

Tidal Power in the UK

Research Report 5 - UK case studies

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Tidal energy case studies

Review of seven UK tidal energy case studies

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Executive summary

As part of a wide ranging review of the UK's tidal energy potential, the Sustainable Development Commission (SDC) has commissioned a series of five reports to evaluate various aspects of tidal power in the UK. This report consists of a series of seven case studies of different tidal energy technologies around the UK. These case studies were selected to illustrate different tidal energy technology concepts from a range of different locations throughout the UK (Figure 1.1). It should be emphasised that these case studies are not based on any proposed commercial projects.

In each example the background to the scheme is outlined including the rationale for the location, the capital cost, energy output and estimated carbon savings. Each case study also includes a section on regional benefits including employment, related benefits from tourism, leisure pursuits or where appropriate transport infrastructure might also be developed. The potential environmental impacts that each scheme might cause are also outlined including the preliminary conclusions from previous studies.

Table 1 Summary of key data from tidal energy case studies

Case study	Technology	Region	mean Spring tidal range (m) or peak Spring current velocity (m/sec)*	Installed Capacity (MW)	Annual Average Energy Output (GWh/year)	CO2 saved/year (tonnes)
Strangford Lough Tidal Current Array	Tidal Current	Northern Ireland	3.0*	30	137.14	58,910
Pentland Firth Tidal Current Array	Tidal Current	Northern Scotland	4.15*	195.75	636.74	273,798
Liverpool Bay lagoon	Tidal lagoon	North Wales	6.7	340	938.0	403,424
Mersey Barrage	Tidal energy barrage	North West England	8.0	700	1,450.0	623,500
Loughor Barrage	Tidal energy barrage	South Wales	3.9	5	15.1	6,622
Duddon Barrage	Tidal energy barrage	North West England	5.8	100	212.0	91,160
Wyre Barrage	Tidal energy barrage	North West England	6.6	63.6	133.0	57,190

Strangford Narrows tidal current array

This case study is based on a hypothetical array of tidal current devices deployed in Strangford Narrows, which connects the Strangford Lough with the open sea. The exchange of water between the lough and the sea creates strong currents with peak velocities typically over 3m/s.

As there are no commercial tidal current devices we have chosen for our case studies a pile mounted, twin rotor concept similar to MCT's SeaGen concept. This concept is one of the best known and most advanced tidal current devices. **It must be emphasised that MCT have no plans for commercial development of this technology at this site.** This case study was selected to illustrate the full range of potential environmental impacts from tidal

current technology and because we were required to include at least one case study from Northern Ireland.

This tidal stream concept is a pile-mounted device and is best suited to sites where the water is up to 40m deep. The machine has two, 16m diameter, two-bladed rotors attached to the ends of a horizontal cross beam that is supported on a vertical pile. The pile is a steel tube 3m in diameter, 55m long and weighs 270 tonnes. It is cemented into a 21m deep socket that is drilled into the seabed.

The rotors always point in the same direction but can be operated on both the ebb and flood tides by changing pitch of the blades through 180°.

In this example 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 5m and at low tide the rotors occupy two thirds of the depth of the water column.

The powertrains (rotors, gearboxes and generators) are mounted on the cross beam, which is attached to a collar that can slide up and down the pile. Hydraulic rams lift the crossbeam and rotors out of the water for inspection and maintenance. The control systems are in a pod on the top of the pile and the transformer is in the top of the pile just below the pod.

It must be stressed that tidal current technology is still at an early stage of development and capital and operating costs and performance have yet to be determined and are highly uncertain. We have therefore assessed the cost of energy for a range of possible future capital costs, between £6,000/kW installed and £1,000/kW installed.. The highest figure we used was derived from the published information on the Government grant to SeaGen, together with assumptions about how much of that is for the machine itself; this gives an estimated capital cost of the project of £183 million, which is equivalent to ~£6,000/kW. However, some caution needs to be applied to this estimate because it is based on a technology at a very early stage of development. Experience from other technologies has shown that through economies of scale, experience and innovation, technologies that can be deployed in modular units should be able to achieve cost reductions. However, the extent of future cost reduction that may be achieved is not known.

A machine at this location could be designed to produce up to 1MW of electricity when the water velocity is 2.8m/s. At lower water speeds it would produce correspondingly less electricity, roughly in proportion to the cube of the current speed. An array of these devices could generate an estimated 137.14 GWh/year at the following unit costs of generation.

Capacity	Energy Output	Capital cost (£/kW installed)	Unit Cost of generation (p/kWh) (% discount rate assuming a 20 year technical life)			
(MW)	(GWh/year)		3.5%	8%	10%	15%
30	137.14	6,000	12.45	15.30	16.63	20.02
30	137.14	1,000	2.07	2.55	2.77	3.34

Although there are no plans that we are aware of, a hypothetical array in the Strangford Narrows could benefit the local economy by about £9.2 million. The Belfast shipyard, Harland and Wolfe, could provide a reliable regional base for assembly of the device components prior to shipment and installation in the Strangford Narrows.

There would be a limited demand for possibly 5 permanent staff on site to operate the array.

Strangford Lough is a popular area for recreational activities including water sports, boating, sailing, walking, bird watching and tourism. The array would be confined to the Narrows and would not necessarily affect these activities elsewhere although the presence of prominent monopile structures in this stretch of water would present a collision risk for vessels moving within the Narrows.

Strangford Lough and the Narrows have important nature conservation status and are protected by five different designations. Strangford Narrows is a Special Protection Area, a Marine Nature Reserve and an Area of Special Scientific Interest. These designations would be important to any development activity considered or proposed for Strangford Lough. There are specific concerns that submerged turbines might present a collision risk to marine mammals and possibly to sea birds above the water. During construction there is potential for contamination of the sea-bed and temporary increases in turbidity. Tidal current turbines could cause localised changes to tidal flows and sediment transport, although the extent of these changes has not been quantified by research.

