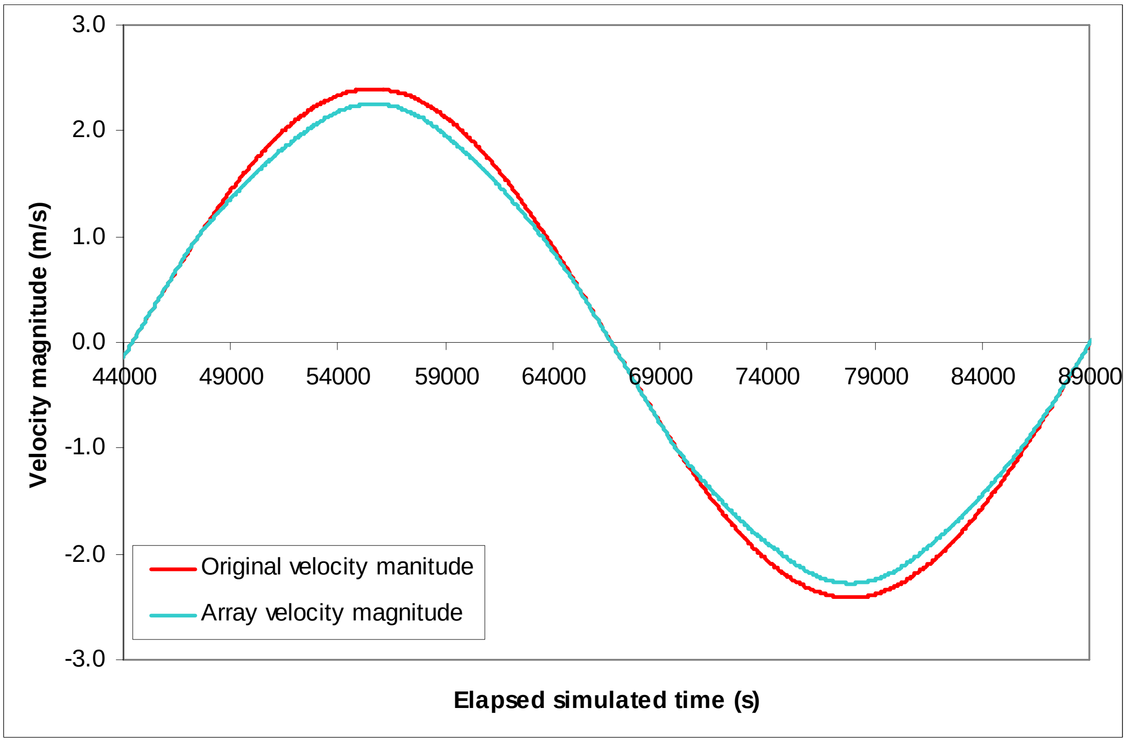
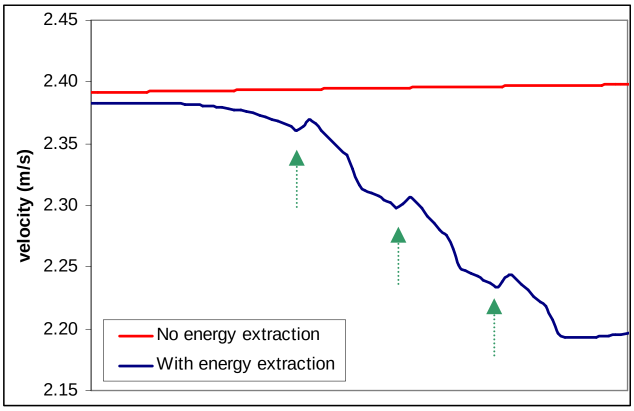


Figure A3.6 – Comparison of temporal variation of velocity conditions at the centre of the array location with and without energy extraction

The results presented in Figure A3.7 are stream-wise cross-sections taken through the centre of the model domain, which is coincident with the centre of the array (see Figures A3.5 and A3.8). Figure A3.8 indicates the residual velocities obtained across the array at spring peak tide conditions from array operation compared with the no extraction case. Results obtained for a flood tide are presented. Substantially the same results are obtained on an ebb tide, with the obvious difference that the stream-wise flow has reversed direction, and consequently the attenuating effects of energy extraction are also acting in the opposite direction.



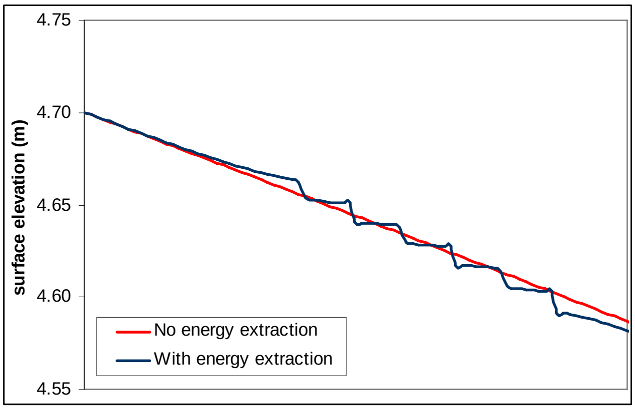


Figure A3.7 – Comparison along a stream-wise cross-section of flow properties at High Water for an equivalent spring peak tide (a) tidal current velocity, (b) surface elevation

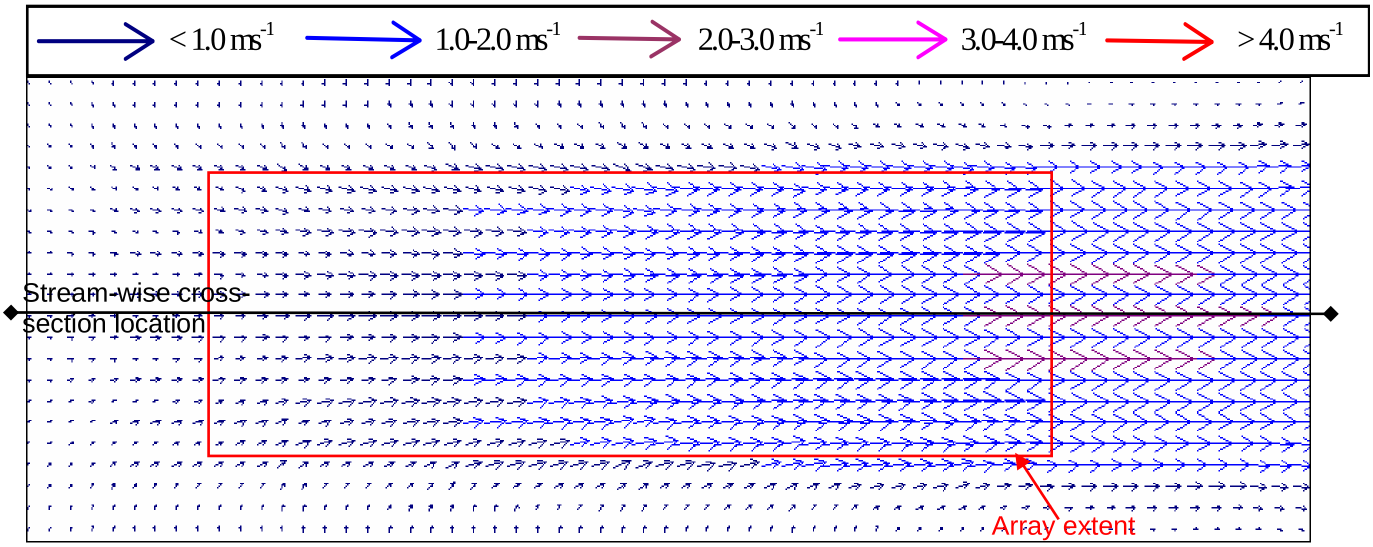


Figure A3.8: Modelled residual current velocity at High Water spring tide peak between no extraction and with extraction (i.e. with extraction result subtracted from the no extraction case) by the array outlined in Figure A3.4 in a highly idealised domain.

In summary, the results demonstrate that operation of the array has a very limited and localised impact on surface elevation and hence water depths. The major impact observed is on the flow velocities in the region of the array. It is clear that flow velocities across the array are progressively reduced as energy is extracted by each row of devices. The cumulative effects of this velocity retardation across the length of the array can be expected to reduce the flow velocity across the final row of tidal current devices in this 45 device array by approximately 9% during peak spring tide conditions. These findings are in-line with the existing literature on the subject.