The monopile structures would be clearly visible from each shore of the Narrows as slim linear features.

Pentland Firth tidal current array

This case study is based on another hypothetical array of tidal current devices deployed in the Pentland Firth close to Duncansby Head off the north coast of Scotland. In this case a larger 200MW array was considered consisting of 65 3MW devices. The site selection has had to take account of the high current velocity (4.15 m/s mean maximum Spring) and the water depth. Assessment of the resource at this location included the potential energy loss caused by a number of devices operating in relatively close proximity to each other.

This case study is also based on a device similar to Marine Current Turbines Ltd's (MCT) 'Seagen' type machine as this is the furthest developed tidal current device concept. As a pile mounted concept the device is best suited to sites where the water is up to 40m deep. Two-way generation can be achieved by changing pitch of the blades through 180°.

In this case study the dimensions of each device have been scaled up and would have an installed capacity of 3MW and a rotor diameter of 20m. The entire output could generate an estimated 637 GWh/year.

The highest capital cost estimate is based on a technology at an early stage of development; therefore great caution needs to be applied to any estimates of the unit costs of generation. Economies of scale, experience and innovation from other technologies should enable cost reductions to be achieved. There are, however, significant uncertainties related to the development, installation and operation of tidal current devices and cost reductions cannot be guaranteed. We have therefore included a range of capital costs between £6,000/kW installed and £1,000/kW installed. Similarly firm estimates of operating costs have yet to be established and we have also applied a range of estimates equivalent to 4% of the capital cost. Assuming that a hypothetical array could generate 636.74 GWh/year the estimated unit costs of energy for the highest and lowest estimated capital and operating costs are as follows:

Capacity	Energy Output	Capital cost (£/kW installed)	Unit Cost of generation (p/kWh) (% discount rate assuming a 20 year technical life)			
(MW)	(GWh/year)		3.5%	8%	10%	15%
195.75	636.74	6,000	20.34	26.42	29.48	37.87
195.75	636.74	1,000	3.39	4.40	4.91	6.31

There are two ports, Wick and Scrabster, which would be suitable for deployment and maintenance operations. Both are about 30km from the site. The value to the local economy of these developments has not been quantified, although an array of this scale would require a permanent local work force to maintain the array.

Because of the size of the array there would be a potential navigation hazard over an area of approximately 56 km² which would need to become an exclusion area except for maintenance craft. The Pentland Firth is a busy shipping lane and although an array on this scale would not obstruct the deeper water passage north of this site an exclusion area would need to be clearly marked with a hazard warning system to avoid the risk of collision.

There are no designated conservation areas in the immediate vicinity of the hypothetical array site. There is a potential risk during construction of contamination. There will also be localised change to the hydrodynamic regime (flow pattern) on either side of the array. A reduction in energy from the natural flow regime is likely to affect sediment movement although the extent to which sediment movement could change has not been quantified.

Marine mammals including harbour porpoise, white-beaked dolphin and minke whale are reportedly common in the area. Seals are also widely distributed through the region. Breeding sites for grey seals are also reported. The potential effects on marine mammals might include collision risk and disturbance from the noise both during installation and operation although these effects have not been quantified for this example.

The Pentland Firth area supports large populations of sea birds of international and national importance. It is possible that a tidal current array may present a collision risk to them although this has not been quantified.

Areas with the highest tidal current flows are unlikely to provide the most suitable habitat for spawning or nursery grounds for fish or shellfish. More sheltered waters are known to support spawning grounds for commercially important species. Plankton in the area is known to be influenced by high levels of mixing induced by tidal currents. There could be changes in plankton productivity if these flows were reduced but this is likely to be proportionate to the scale of the array.

Liverpool Bay tidal energy lagoon concept

This case study is a review of a tidal energy lagoon off the coast of North Wales. The concept has been proposed as an alternative method for exploiting tidal energy. A large artificial lagoon would be created by building an embankment to enclose an area of up to 60 km² in an intertidal or subtidal area with a high tidal range. A power-house consisting of a series of turbines and generators would be installed along one section of this structure within a concrete section. The power house could be built from prefabricated units known as caissons which are built from reinforced concrete in dry docks. Once complete each unit would be floated out, towed to the offshore location and carefully ballasted into position until complete closure was achieved. Energy capture would be achieved by retaining water within the lagoon and allowing a head (difference in the vertical water levels on either side of the embankment) to build and then allowing water to flow through the turbines to generate power. The power plant operation could also be operated in the reverse direction by allowing a head to build on the seaward side of the lagoon during the flood tide.

Our case study summarises a proposal for a 340MW tidal energy lagoon off the coast of North Wales. Based on previously reported energy generation and capital costs for the 340MW scheme, we have inflated the results from that study to bring the costs on to a common basis with the other case studies. The following unit costs of generation were calculated.

Capacity	Energy Output	Unit Cost of generation (p/kWh) (% discount rate assuming a 120 year technical life)			
(MW)	(GWh/year)	3.5%	8%	10%	15%
340	938	3.11	6.80	8.64	13.75

However, we should point out that there are widely differing estimates for the cost of energy for the most well-studied tidal lagoon concept, Swansea Bay.

A scheme of this scale would require a base within reasonable proximity to the site. The smaller ports of Mostyn, Rhyl and Connah's Quay could fulfil this function although larger dry docks would be required for caisson construction if this method of construction was selected. These could be purpose built possibly on Merseyside or at existing facilities for example Loch Kishorn.

Comparison with estimates of projects of similar size suggests direct employment could be between 1,200 and 2,000 at the height of construction. During operation the power plant might require possibly as many as 70 personnel to operate.

A large structure of this size and in a location close to busy shipping lanes would need to be clearly identified with navigation markers as it would present a hazard to shipping. It would be clearly visible from the shore especially at low tide when the embankment would be more exposed. Its appearance would also vary depending on different climatic conditions and times of the day.

An offshore tidal energy lagoon would cause some environmental impact particularly sediment movement induced by alterations to tidal currents. The interaction of wave and currents in Liverpool Bay is known to have a complex sediment circulation pattern. The extent to which a lagoon could change this pattern would depend on where it was located and its size. The effects have not been quantified. Potential changes to beach and coastal processes would also need to be carefully assessed because of their importance to creating and sustaining shoreline habitats.

Water quality could be affected by increased turbidity particularly during construction when there would be extensive dredging. It is also possible that historic contaminants in the sediment could become mobilised and redistributed.

The Liverpool Bay area and the Dee Estuary support over wintering waders and wildfowl. Liverpool Bay, particularly the area for a potential lagoon, is also important for the common scoter and red-throated diver. The area has International Bird Area designation. Disruption to feeding grounds caused during construction and once in operation could affect bird populations although the extent is not known. Marine mammals including harbour porpoise and grey seals may also be affected by disturbance during construction.

Mersey tidal energy barrage

This case study is a summary of a potentially large (700MW) scheme for a tidal energy barrage across the Mersey Estuary that was conceived during the late 1980s by the former Merseyside County Council. It also attracted commercial interest from a consortium of local companies including the former Mersey Docks and Harbour Board. The scheme was led by a two leading construction companies who completed a detailed technical evaluation of the scheme costs and energy capture. Because of its impact on shipping the effect of a barrage on ship operations both during and post construction had to be undertaken. Studies on the environmental impact and regional benefits were also completed.

The eventual preferred alignment of the Mersey Barrage conceived in the 1980s would extend between Rock Ferry and the former Herculaneum Dock. This is upstream of the narrows but downstream of the entrance to the Manchester Ship Canal and Garston Docks. Two ship locks were therefore incorporated into the design. The ship locks would need to be built insitu although the remainder of the barrage would be constructed from prefabricated concrete caissons built in artificial enclosures adjacent to the barrage landfall. Each completed unit would be floated out and carefully ballasted into position to form a complete barrier across the estuary. Most of the 1.9 km length of the barrage would consist of sluices to maximise the flow into the impounded estuary on the flood tide. A shorter section would contain turbines and generators which would be operated on the ebb tide once a sufficient head had been created. The developers concluded that single generation on the ebb tide would be the most efficient and economic mode of operation.

A tidal energy barrage could generate 1,450 GWh/year on average which is about 8.5% of the annual estimated output from a Severn Barrage between Cardiff and Weston. The Mersey Barrage would generate electricity at the following discount rates (based on 2006 costs).

Capacity (MW)	Energy Output (GWh/year)	Unit Cost of generation (p/kWh) (% discount rate assuming a 120 year technical life)			
		3.5%	8%	10%	15%
700	1,450.0	5.82	12.27	15.79	26.52

All the civil engineering work would be completed on or near the barrage providing immediate benefit to the region. An estimated workforce of up to 2,000 would be required to build the barrage which would take 5 years to complete. A further 600 would be required to operate the generation station and the ship locks.

Commercial shipping especially vessels using the QE II oil dock, lower Manchester Ship Canal and Garston Docks would have to pass through ship locks. During the development studies a model was developed to simulate the movement of ships approaching and leaving locks. The same model was also used to model the movement of super tankers manoeuvring downstream of the barrage as they prepared to dock or depart from the Tranmere oil terminal. The model anticipated over 7,000 arrivals would be affected by the barrage in one year. The overriding conclusion from these simulated ship movements was that the provision of two locks would be an acceptable balance between the additional construction cost and the increased operating costs for shipping companies.

The benefits of new amenities, leisure, tourism, a new road crossing plus the negative impacts caused by blight and loss of habitat were assessed in monetary values. The total value of these non energy benefits and impacts was estimated in 1992 to be between £90 million and £213 million. The number of visitors was estimated to be between 200,000 and 500,000 per year.

The Mersey Estuary has an extensive intertidal area which supports large numbers of migratory waders and wildfowl. The estuary's importance to conservation is recognised in its environmental designations which include a Special Protection Area, an International Bird Area and as a Ramsar site. There have been concerns raised over the falling numbers of birds on the Mersey. The extent to which the numbers of birds in the estuary would be affected by a barrage has not been predicted. Changes to the intertidal area, sediment type, and invertebrate population will all influence bird populations.

Construction of a barrage would change the hydrodynamic regime of the estuary and reduce the tidal range upstream of the barrage by about half. Sedimentological studies conducted as part of a broader environmental assessment concluded fine sediment disposition rates

upstream of the barrage would double although sand movement would decrease. There would be a change in the distribution of fine and coarse sediments in the estuary but the extent of this change would need to be determined with more modelling. One consequence of these changes could be the mobilisation of contaminants such as heavy metals that are currently trapped within existing sediments.

In 2006, the North West Development Agency and Peel Holdings, owners of the Mersey Docks and Harbour Company, initiated a new appraisal of the estuary's tidal energy potential. This new assessment will explore a number of different technology options including a conventional barrage. The assessment will also review the tidal energy potential of tidal current technology within the open estuary and the use of different turbine designs, including water wheels. Potential options include power generation from turbines that could be housed in structures positioned within the estuary although not necessarily extending right across it. A tidal lagoon located in Liverpool Bay has also been included.

Loughor tidal energy and amenity barrage

The Loughor estuary extends from Burry Point at the entrance to the Carmarthen Bay to Pontardulais. There is a natural constriction where the A484 and a railway line between Swansea and Llanelli cross the estuary. This location was identified as a potential site for a small scale tidal energy barrage which would impound the upper estuary. A consortium of local interests, including local authorities and the Welsh Development Agency, were interested in a barrage not only to generate renewable energy but also to create a marina upstream of the barrage. A feasibility study, commissioned in 1988, evaluated the potential for a combined amenity and energy barrage scheme.