It is not possible to reach any definitive conclusions on the impact of the array on the far-field flow due to constraints of the model employed. However, if the simplified generic domain was to continue far downstream, it is reasonable to assume that the slight reduction of surface elevation downstream of the array will promote a favouring pressure gradient toward the wake of the array and slowly redistribute or ‘recharge’ the flow velocity until an equilibrium position is reached. This equilibrium position would of course be at a reduced velocity from that observed upstream of the array. How much ‘recharge’ can be expected would be dependent upon the relative cross-sectional area of the array in comparison with the channel, estuary or open sea cross-sectional area that it occupies. At Foreland Point, the width of the Bristol Channel cross-section is significantly more than an order of magnitude larger than the width of the array, and therefore the far field effects are likely to be minimal. Energy extraction effects would in this case be limited to the vicinity of the array and immediately downstream (of the order of 2-3 kilometres if the typical effect of an island on flow development in the Firth is to be used as a benchmark).

A3.5 Energy output

This case study is extrapolating from one pre-commercialisation prototype device technology to a large energy production facility employing multiple devices. A realistic timeline would suggest that the existing Seagen prototype testing program at Strangford Narrows would be completed before any large-scale deployment. It is also realistic to expect that part of the development plan for tidal current device technologies would require the long term testing of multiple devices. The DTI Marine Renewable Deployment Fund (MRDF) program has been established to support this further stage of pre-commercial technology development [A3.20]. The MRDF is expected to offer support for up to seven years of TEC device operation. A realistic time-scale for the commercial development of farms of multiple TEC devices is likely to be several years away. It is therefore logical to assume that substantial technology development would continue during this period. This is factored into the analysis presented as enabling the deployment of a scaled-up version if deemed appropriate. This thinking follows the approach presented in a report for government by Marine Current Turbines Ltd. and associated partners [A3.17].

There are two simple mechanisms for tuning the installed capacity of a TEC device: either to alter the rated velocity, or alter the performance surface of the device by increasing or decreasing the swept area of the device by altering the diameter of the rotors. However, variation of either parameter has a big impact on the device design, and on tuning the device performance to the intended deployment site. For this analysis, a revised design from that proposed for Strangford Narrows [A3.17] is preferred. This was achieved by reducing the rated velocity to better fit with the local resource (see Table A3.2). It was necessary to adopt a particular value for the coefficient of performance (power output relative to the swept blade area and current velocity, see Glossary) of the device in order to conduct this analysis. Reverse engineering the data presented in the relevant literature it would appear that values of 0.221 and 0.404 have been variously adopted [A3.16, A3.17]. In order to enable comparison between this case study and the accompanying studies presented under Contract Report 5 [A3.20], a value of 0.404 was adopted. It is acknowledged that more in-depth analysis than was conducted to inform this case study would enable fine-tuning of device performance to local conditions. In particular, it has not been possible to take full account of the array effects detailed in the preceding section. Data from testing of a full-scale operational Seagen type device would also enable significant improvement in the reliability and veracity of the figures presented.

The proposed array has been identified as containing 45 installed devices, and the tidal current resource in the region has been characterised in section A3.2.2. Assuming that the generic Spring-Neap velocity variation in section A3.2.2 repeats throughout the year, it is possible to derive the total energy flux acting across the performance surface of a representative Seagen-type device intended for deployment at the site. Again, assuming that each of the devices installed has the same performance characteristics, the annual energy production from the farm of devices can be derived assuming 100% availability. The output from such an analysis is presented in Table A3.2. In practice there is potential that a range of devices would be deployed across the array. For instance, taking account of the array effects discussed in section A3.4.1, it is likely that devices with larger diameter rotors and a slightly reduced turbine rated velocity would provide the most efficient and therefore cost effective solution towards the centre of the array compared with the outer reaches of the array in the stream-wise direction. Without detailed analysis beyond the scope of this study it is not prudent to attempt to provide an exact best-fit solution for each individual device; as already highlighted, there is a large degree of uncertainty in the exact values of the resource and device performance characteristics.

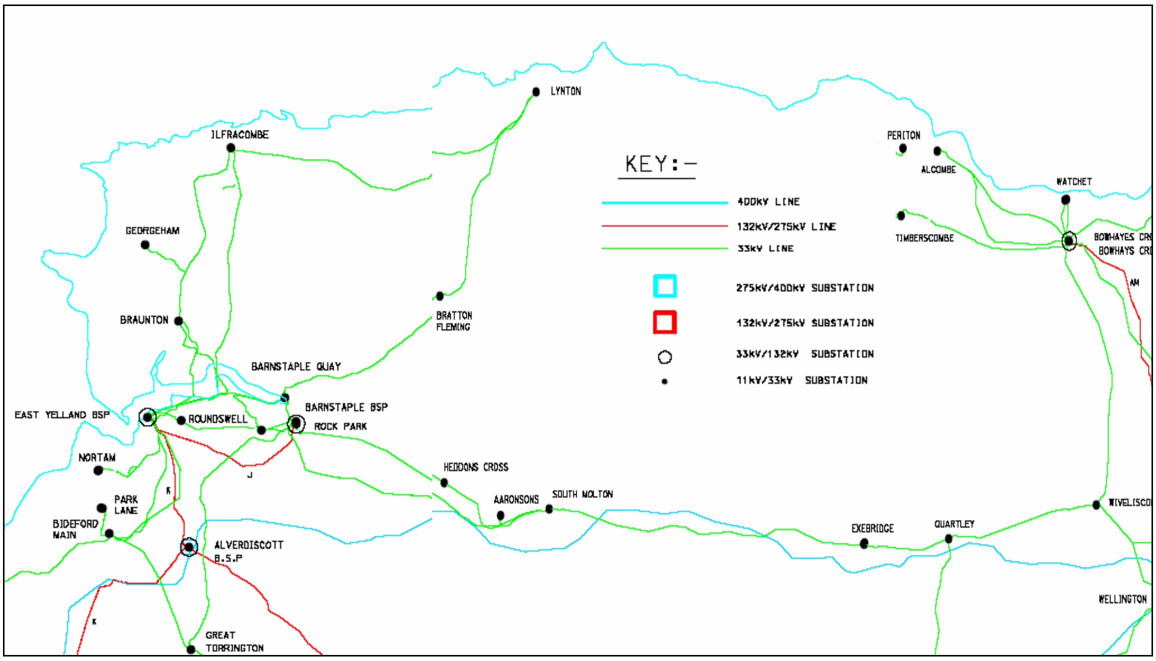
Table A3.2 Characteristics of the Seagen-type device and array proposed for deployment.

Number of rotors	2
Diameter of rotors (m)	16 m
Area of rotors (m^2)	402.124 m^2
Assumed density of water (kg/m^3)	1025 kg/m^3
Start up velocity (m/s)	0.75 m/s
Turbine rated velocity (m/s)	2.00 m/s
Device rated power at turbine rated velocity (kW)	666.1 kW
Number of devices in the array	45
Installed capacity of the array (MW)	29.975 MW
Coefficient of performance, Cp	0.404
Energy capture per year per device (GWh)	1.848 GWh
Nominal energy capture per year by the array (GWh)	83.16 GWh
Load factor of the array	31.67%

A3.6 Grid connection and electricity integration

It is suggested that for the 30MW Bristol Channel tidal farm case study, the following grid implications are considered.

Figure A3.8 Electricity network in the region of the Lynmouth (Source: Western Power Distribution [A3.22]).



A3.6.1 Offshore cabling

In conjunction with the findings of Granger and Jenkins [A3.23] and in the absence of proven 132 kV offshore transformers, a 33 kV system is suggested to link the individual TEC devices together (each TEC having their own 33kV transformer). Groups of TEC devices would be linked together, with two 33kV links to shore. It is suggested that both these cables would share the same route to shore to minimise cable laying costs. Cliffs predominate along the shoreline at Foreland Point. The first candidate option for bringing cables onshore would be directly into Lynmouth itself, perhaps adjacent to the harbour.

A3.6.2 Onshore cabling

It is unclear whether electricity produced by a 30MW installed capacity tidal array in North Devon could be utilised locally. If this was the case, it is likely that the only onshore cabling requirement would be to connect to the local 33kV network at Lynton. If it was necessary to provide provision of a link to the 132kV network, the nearest connections are either at Barnstaple, approximately 25 kilometres to the west, or alternatively at Bowhays Cross near Williton, approximately 36 kilometres to the east. This would then enable transmission across the whole of the south-west network.