Because of the existence of a railway bridge a barrage at this location would need to be built insitu by building some of the sections within temporary coffer dams. Final closure would be achieved by creating two short lengths of embankment from dumped material. The scheme could generate 15.1 GWh/year if it were allowed to operate all year round. However, the use of the scheme for amenity purposes would mean that less electricity could be generated depending on whether the marina were only used in the summer or all year round. The following unit costs of energy assume unrestricted year round operation as a power station.

Capacity	Energy Output	Unit Cost of generation (p/kWh) (% discount rate assuming a 120 year technical life)			
(MW)	(GWh/year)	3.5%	8%	10%	15%
5	15.1	6.98	14.5	18.14	27.93

Construction of the Loughor barrage would offer a limited number of local jobs. The number has not been estimated. Comparison with other small scale barrage schemes suggests that for a barrage on the scale of the Loughor the number would be minor.

The benefits that could be accrued from the marina were not assessed. The value of the leisure function could depend on whether year round energy generation became the primary objective of a barrage or whether the scheme was designed for seasonal power generation combined with recreational uses. Power generation would impose some restrictions because of the necessity to include an exclusion zone near the barrage.

One of the major concerns for a barrage scheme across this estuary is the quantity of mobile sediment and its propensity to rapidly erode and accrete. A sediment transport model was applied to determine the post-barrage tidal regime and approximate rates of sediment transport and accumulation. Initial estimates suggest that the basin capacity would be reduced by about half over a period of 45 years unless dredging was instigated. There are

additional concerns that historic contaminants from previous industrial activity could be remobilised by changes in the hydrodynamic regime induced by the barrage.

There are a number of environmental designations within the immediate proximity of the scheme including a Special Area of Conservation, a Special Protection Area, an International Bird Area, a Ramsar site, a National Nature Reserve and a Local Nature Reserve. The extent to which these protected areas would be changed has not been assessed; however, changes to the sediment regime and the upstream intertidal area could affect invertebrate and bird populations. Otters are known to occur in the upper estuary and the River Loughor and could be affected either by the disturbance during construction or from a marina development.

Duddon tidal energy barrage

The Duddon Estuary forms a prominent embayment between Haverigg and Sandscale Haws immediately north of Barrow-in-Furness on the Cumbrian coast. The local authorities and the County Council were interested in the potential of a barrage as a new road crossing to improve the region's transport infrastructure. In 1992, a feasibility study was commissioned by Cumbria County Council in partnership with the local utility company and the local authorities.

The Duddon Estuary is notably shallow and is characterised by extensive intertidal sand banks exposed at low water. The tidal range and prevailing wind have given rise to the formation of numerous dune systems along the north-west coast of England, locally represented at the mouth of the Duddon by Sandscale Haws. This case study briefly outlines the proposed barrage scheme taking account of its potential for both energy capture and as a road crossing.

Unlike most other tidal energy barrages proposed for the UK this scheme would consist predominantly of a sand filled embankment. Only a short central section would be built from prefabricated concrete caissons constructed elsewhere and towed to the site before emplacement to form a complete barrier. Because of the shallow nature of the estuary a channel would need to be dredged to allow the caissons to be floated in. The dredged material would be used to make the embankment. The following unit cost of generation would be achieved for a barrage extending across the mouth of the estuary.

Capacity (MW)	Energy Output (GWh/year)	Unit Cost of generation (p/kWh) (% discount rate assuming a 120 year technical life)			
		3.5%	8%	10%	15%
100	212	7.5	15.42	19.31	29.9

A key element of the original feasibility study and our case study is a review of the potential to improve the local road infrastructure. The feasibility study concluded that there would be notable improvements for both local traffic and longer distance movement further up the Cumbrian coast. However, this benefit has to be counterbalanced against the environmental sensitivity of the estuary which has several environmental designations.

The combination of intertidal, saltmarsh and dune ecology is recognised as an area of national conservation value. Virtually the entire estuary is a designated Special Site of Scientific Interest (SSSI). Therefore, construction of a barrage across this estuary would need careful consideration to avoid potentially detrimental effects. Of particular concern is the potential disruption to the sediment movement and related dune system. There are a number of rare species of plant and amphibians which could be directly affected by a barrage.

Wyre tidal energy barrage

The River Wyre flows into the Irish Sea at Fleetwood mid way between Blackpool and Morecambe Bay. Fleetwood was an important fishing port with a dock which has the potential to be developed for alternative uses. There is no crossing between the port of Fleetwood and the neighbouring community of Knot End on the opposite bank. Lancashire County Council, in combination with other partners, commission a study in 1991 to assess the tidal energy potential of the estuary and the regional benefits of a new road crossing at the mouth of the estuary. The case study examines the benefits of this road crossing as well as the renewable energy potential.

The feasibility study concluded that a barrage could be constructed by emplacing a prefabricated structure across the entrance to the estuary. A small ship lock and embankment would also be included. A barrage built at this locality would generate 131 GWh/year for the following unit costs of generation.

Capacity (MW)	Energy Output (GWh/year)	Unit Cost of generation (p/kWh) (% discount rate assuming a 120 year technical life)			
		3.5%	8%	10%	15%
63.6	131	5.37	10.42	12.85	19.27

The road crossing would substantially cut the time between Fleetwood and the hinterland on the opposite bank. However, a new road connection would require a link road to be built across an existing golf course. Neither the barrage nor the road crossing at the mouth of the estuary have been progressed although there are plans to develop the marina site.