A3.6.3 Costing

The following indicative costing only covers the sub sea cable that interconnects the tidal current array and links the array to shore, and a nominal 2 kilometres of onshore cable to link into the existing 33kV/11kV substation at Lynton. It is likely given the relative size of the proposed array that the majority of the energy produced would be used to service local electrical requirements.

The Scottish Executive [A3.24] suggests the "Technology Type Voltage (kV) Cost function (£/MW) Distance weighting costing method" as detailed in the following table.

Table A3.3 Grid connection cost functions [A3.24].

Technology	Type	Voltage (kV)	Cost function (£/MW)	Distance weighting
Onshore wind	MVAC HVAC	33 132 & 275	18,730 + d * 1.25 * 4,440 18,730 + d * 1.25 * 1,080	10 for water and natural heritage areas, 1 elsewhere
Offshore wind, tidal current	HVAC	132 & 275	47,630 + d * 1.25 * 3,250	1 for water and natural heritage areas, 0.3 elsewhere
Wave	HVDC	150 DC	162,360 + d * 1.25 * 540	1 everywhere

Table 4.8 Grid connection cost functions, in 2005 prices.

Similar cost functions also adopted for various renewable technologies have been presented [A3.25]. Using the offshore wind, tidal current calculations the following costing can be estimated

Table A3.4 Cable costings for the hypothetical Lynmouth case study

	Distance (kM)	Cost £/MW	Weighting	Total Cost
Land calculation	2	1672650	0.3	501795
Sub sea calculation	16.05	3384994	1	3384994
			Total £	**3,886,789**

Using the 'offshore wind, tidal current' calculation it can be seen from Table A3.4 that a total transmission infrastructure cost of £3.89 million is required to facilitate this development under the assumption that the proposed connection to the local 33kV grid infrastructure was suitable for this location. This would require more in-depth research and analysis to confirm if this was the case. Within the land calculation the 2km accounts for the new overhead lines from the shore landing point at Lynmouth to Lynton, whilst in the sub sea calculation the 16.05km accounts for two individual shore cables linking the multi circuit TEC array to the shore. It should be noted that no cost has been included to cover the possible upgrading requirement of the existing grid to support the input of an extra 30MW potential at that location.

A3.7 Unit cost of energy

Although indicative figures for grid integration have been presented, there remains a lack of evidence in the public domain upon which to base a reliable economic assessment of the cost of developing the hypothetical case study currently under discussion. In particular this relates to project development, tidal current technology production and device installation costs. It is likely that the development window for such a large energy production facility based upon a technology still at the pre-commercialisation stage is likely to be several years from today (assuming successful prototype testing). Even if reliable data were available relating to the present day cost of the technology, its future relevance would be questionable.

Furthermore, development in analogous industry sectors indicates that significant cost reductions can be expected through learning-by-doing and economies of scale once early full-scale prototypes reach the stage of mass production [A3.26].

A3.7.1 Capital cost

The turbines used in this hypothetical case study are similar to MCT's Seagen demonstrator. They have the same diameter rotors and are deployed in the same depth of water. The only difference is that for this location the turbines have been given a lower "rated capacity". This means that a smaller gearbox and electrical generator is used, which saves some capital cost at the expense of sacrificing some generation.

There is very limited published data on the capital cost of specific tidal current technologies. The only cost which relates to a specific device is MCT's Seagen demonstrator project (£8.6M). However, this sum includes design and development costs as well as the capital cost of equipment. It is therefore difficult to make accurate projections of the future cost of this technology based on the cost of a demonstrator project.

It is anticipated that as the technology advances from a single demonstration device to progressively larger arrays there would be a corresponding decrease in the capital cost per unit of installed capacity achieved through a combination of innovation, economies of scale and from experience. However, the actual cost of the technology and the ability to achieve cost reductions is not presently known with confidence. For these reasons it is appropriate to include a range of costs to reflect this uncertainty. We have assumed an upper bound of ~£6,000/kW [A3.27]. It must be stressed that this capital cost is based on the first single full-scale demonstrator device. We have therefore assumed that as the technology is developed progressive reductions in capital cost could be achieved down to a lower limit of £1,000/kW installed.

A3.7.2 Construction Time

There is very little information to rely on to inform a decision on how long construction of a large TEC device array will take. Our assumption is that the construction would be completed in 2 years. Spend in the first year is assumed to equate to 80% of the complete project cost, with the other 20% of capital expenditure occurring in the second year of construction. There is no obvious reason to choose these or any other particular figure directly relevant to TEC project development other than that they seem reasonable.

A3.7.3 Operating costs

No information is available on the operating and maintenance (O&M) cost of a tidal current array. We have therefore assumed that the annual O&M cost is 4% of the capital cost of the project. This is towards the lower end of the range usually assumed for marine energy projects. In this case the array lies relatively close to shore, and is partially sheltered from extreme weather events compared with an open sea location. However the prevailing wind and hence wave direction is from the south-west, which matches the orientation of the Bristol Channel.

A3.7.4 Plant lifetime

There is limited data on which to base an estimate of the expected lifetime of such a plant. A plant lifetime of 20 years has been assumed as this is typically assumed in technical and economic studies of marine energy projects.

A3.7.5 Decommissioning

Little or no discussion of decommissioning strategies for marine renewable technologies lies in the public domain. As this particular site has been identified as a primary location within the Bristol Channel for deployment of tidal current devices, it is likely that the site would be redeveloped at the end of the plant lifetime by replacement of the devices with potentially more efficient and modern counterparts. A significant amount of the infrastructure and original development costs would therefore have a beneficial 'legacy' effect for a follow-up program at the site.

It remains unclear what would be the most cost and emissions effective arrangement for decommissioning of individual devices which have reached the end of their design life. It is likely that the standard approach would be for the devices to be salvaged, recycled or reused as deemed appropriate.

Initial investigation suggests that decommissioning costs for marine technologies could vary from as little as £25,000/MW to as much as £100,000/MW [A3.28]. It is possible that decommissioning costs will fall as the technology becomes established and with economies of scale following the development of large arrays. Technical expertise developed from the offshore oil and gas industry could be used effectively for this type of marine technology [A3.28]. However, by their very nature marine current devices are deployed in regions with powerful currents which would limit recovery to specific seasons and times of the day. The review has identified that the most difficult and expensive stage of decommissioning is the removal of the foundation, especially for monopiles. Only 1-2 m of the pile would need to be removed from below the sea bed if the monopile were embedded in hard rock. However, piles emplaced in soft sediment may require removal of up to 10 m below the sea bed because of the potential for sediments to shift with time.

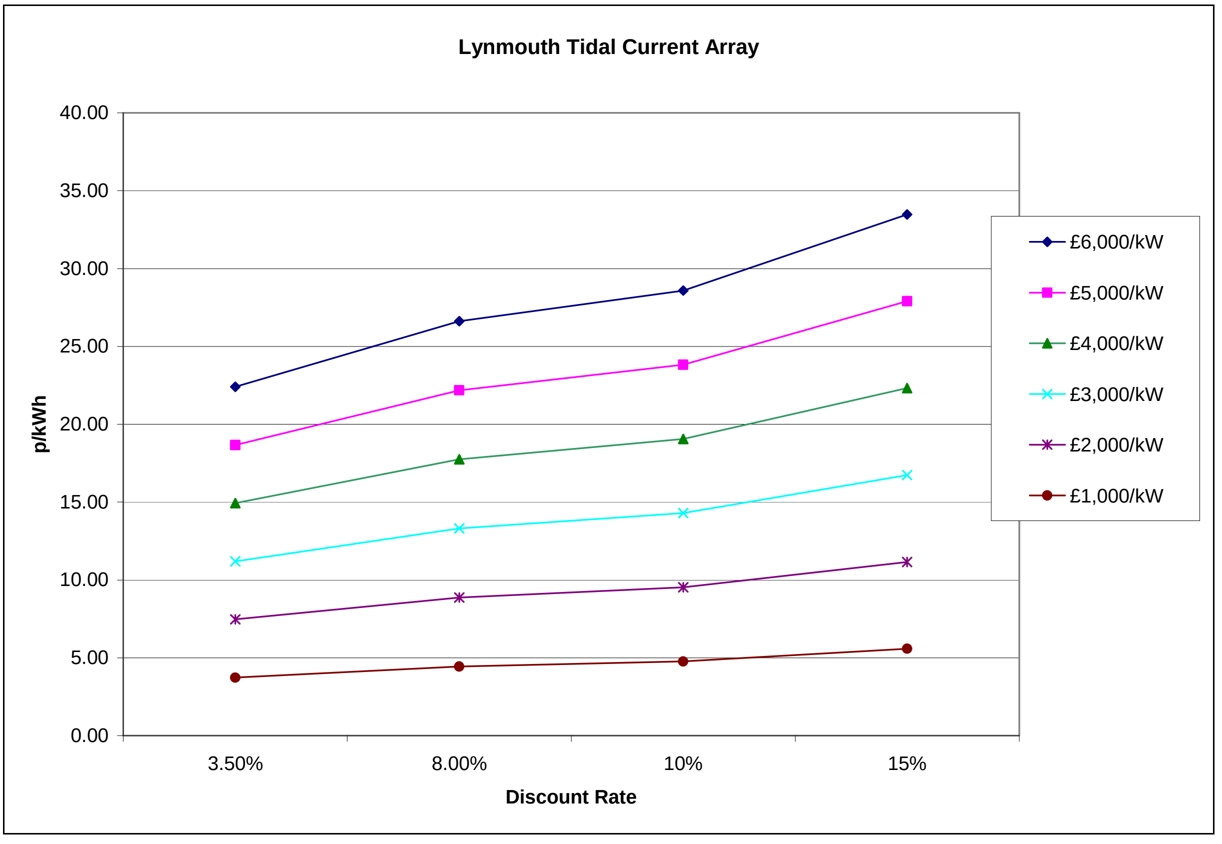
A3.7.6 Unit cost of energy

The unit cost of energy has been calculated using a discount cash flow analysis over a technical life of 20 years (see Appendix 5). Because of the uncertainty and lack of technology specific information on capital cost we have assumed a range of between £6,000/kW installed and £1,000/kW installed. We have assumed in each case that operation and maintenance costs would be 4% of the capital cost. The unit cost of generation over a range of discount rates is shown in Table A3.5 and graphically in Figure A3.9.

Table A3.5 Unit cost of generation relative to capital cost and discount rate for the Lynmouth hypothetical tidal current array

Discount rate →	3.50%	8.00%	10%	15%	
Unit cost per kW installed					
£6000/kW	22.40	26.63	28.59	33.48	p/kWh
£5000/kW	18.67	22.19	23.82	27.90	p/kWh
£4000/kW	14.93	17.75	19.06	22.32	p/kWh
£3000/kW	11.20	13.31	14.29	16.74	p/kWh
£2000/kW	7.47	8.88	9.53	11.16	p/kWh
£1000/kW	3.73	4.44	4.76	5.58	p/kWh

Figure A3.9 Unit cost of generation relative to capital cost and discount rate for the Lynmouth hypothetical tidal current array.



Two technology assessments commissioned by the Carbon Trust have estimated projected future costs for tidal current technology [A3.29, A3.30]. These assessments were based on four different device concepts. Projections of future costs were based on a numerical model to calculate costs and energy capture performance. Cost projections in the numerical analysis have also factored in the benefits gained from experience. The results of this analysis suggests that the unit cost of generation for sites with a mean spring peak (msp) velocity of <2.5m/s could range from 5.5 – 9.0 p/kWh at an 8% discount rate and as low as 3.0 p/kWh for sites with msp velocities >4.5m/sec. These projections suggest that an array in an area with a msp of <2.5m/s would cost <£2,000/kW installed. We are, however, unable to verify the assumptions and calculations used in the Carbon Trust studies.

It must be stressed that there are considerable uncertainties in the development of this technology which will need to be resolved through initial demonstration and deployment before the extent of cost reduction can be accurately predicted.

A3.8 Embedded carbon analysis

The only detailed figure for the mass of any part of the Seagen machine refers to the pile, which is stated as 270 tonnes [A3.31]. Based on the dimensions shown in Figure A3.3 above, the volume and hence the mass of the other components of the machine can be estimated. On this basis one turbine contains approximately 366 tonnes of steel and 2.35 tonnes of copper implying an embedded carbon figure of 645 tonnes of CO_2. Consequently the array of 45 devices would have a total embedded carbon of $645 \times 45 = 29,025$ tonnes of CO_2.

Assuming the array generated 83.16 GWh/year the scheme would save 35,759 tonnes of CO_2 per year assuming 430 kg CO_2/MWh (i.e. the average CO_2 /MWh from the current UK generation mix). The scheme would save 715,176 tonnes of CO_2 assuming consistent energy output over a 20 year technical life. The scheme would achieve a carbon payback of 9 months.

Table A3.6 Lynmouth tidal current array embedded carbon

Material	**Embedded carbon**
Total mass of steel (te)	16,470
Total mass of copper (te	105.75
Estimated embedded CO_2 (tonnes)	
Minimum	27,045
Maximum	29,025
GWh/y	83.16
CO2/year displaced (te/GWh)	35,759
CO2 saved over life of the scheme (te)	715,176
Carbon payback minimum (months)	9.5
Carbon payback maximum (months)	10

A3.9 Regional & social benefits

A3.9.1 Local employment

The proposed TEC array development would create significant employment opportunities in the manufacture of the devices; however it is unlikely that these would be located in the local area and are more likely to involve centralised manufacture elsewhere.

There will, however, be the possibility of local employment during the construction phase. It is also realistic to assume that a component of ongoing O&M operations during the operational life of the project would provide local employment and economic benefit. It should be noted that there is a lack of evidence related to the issue of local employment generation.

A3.9.2 Community benefit

It is unclear what the position would be with regard to whether there would be an adoption of the onshore wind model of community payments for offshore tidal power projects. The npower North Hoyle offshore wind farm has set up a community fund as part of this project. Given differences in the maturity of the two technologies, it may be some time before the economics of tidal current array projects could facilitate this type of local payment.

Local payments are an incentive to gain local acceptance for a project in their area. As there are significant differences in the visual impact of tidal current devices compared to wind turbines, it is unclear if this model will transfer and if community acceptability is significant to the success of a project. However, it is possible that some local incentive might be required where there was direct negative impact on other users of the sea space, such as fishing, shipping and leisure craft.

A3.9.3 Port availability

Although there are numerous small harbours in close proximity to the location proposed along the Devon coast, within the confines of this hypothetical case study, none of those identified is deemed suitable for use during deployment or major maintenance operations for the proposed array. It is likely that the most suitable nearby ports worth utilising, particularly during the installation / construction phase, will be located in South Wales. Port Talbot, for instance, is a major port with appropriate heavy duty facilities in place located 35 kilometres from the identified array location.

The utilisation of local port facilities during the installation and operational phases of the tidal current arraym would help facilitate some direct economic benefit to the area.

A3.10 Environmental Issues

The environmental impacts associated with this scheme are summarised in Table A3.7.

Lynmouth is situated within the Exmoor and North Devon High Coast, a relatively narrow coastal fringe along the northernmost coast of Devon adjacent to Exmoor National Park. The coastline around the proposed tidal array site is sparsely populated with the main means of income being agriculture and tourism [A3.32].

The environmental impact of a tidal current array on this scale is likely to be limited to the immediate area of the devices. Although the area is dominated by strong tidal flows there will be some loss of energy in the currents immediately downstream of the array. This could lead to some changes in sediment deposition. The extent of the change will depend on the interaction between the modified hydrodynamic regime within the vicinity of the array and the conditions in the surrounding sea including storms. There are benthic communities which could be affected by these changes although the surrounding area should stabilise once the array becomes operational. The extent of these changes would need to be carefully assessed, firstly by surveying the area, and then secondly modelling the anticipated changes.

The use of monopiles will require drilling cylindrical foundations into the bedrock. It is assumed that the rock cuttings (crushed fragments of rock generated by drilling) will be retained and transported from each drill site. There will be some disturbance in the form of vibration and noise during the construction phase. Provided caution is exercised during construction and installation emissions should be kept to a minimum.

Once the array is operational there is the potential for collision risk with marine mammals and fish although the level of risk is unknown.

The array will be visible from the North Devon coast, particularly from the cliffs above Lynmouth. However, an array of monopiles is unlikely to have a dramatic visual impact because of the narrow sub-aerial profile. Nevertheless the developers should be expected to demonstrate what an array should look like from vantage points in different climatic conditions.