The Wyre Estuary has important conservation designations including a Site of Special Scientific Interest. The estuary is in close proximity to extensive intertidal areas in Morecombe Bay which are important for waders and wildfowl. The construction of a tidal energy barrage would cause changes to the hydrodynamic regime and related sediment movement into the estuary. Although these have not been accurately quantified there is a concern that with a change to the estuary profile there could be localised erosion and loss of saltmarsh habitat. This may affect some species of birds which roost in this area.

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Appendix 1 Methodology for calculating the unit cost of energy

Appendix 2 Methodology for estimating Embedded Carbon

Appendix 3 Energy Generation Modes for Tidal Energy Barrages and Lagoons

1 Introduction

As part of a wide ranging review of the UK's tidal energy potential the Sustainable Development Commission (SDC) has commissioned a series of five reports to evaluate various aspects of tidal power. The other reports have examined the resource, the status of the technology and its potential environmental impacts. Two contracts, three and four, concentrated on the tidal energy potential from the Severn Estuary and Bristol Channel. The SDC also sought a complementary set of case studies to provide examples of tidal power resource, technologies, and potential locations in England, Wales, Scotland and Northern Ireland. AEA Energy and Environment has compiled a review of five different case studies of tidal energy schemes that have previously been investigated and two hypothetical tidal current schemes. All the information presented in this study has been taken from referenced sources listed at the back of each section. The University of Edinburgh was subcontracted to undertake a technical assessment of a hypothetical tidal current array in the Pentland Firth and the associated regional implications of such a development. The environmental consultancy, Hartley Anderson, was subcontracted to review the environmental implications of each of these tidal energy technology case studies.

The selection of these case studies was designed to provide a series of examples of tidal energy concepts and their impacts. In each case there are specific features that have been highlighted. The implications of development in addition to the generation of renewable energy have been reviewed. These impacts include marine spatial planning, navigation and commercial shipping, regional benefits including employment and flood defence, potential effects on designated sites, recreational use and impact on the seascape. The selection of case studies has also taken account of different technologies, size and locations. The key reasons for selecting each case study are summarised in Table 1.1

Table 1.1 Tidal energy case studies included in this report.

Case study	Country	Technology	Rationale for Case Study and Main issues explored
Strangford Lough 30MW	Northern Ireland.	Tidal current.	An example of a relatively small scale hypothetical scheme developed in an environmentally sensitive area.
Pentland Firth tidal current array +200MW.	Scotland.	Tidal current.	A potentially strategic location for tidal current development on a large scale. Grid connection implications. Implications for navigation. Environmental impacts. Decommissioning.
Liverpool Bay/North coast of Wales 340MW	Wales/England.	Tidal lagoon.	A larger offshore tidal lagoon proposed for an area off the coast of North Wales. Environmental issues for the scheme are explored.
Mersey Barrage. 700MW	England.	Barrage.	A previous candidate for a barrage that has been explored in detail. The impact on commercial shipping was a major issue. Regional benefits and environmental impacts have also been assessed.
Loughor Estuary 5MW	Wales.	Barrage.	A small barrage, integrated with a potential marine development. Environmental issues, particularly European designated sites are examined.
Duddon 100MW	England.	Barrage.	A tidal energy scheme where regional development and environmental sensitivity are key features.
Wyre 64MW	England.	Barrage.	A small-scale tidal energy scheme where regional development is a key feature.

These case studies examine different tidal energy options from a number of locations around the UK (Figure 1.1). In each example the background to the scheme is outlined including the rationale for the location, the estimated capital cost, energy output and estimated carbon savings. Each case study also includes a section on regional benefits including employment, related benefits from tourism, leisure pursuits or where appropriate transport infrastructure might be developed. The likely environmental impacts that each scheme might cause are also outlined including the preliminary conclusions from previous studies. It must be stressed that the tidal current case studies are entirely hypothetical. There are no plans for commercial development at any of these locations.

Most of the selected examples were previously investigated as part of the UK's tidal energy R&D programme between the early 1980s and 1994. The primary interest of this programme was the development of tidal energy barrages principally across the Severn and Mersey Estuaries. The latter is one of the selected case studies. A number of smaller estuaries also attracted interest from both local authorities and industry and were the subject of initial feasibility studies. These estuaries included the Loughor, Duddon and Wyre which have been included in this review. Initially these estuaries were identified from an earlier parametric assessment as the more promising sites for tidal energy development primarily because of their relatively high tidal range [1.1]. The local authorities who have jurisdiction over these estuaries wanted to evaluate their potential for regional development as well as sources of renewable energy. This local interest provided the rationale for the feasibility studies.

Since the conclusion of the R&D programme interest has emerged in the tidal energy potential from offshore lagoons and tidal current arrays. An example of a lagoon that could be developed in Liverpool Bay has been included.

The two tidal current array case studies, the Strangford Narrows and the Pentland Firth are hypothetical examples of the technology. They were selected to consider the potential of the technology assuming it was deployed at the scale of an array in locations where there is known to be a tidal current resource. These technology examples are based on a similar concept currently under development by Marine Current Turbines (MCT) as is the most advanced tidal current concept under development in the UK. There are no published examples of tidal current arrays, although MCT, a leading UK developer in the technology, have stated their intention to develop small (10MW) arrays in the near future [1.2].

Information on capital costs and resource evaluation are publicly available, however, capital and operating costs are currently very uncertain. For this reason a range of capital and operating costs have been assumed.

Each case study includes an economic analysis of the scheme expressed as the unit cost of energy at four selected discount rates of 3.5%, 8%, 10% and 15%. The values have been derived using a discounted cash flow analysis of the technical life of each scheme using original capital costs inflated to 2006 prices. Although this methodology provides a rational basis for comparison it must be treated with some caution as inflation indices will not necessarily reflect the same rate of cost inflation for each scheme. Secondly, the capital cost estimates and energy output for the Mersey were based on a detailed development study in contrast to the smaller scale barrage feasibility studies. Thirdly, tidal current technology is still at an early stage of technical development. Performance data presented in this report for this tidal current technology should therefore be regarded as generally indicative. The methodology for calculating the unit cost of energy is described in Appendix 1.