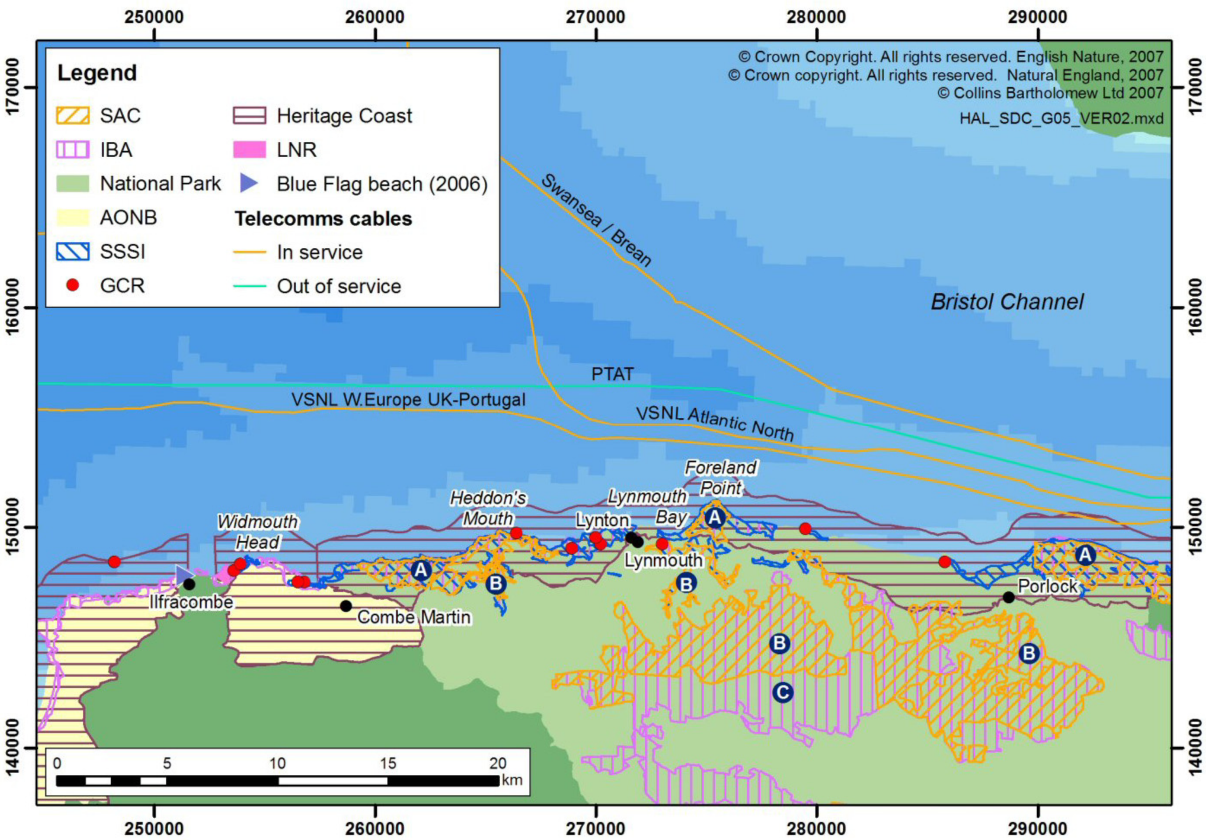
A3.10.1 Summary of key environmental sensitivities/constraints

Table A3.7 – Summary of key environmental sensitivities/constraints

Feature	Summary	Potential adverse factors
Seabed sediment and transport processes	• Coastal sediments consist of sandy gravel becoming gravel further offshore. Beyond 30m depth, the seabed tends to gravelly mud. In general, sediment cover thins eastwards as tidal currents speeds increase. • Seabed on the site generally hard and featureless [A3.33]. Mobile sand ridges, waves and ridges also present. • Strong tidal currents in combination with winter storm conditions may transport gravel sediments [A3.34]. • Net drift of sediment eastwards along the coast towards Bridgewater Bay.	• Physical disruption to tidal flows may affect sediment transport.
Hydrology	• Peak flow for a mean spring tide is about 2m/s [A3.35]. • Between ebb and flood, tidal currents move water large distances (10-22km) up and down the Channel [A3.36]. • The mean spring and neap ranges are 8.7m and 3.7m respectively. • Annual mean significant wave height is 1.4-1.6m [A3.35].	• Disruption of tidal flows, levels of vertical mixing and light penetration, salinity
Water quality	• Exmoor National Park identifies water quality along the Exmoor Coast as 'moderate' [A3.34]. • Lynmouth Bay has received EC Mandatory Pass under the Bathing Water Directive (76/160/EC). However there are concerns about other bathing waters along the coast meeting the required standards.	• Pollution during construction • Disruption of tidal flows may allow accumulation of contaminants..
Landscape/seascape	• Landscape character types include: Cliffs and shorelines, coastal moor and heathland, mature woodland on steep slopes, farmed landscapes on gentle slopes, and archaeological interest [A3.33]. • Protected landscapes include the Exmoor National Park, North Devon AONB and the Heritage Coast designation. • Unspoiled landscape/seascape important factor for the local tourism industry. • Seascape features include the cliffs and shoreline. Lynmouth Bay is framed by the cliffs of Foreland Point and the wooded slopes of Lynmouth and Hollerday Hill.	• Visual intrusion • Noise • Change to landscape/seascape character • Effects on tourism due to development
Coastal habitats	• The coastline is a designated protection zone under the Exmoor LBAP and priority habitats include vegetated sea cliffs and lowland heath which dominate this stretch of coastline [A3.37]. • Most of the coast is within the Exmoor Coastal Heaths	• Physical disruption to tidal flows may affect sediment transport and rocky shore species assemblage.

Feature	**Summary**	**Potential adverse factors**
	and West Exmoor Coast and Woods SSSI. • The steep-sided combes and coastal slopes of Exmoor still support large expanses of ancient woodland.	
Intertidal and subtidal habitats and communities	• Much of the subtidal seabed comprises bare rock subjected to strong tidal scour with areas of sand/gravel closer inshore. • Reduced species diversity occurs on this rocky habitat and typical associated species include polychaetes such as *Typosyllis armillaris, Eulalia tripunctata, Sabellaria alveolata* and *S. spinulosa* [A3.34]. • Both *Sabellaria* species listed as priority species on the Exmoor LBAP. • Other important species include mussels *Mytilus edulis,* barnacles *Balanus crenatus,* encrusting bryozoans and porcelain crabs *Pisidia longicornis.* • Intertidal characterised by a gentle slope with small boulders, pebbles and kelp forest. • Unusual feature for Lynmouth Bay is the abundance of *Radicilingua thysanorhizans*. [A3.34].	• Habitat loss/quality shift • Physical disturbance • Increased turbidity or smothering from construction • Changes in species composition
Plankton	• Plankton in the area is influenced by high levels of mixing in the water column associated with strong tidal flows	• Changes in plankton productivity/community associated with changes in tidal mixing
Fish and shellfish	• Species of conservation interest recorded in the area: sturgeon, sea lamprey, allis and twaite shad (BAP priority species), sand and common gobies, and basking shark [A3.34] • Provides nursery areas for: whiting, plaice and sole [A3.38]. • Sprats widely distributed throughout shallow inshore area, and juveniles often found mixed with juvenile herring. • Lynmouth Bay is a potential migration route for salmon and sea trout returning to the East Lyn River. • Lobsters distributed inshore on exposed or rocky shorelines. Edible crabs and spider crabs uncommon off Lynmouth.	• Physical disturbance to spawning ground • Collision risk • Noise
Birds	• Seabird vulnerability is high all year round in Lynmouth Bay [A3.39]. • Small numbers of seabirds breed on the cliffs at Foreland Point including: fulmar *Fulmarus glacialis*, cormorant *Phalacrocorax carbo*, razorbill *Alca torda*, guillemot *Uria aalge*, and gannet *Morus bassanus*. • Majority of seabird activity on the water takes place in relatively sheltered inshore waters, away from the main Bristol Channel [A3.33].	• Collision risk • Disturbance during construction and maintenance • Attraction of birds to lit structures (if surface piercing structures used)
Marine mammals	• Bottlenose dolphins *Tursiops truncatus,* common dolphin *Delphinus delphis, and* harbour porpoise *Phocoena phocoena* are sighted in coastal and nearshore waters during July to October, with some animals' present near shore all year round [A3.40]. • The area around Lynmouth is not significant for seals. A colony of 60-70 grey seals is found at Lundy Island.	• Collision risk • Noise

Figure A3.10 – Conservation sites and other key features



Notes: Letters refer to sites described in Table A3.10.2

A3.10.2 Conservation sites and other key environmental sensitivities

A number of international and national conservation sites can be found along the coastline around the proposed tidal area. Table A3.8 provides an overview of these sites and lists the qualifying species of the Special Areas of Conservation (SAC) and IBA (Important Bird Area).

Table A3.8 – Nature conservation sites of international importance

Map ref	Site	Area (ha)	Key features
A	Exmoor & Quantock Oakwoods (SAC)	1,895.2	Old sessile oak woods with *Ilex* and *Blechnum* in the British Isles, alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (Alno-Padion, *Alnion incanae*, *Salicion albae*), barbastelle bat, Bechstein`s bat, otter.
B	Exmoor Heaths (SAC)	10,705.9	Northern Atlantic wet heaths with *Erica tetralix*, European dry heaths, vegetated sea cliffs of the Atlantic and Baltic coasts, blanket bogs, alkaline fens, old sessile oak woods with *Ilex* and *Blechnum* in the British Isles

Map ref	Site	Area (ha)	Key features
C	Exmoor Coast & Heaths (IBA)	24,300	*Breeding:* Eurasian nightjar *Caprimulgus europaeus,* whinchat *Saxicola rubetra* *Resident:* Peregrine falcon *Falco peregrinus,* common stonechat *Saxicola torquata*

Source: JNCC Website, IBA website.

The coastline in the vicinity of the proposed tidal array site between Ilfracombe and Porlock also includes a number of nature conservation sites and landscape designations of national importance. The area lies within the North Devon Area of Outstanding Natural Beauty, due to its maritime cliffs and slopes as well as lowland heathland. The Heritage Coast covering the area with its unique rounded 'hogs-back' cliffs (at their grandest near Combe Martin) is part of, and managed within, the Exmoor National Park. The coastline, with the exception of the developed areas of Ilfracombe, Combe Martin and Lynton/Lynmouth is designated by Devon County Council as a Coastal Preservation Area [A3.32]. In addition, the coastline is the subject of local biodiversity action plans (LBAPs) which contribute to national biodiversity action plans (BAPs). Of special interest in the area are the maritime cliffs and slopes, lowland heathlands, and woodlands.

The area also contains eight Sites of Special Scientific Interest (SSSIs), designated for a variety of habitats and species. There is a North Devon Voluntary Marine Conservation Area along the coast from Woolacombe to Hangman Point [A3.41]. This is a community imitative administered by Devon Wildlife Trust. The area also contains 12 Geological Conservation Review (GCRs) sites.

A3.10.3 Other uses/users/impacts

The coastline around the proposed tidal array site is sparsely populated with the main income being from agriculture and tourism [A3.32]. Tourism is a very important contributor to the Devon and Somerset economies, focussed around traditional seaside resorts, and landscape features. Main activities include recreational angling, sailing and other watersports and wildlife watching. Both Lynmouth and Lynton are highly dependent on tourism, which currently comprises approximately 50% of the local economy [A3.33].

Within the Exmoor National Park area the sea fishing industry is very small and confined to Lynmouth. Both boats and catches are small but the catches are of relatively high value, concentrating on shellfish. The channel around Lynmouth is used by a small number of vessels with the majority of larger craft using the area to the north of the proposed tidal array [A3.34]. There are no significant ports in the region but small harbours are found at Lynmouth, Porlock Weir and Combe Martin. Once important for coastal trade, their primary use now is for pleasure sailing and fishing [A3.42]. These pursuits are unlikely to be affected by a tidal current development on this scale, although for safety reasons an exclusion zone is likely to be required. The array would have the affect of forming a fisheries exclusion zone possibly allowing an increase in local fish stocks.

There are no proposed offshore windfarms around the Lynmouth Bay area. However the area is of interest to tidal arrays [A3.43]. There are currently no licences to extract aggregates from Lynmouth Bay and the closest aggregate extraction site is 50km to the north. In addition, there are no oil and gas exploration or production interests in the Bristol Channel. There is no known military activity in the area.

While the coastline along the Severn Estuary is famous for its archaeological interest, the area between Ilfracombe and Porlock itself has only a very limited number of archaeological sites. There are Roman finds near Ilfracombe, two Saxon and medieval sites in Somerset at Gore Point and Porlock, as well as one post-medieval intertidal fishing structure close to Lynmouth [A3.44]. There are no marked wrecks within the study area.

Several subsea cables are laid in the area: Brean to Swansea, TGN Atlantic North, TGN UK-Portugal, and the redundant PTAT [A3.45].

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Appendix 4
Energy Generation Modes for Tidal Energy barrages and Lagoons

Tidal barrages or lagoons can be designed to operate in various modes (Figure A4.1). These are:

- *Ebb generation*, in which the direction of the flow of water during power generation is the same as the ebb tide, i.e. towards the sea

- *Flood generation*, in which the direction of the flow of water during power generation is the same as the flood tide, i.e. from the sea towards the enclosed basin

- *Ebb generation plus flood pumping*, which is a variation on ebb generation, with additional water being pumped from the sea into the basin, at or soon after high tide, by running the turbines in reverse (Figure A4.2).

- *Two-way generation*, where power is generated during both flood and ebb tides.

- *Two-basin schemes*, in which two adjacent basins are formed and equipped with sluices and turbines. The storage available within the two basins, and the increased control of the water movement, allows the turbines to operate for longer than in single basin schemes. For small turbines, continuous operation is possible.

The third of these, ebb generation with flood pumping, has been identified as the most appropriate for potential UK tidal barrage schemes. This decision has been influenced by operating experience from the Rance tidal energy scheme in France, which has been in operation since the 1960s. The Rance scheme is equipped with machines that were designed to operate as turbines and pumps in two directions. Experience has shown that the reverse turbine and reverse pump modes (from the basin to the sea) offer negligible energy benefit, whereas annual net gains from flood pumping of 11% have been achieved. Since the construction of the Rance scheme, significant advances have been made in the design of low head water turbines. Furthermore, restricting the turbine operation to only two of the four possible operating regimes would avoid a compromised design and lead to an overall improvement in performance.