Figure 1.1 Location of selected UK tidal energy case studies

The embedded carbon has been estimated for each scheme by calculating the amount of carbon emissions related to the key materials that would be used for construction: steel; concrete and copper. The amount of carbon emissions required for pumping operations related to dredging has also been included. The carbon saved and carbon pay back period have been estimated from the annual energy output from each scheme assuming the displacement of carbon emissions from the current UK generation mix. The methodology for estimating carbon emissions has been outlined in Appendix 2.

The final appendix (Appendix 3) provides an explanation of how tidal energy barrages and lagoons can be operated throughout each tidal cycle.

A glossary of technical terms used in this report has also been included.

1.1 References

- 1.1 The UK Potential for Tidal Energy from Small Estuaries, ETSU TID 4048-P1, 1989
- 1.2 Marine Current Turbines website visited 15th May 2007.
<http://www.marineturbines.com/projects.htm>

2 Strangford Narrows tidal current array

2.1 Background

Tidal-current energy is the direct extraction of energy from naturally occurring tidal currents. This is done in much the same way as wind turbines extract energy from the wind.

Strong tidal currents are most frequently found near headlands and islands. These retard the progress of the tidal bulge as it moves around the earth, leading to head-differences that can only be equalised by a flow of water around and between the land features. It is this flow that constitutes the tidal current. The detailed flow regime is determined by the topography of the coast and the bathymetry of the seabed.

A number of different tidal current generator concepts have been proposed in recent years. With a few exceptions the majority are variations on the theme of a horizontal-axis turbine. The main differences are the method of holding 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 device, the 'Seaflow', was installed in the Bristol Channel off Lynmouth in 2002. The second version, the 'Seagen' is planned to be installed in Strangford Narrows in Northern Ireland during 2007. This device is described in detail in Section 2.4.

It must be stressed that MCT has no plans to develop the Strangford Narrows as a commercial site for its technology. This case study was selected by us to illustrate the full range of potential environmental impacts from tidal current technology and because we were required to include at least one case study from Northern Ireland.

This case study is therefore a hypothetical one based on what are considered to be reasonable assumptions concerning the number, size, location and configuration of a likely array of tidal-current turbines in Strangford Narrows based on the MCT concept. 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, but will inevitably involve more uncertainty than if a detailed proposal for an array had been developed.

The physics of the exploitation of tidal currents is not yet fully understood and is currently an area of active research at a fundamental level. Because of this, the size of the resource and the amount of energy that can be extracted from it is uncertain. 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 treated with some caution.

An important aspect of this case study is a review of the potential environmental impact of a hypothetical array using this design of current turbine and consideration of the consent requirements that a scheme might require.

2.2 The location

Strangford Narrows is a channel connecting Strangford Lough with the Irish Sea. It is around 9km long and varies in width from about 2.3km at the sea entrance to less than 500m at its narrowest point. The depth along the centre line of the channel is in the range 20 to 30m.

Tidal currents with peak speeds typically over 3m/s flow in this channel potentially making it a good site for exploiting tidal current energy. These velocities are, however, not exceptional by UK standards, and there are several sites around the UK that have velocities greater than this. The most notable example being the Pentland Firth, where peak spring velocities of over 7m/s can be found and which is the subject of another case study in this report.

Because Strangford Narrows is a long narrow channel, the tidal current is substantially unidirectional with a 180° change in direction when the tide reverses. This could be advantageous to a tidal current energy facility, removing the need for a yawing mechanism.

Strangford Narrows is also known to be environmentally sensitive, containing a number of protected species as well as an important breeding site for the common seal. For this reason it has been designated a Marine Nature Reserve. This channel is also used by various craft moving between Strangford Lough and the Irish Sea. This means that placing an array of turbines completely across the channel would not be possible. Section 2.13 discusses environmental issues in more detail.

Figure 2.1 shows a map of the narrows and indicates the location of the current 'Seagen' turbine and the hypothetical array that will be the main focus of this case study.

Figure 2.1 Map of Strangford Narrows

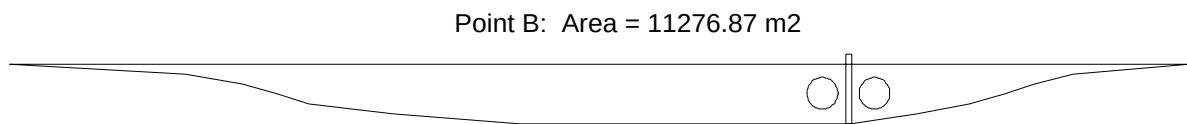


'A', 'B' and 'C' were points at which detailed calculations of tidal flow were reported in (Whittaker et al, 2003).

The Seagen machine is to be installed at position 54°22.119N, 5°32.749W.

Figure 2.2 shows a cross section of Strangford Narrows at point 'B' in Figure 2.1, along a line roughly perpendicular to the direction of flow.

Figure 2.2 Cross section of Strangford Narrows at point B in Figure 2.1



The cross sectional area of the channel at this point, along a plane roughly perpendicular to the direction of flow, is about 11,300m². An array of 20 turbines each with two 16m diameter rotors would have a capture area of $20 \times 2 \times \pi \times \left(\frac{16}{2}\right)^2 = 8,042.5\text{m}^2$ which represents 71.3% of the cross sectional area at this point in the channel.

(Whittaker et al, 2003) [2.1] states that in the vicinity of this point, the spring peak velocity is 2.95m/s, the neap peak velocity is 2.28m/s and the ebb to flood ratio is 0.91. Calculating the velocity using a simple bi-sinusoidal formula (see Box 1 for an explanation of this formula) with these parameters and integrating over a whole year gives a total energy flux through the channel at this point of about 346GWh/year. This is, however, a grossly oversimplified approach and should only be taken as indicative. For example, it does not take into account the variation in cross sectional area due to the tidal range or include the effects of velocity shear and in any case a bi-sinusoidal formula cannot predict the velocity accurately, as its variation follows a more complex pattern. But, it does give a rough estimate of the energy present in the channel.

This amount of energy cannot all be extracted however, for the following reasons:

1. There is a technical limit to the amount of energy that a turbine can extract.
2. If too many turbines are installed in a channel and the water is slowed down too much then patterns of sedimentation can be changed, leading, in extreme cases, to changes in the morphology of the coast and seabed.

In any situation, there will be a maximum amount of energy that can be extracted before unwanted effects occur. This is called the significant impact factor [2.2]. This factor needs to be determined in each case by computational modelling of the flows and sedimentation processes. However, in cases where such detailed modelling studies have not been carried out, a figure of 20% is often used as a rule of thumb. This figure was used, for example, by [2.2] in their most recent resource assessment of the UK's tidal-current energy resource for the Carbon Trust's Marine Energy Challenge.

(Whittaker et al, 2003) [2.1] states that the proposed 20 machine array, not including the demonstration device, would generate about 137GWh/year, which would be 40% of the energy present in the flow based on the above calculation. This would suggest that an array of this size may be too big for the Narrows and that a smaller one may be more appropriate.

However, it is too early to draw firm conclusions regarding this question and detailed modelling and measurement work would be needed if a definitive answer to this question were required.

2.3 The local context

Northern Ireland's electricity demand has been steadily growing over the last decade at a rate of about 150GWh/year each year. Figure 2.3, using data from (NIAAS, 2005), shows this trend.

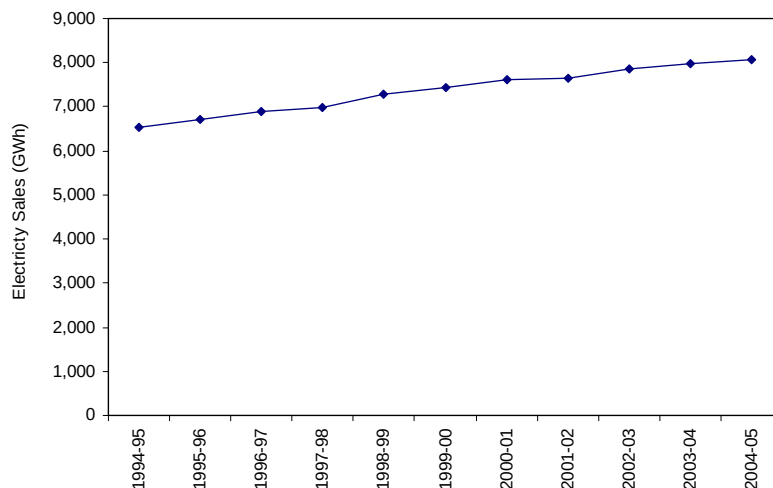


Figure 2.3 Electricity Sales in Northern Ireland, 1994 to 2005 (from (NIAAS, 2005) [2.3]).

Demand in 2004/05 was 8,067GWh/year representing 2.5 % of the total UK electricity sales of 312,148GWh in 2004 [2.4]. In 2005, electricity demand was 1,538GWh/year more than it was in 1994.

This represents electricity delivered to consumers, not the amount generated, which would be greater because of transmission losses, which are typically about 5%. The 137GWh/year that a Strangford Tidal-current array could generate would, if it could all be sold, equate to 130GWh/year delivered to final consumers and would represent about 1.6% of Northern Ireland electricity sales.

Northern Ireland Electricity plc (NIE), part of the Viridian Group, is responsible for power transmission, distribution and supply. Generation is carried out by three companies that own the four major power stations.

There is a link (re-established in 1996) between the Northern Ireland grid and that of the Irish Republic, with a capacity of 600MW, along which electricity is both imported and exported. In December 2001, a link between Northern Ireland's grid and that of Scotland was inaugurated, with a capacity of 500MW.

Northern Ireland has a mix of coal, gas and renewable generation. Table 2.1 lists the province's power stations and their characteristics.

Table 2.1 - power generation in Northern Ireland [2.5])

Operator	Station Name	Fuel	Installed Capacity (MW)	Year of commission or year generation began
AES	Kilroot	coal/oil	520	1981
	Tappaghan	wind	20	2005
Coolkeeragh ESB Ltd	Coolkeeragh	CCGT	420	2005
	Bessy Bell	wind	5	1995
Premier Power Ltd	Ballylumford B	Gas/oil	380	1968
	Ballylumford C	CCGT	616	2003
	Corkey	wind	5	1994
	Elliot's Hill	wind	5	1995
	Rigged Hill	wind	5	1994
Total			1976	

Total generating capacity is therefore 1,976MW with a further 1,100MW available via links to Scotland and the Irish Republic.