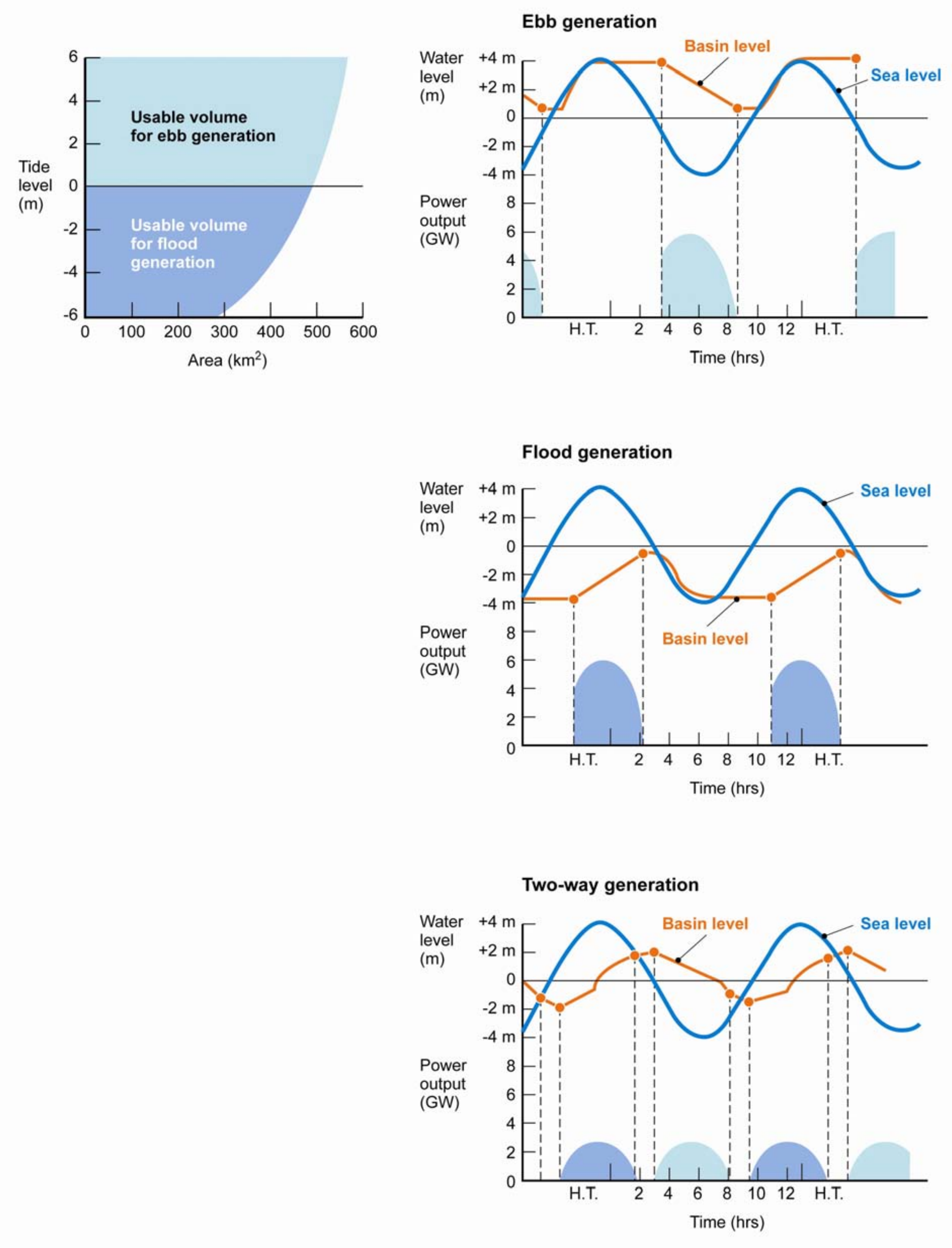

Figure A4.1 Energy generation modes for tidal energy barrages and lagoons.

Ebb generation plus flood pumping

A tidal barrage or lagoon would operate in a four stage sequential cycle:

1. The basin is allowed to fill during the flood tide through open sluices.

2. The sluice gates are closed when the levels on the basin and seaward sides of the barrage are equal, thereby holding the water in the basin until the optimum time to begin generation has been reached.

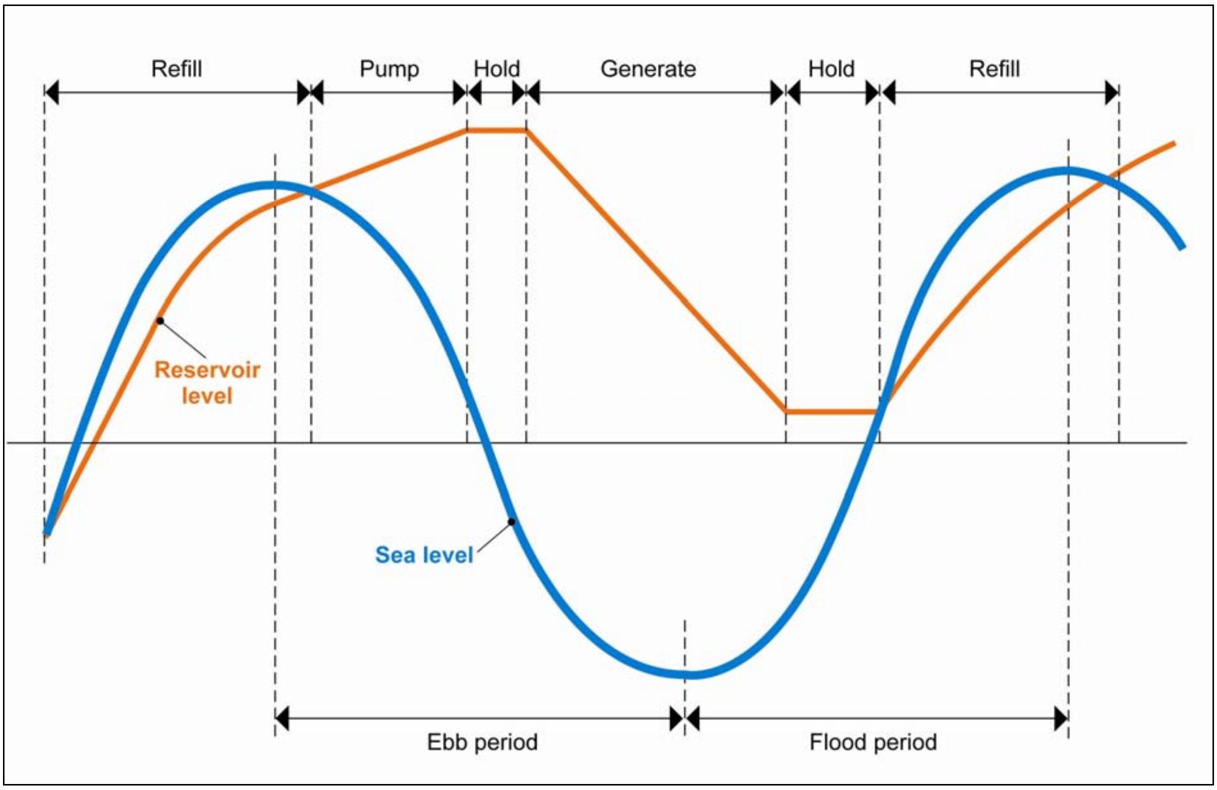

Figure A4.2 Energy generation for tidal energy barrages or lagoons using ebb generation in combination with flood pumping.

3. At the optimum time, generation is initiated by allowing water to pass through the turbines from the basin to the sea until the tide turns and rises to reduce the head to a minimum operating point.

4. The turbines are shut down when the net power output from the barrage system has reached this point. The sluices are reopened and the first step is repeated when the tide rises to a sufficient level.

Ebb generation with flood pumping is a modification of this mode which has been favoured by UK developers because of the ability to increase energy output. Using the turbines in reverse as pumps at or near high water, the basin level, and hence the generating head, can be raised. The energy required for pumping must be imported but, since the pumping is carried out against a small head at high tide and the same water is released later though the turbine at a greater head, this can produce a net energy gain with some limited ability to re-time output. UK studies on a number of tidal energy schemes indicate that the energy gain through pumping could be small but useful in the range 3-13% [A4.1, A4.2]. This method of operation also offers additional control of the basin water level, which has benefits for the estuarine environment and shipping. Figure A4.2 illustrates this mode of operation and the effect on water levels and energy output.

A4.1 References

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Appendix 5
Methodology for calculating the unit cost of energy

The unit cost of energy for tidal, or any other power plant, is the value of energy, expressed as p/kWh, that would be required to repay for the capital investment in the power plant. The methodology relies on a discounted cash flow over the technical life of project. In the case of barrages and lagoons a technical life of 120 years has been assumed with replacement of turbines and generators at 40 year intervals. For a tidal current array a technical life of 20 years has been assumed. The methodology also assumes an annual operation and maintenance or running cost which must be included for each year of operation. For renewable energy schemes the energy is free.

A Discounted cash flow (DCF) analysis uses future free cash flow projections and discounts them (most often using the weighted average cost of capital) to arrive at a present value, which is used to evaluate the potential for investment. The analysis in this study takes no account of taxation, inflation or profit and should be regarded as a simplified method to indicate the value of energy for a specific scheme in present day values. The discounted cash flow can be calculated using the following equation where n equals the number of years that the scheme is in operation. The energy that is generated each year is also discounted using the same methodology and over the same number of years. The unit cost of energy is the sum of the discounted cash flow divided by the sum of the discounted energy.

Calculated as:

$$DCF = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \ldots + \frac{CF_n}{(1+r)^n}$$

CF = Cash Flow

r = discount rate (WACC)

The unit cost of energy has been calculated using four different discount rates to reflect variable investment conditions that could be applied.

The methodology used in this study has assumed an average annual energy output for each year of operation. This should be regarded as a simplification. In reality the energy output of tidal energy schemes (barrages, Lagoons or tidal current devices) will fluctuate through a 18.6 year cycle caused by the variations in the astronomical configuration of the earth and moon with the sun. Artificial basins created to generate tidal power will also accumulate sediment reducing the volume of water within the impounded basin reducing the amount of energy. The rate of sediment accumulation and energy loss will depend on site-specific conditions.

Appendix 6
Methodology for estimating embedded carbon

The tidal energy generation system emits carbon dioxide indirectly during non-operational phases of the lifecycle other than energy generation. This 'embedded carbon' is the carbon dioxide emitted indirectly during the production of materials and construction of the project (decommissioning was not assessed).

Production

The carbon dioxide produced during the extraction and production of materials used to construct the tidal barrage, lagoon or tidal current projects are calculated by multiplying to total amount of the material (in this analysis the amount of steel, concrete and copper was obtained) by a carbon conversion factor. Table A3.1 shows the carbon conversion factors apply for these materials. Where more than one factor was obtained a high and low scenario was undertaken applying the maximum and minimum factor respectively.

Table A6.1 carbon emissions associated with primary construction, component and electrical materials

	min	max	
Concrete	0.2	0.374	t CO_2/m^3
Steel	1.63	1.75	t CO_2/tonne
Copper	1.652	1.652	t CO_2/tonne

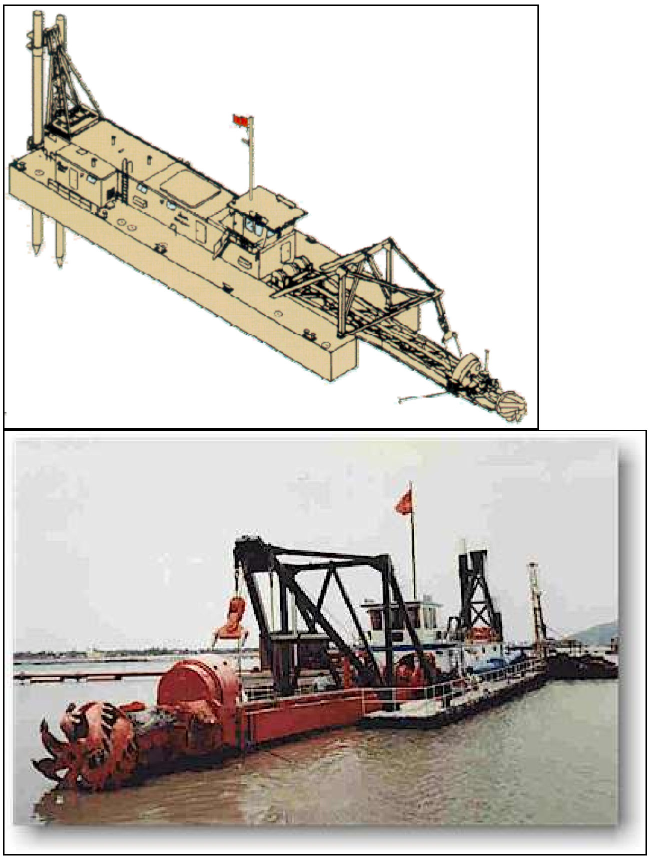
Construction

The amount of energy required to operate the pumps during the dredging of material (e.g. sand, mud gravel etc) from the site was estimated. The calculation was based on details of a dredger manufactured by the American company Ellicott (see www.dredge.com). This company was selected purely because it has published a great deal of technical data on its website that are relevant to this calculation. The choice is not intended to imply that this company's products are more or less suitable to this particular task than any other company's.

This company manufactures a wide range of dredgers. The model 4170 Series "Super-Dragon" was selected as being the most appropriate for this application. This is a portable heavy-duty dredger that discharges the dredged material via a 24" or 27" (609-686 mm) discharge pipeline. It has a centrifugal pump powered by a 2MW diesel engine capable of a pumping rate in the range 306-1830 m3/hr depending on the material being pumped and the length of the pipeline thorough which it must be pumped.

Figure A6.1 shows the configuration and layout of this dredger.

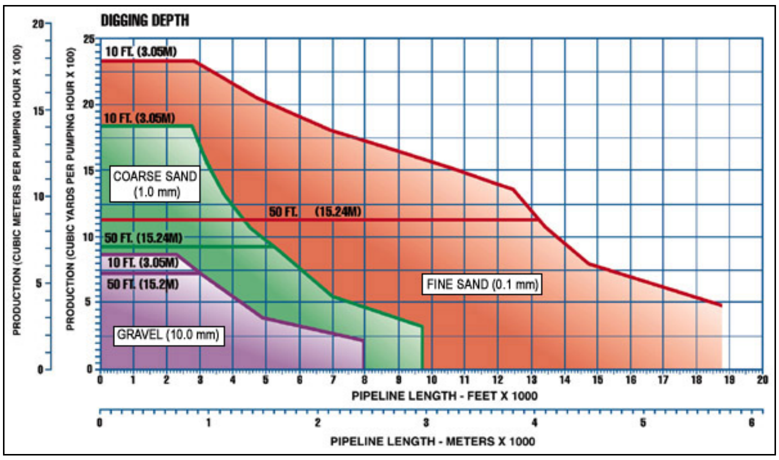
Figure A6.1 - Ellicott 4170 Series "Super-Dragon" dredger



The vessel consists of a rectangular pontoon with hinged arm capable of being lowered to the seabed. At the end of this arm is a rotating cutting tool and a centrifugal pump. The cutting tool dislodges material from the seabed and the pump transmits it along a pipeline either to shore or to a barge. Overall, its operation resembles that of a vacuum cleaner.

The company has published a chart showing the pumping rates as a function of the type of material being pumped and the length of the pipeline.

Figure A6.2



To estimate the energy required in dredging the following assumptions have been made:

- The material being pumped is coarse sand roughly corresponding to the middle of the green region in Figure A6.22.
- The length of the pipeline along which it is pumped is 1000m.
- The pump consumes 2MW of shaft power while operating at this rate
- The pump is powered by a marine diesel engine operating with an efficiency of 40%, implying a fuel consumption of 5MW.

Based on the chart in Figure A6.22 these conditions would imply that a pumping rate of approximately 1000m3/hour would be achieved.

It has been have assumed that diesel fuel has a carbon emission factor of 0.068 kg(C)/kWh or 0.249 kg(CO_2)/kWh. This factor comes from Defra's Environmental reporting Guidelines, see http://www.defra.gov.uk/environment/business/envrp/gas/index.htm.

This gives an emission rate of 0.340 te(C)/hour or 1.25 te(CO_2)/hour.

Division by the pumping rate gives the emission per m3 of material dredged. This is 0.00034 te(C)/m^3 or 0.00125 te(CO_2)/m^3 of material dredged.

Appendix 7
Material quantities and costs of Russell Lagoons

Cross section (foundation at –3mCD) Russell Lagoon 1		
Item	Quantity (m^3/m)	Total quantity ($m^3x1,000$)
Sand fill	253	5310
Quarry run	192	4028
Armour underlayers	132	2763
Primary armour	120	2525
Secondary armour	62	1312
Cross Section (foundation at –3mCD) Russell Lagoon 2		
Item	Quantity (m3/m)	Total quantity (m3x1,000)
Sand fill	253	8849
Quarry run	192	6714
Armour underlayers	132	4605
Primary armour	120	4208
Secondary armour	62	2187
Cross Section (foundation at –3mCD) Russell Lagoon 3		
Item	Quantity (m3/m)	Total quantity (m3x1000)
Sand fill	253	6675
Quarry run	192	5064
Armour underlayers	132	3474
Primary armour	120	3174
Secondary armour	62	1649

Appendix 8
Aggregate and Crushed Rock used in Lagoon Construction

	Swansea Bay Lagoon	Severn Estuary Lagoons (Russell Basin 1)	Severn Estuary Lagoons (Russell Basin 2)	Severn Estuary Lagoons (Russell Basin 3)
Supply & placement of rock (tonnes)	1,688,000	4,028,353	6,713,921	5,064,215
Coarse Aggregate	101,008	761,051	761,051	761,051
Fine Aggregate	50,862	383,224	383,224	383,224
Aggregate Total	151,870	1,144,275	1,144,275	1,144,275
% UK demand for crushed rock in 2005	1.19%	2.84%	4.74%	3.58%
% UK demand for aggregate in 2005	0.16%	1.21%	1.21%	1.21%

The quantity of crushed rock has been previously reported for the Swansea Bay lagoon. The quantities of materials for the Russell lagoons have been based on an assumed profile and the length of each embankment (see Appendix 7).

The quantity of aggregate used in the concrete for each scheme assumes 1.51 tonnes of coarse aggregate per m^3 Concrete and 0.76 tonnes of fine aggregate per m^3 Concrete. These values have been derived from the composition of concrete reported in the Duddon Barrage feasibility study (Duddon Estuary Tidal Energy Barrage Preliminary Feasibility Study, ETSU T06/00144/REP, 1993.)

The total quantity of UK crushed rock and aggregates produced for construction in 2005 is reported on the Minerals UK website published by the British Geological Survey (http://www.bgs.ac.uk/mineralsuk/commodity/uk/home.html)

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