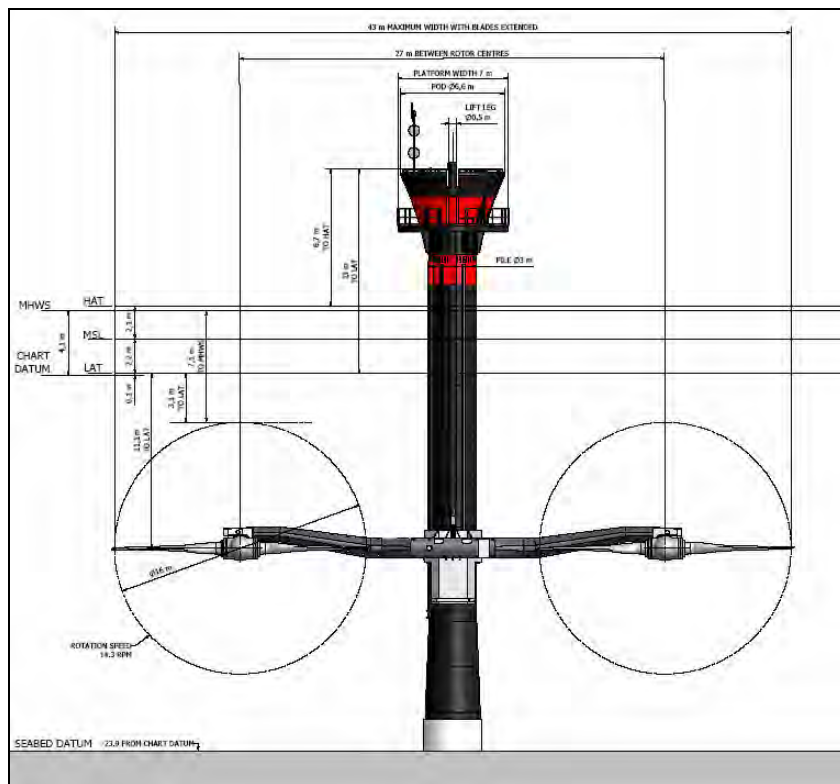
A 30MW tidal current array would therefore represent 1.5% of Northern Irish generating capacity. However, it would be bigger than all but one of the province's wind farms.

2.4 The technology

This case study is based on Marine Current Turbines Ltd's (MCT) 'Seagen' machine. This is the furthest developed tidal-current device-concept and it is likely that, if an array were considered for development in the Strangford Narrows, the machines used would be broadly similar. Figure 2.4 shows a diagram of this machine. MCT's pile-mounted concept is best suited to sites where the water is up to 30m deep, which is another reason why Strangford Narrows is ideally suited to it.

The Seagen machine has two, 16m diameter, two-bladed rotors attached to the ends of a horizontal cross beam that is supported on a vertical pile. The pile is a steel tube 3m in diameter, 55m long and weighs 270 tonnes. It is cemented into a 21m deep socket that is 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 pitch of the blades through 180°.

Figure 2.4 Diagram of Marine Current Turbines Ltd's 'Seagen' machine

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 5m and at low tide the rotors occupy two thirds of the depth of the water column.

The powertrains (rotors, gearboxes and generators) are mounted on the cross beam, which is attached to a collar that can slide up and down the pile. Hydraulic rams lift the crossbeam and rotors out of the water for inspection and maintenance. The control systems are in a pod on the top of the pile and the transformer is in the top of the pile just below the pod.

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 speed.

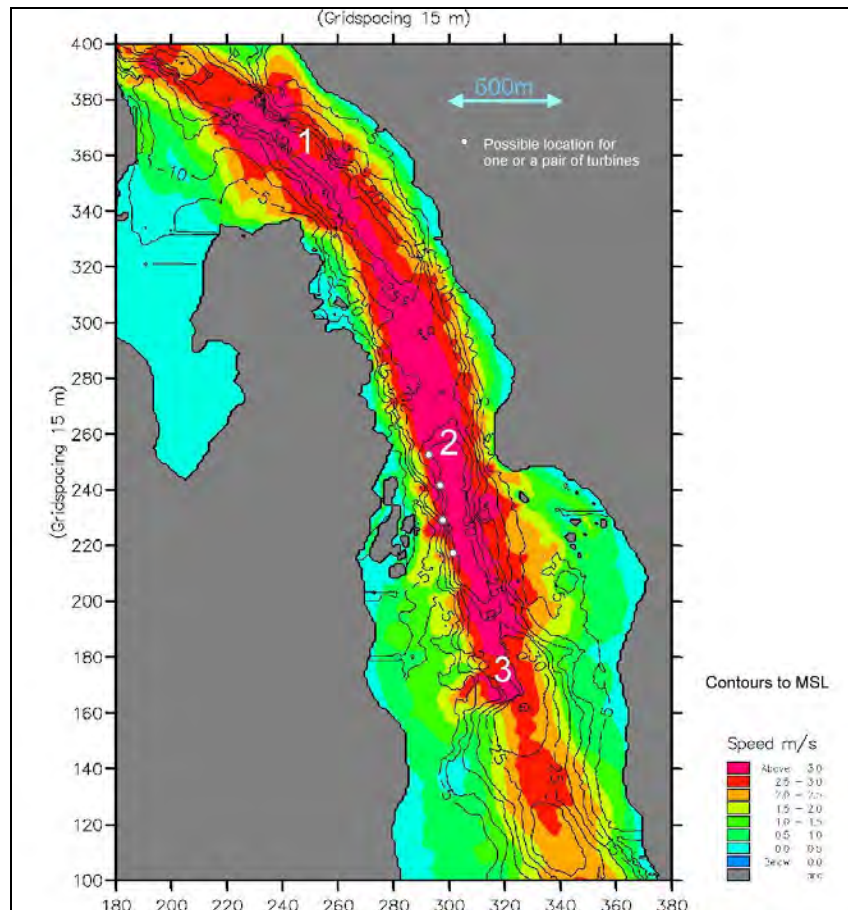
2.5 The proposed array

Neither MCT nor any other company has published detailed proposals for a commercial turbine array. However, (Whittaker et al, 2003) suggests that an array of 20 turbines, with a total nameplate capacity of 32.8MW could be installed in the Narrows. Figure 2.5 shows a possible array configuration suggested in (Whittaker et al, 2003) [2.1].

According to (Whittaker et al, 2003) [2.1], the turbines would be installed in lines parallel to the shore roughly along the 30m depth contour and about 200m apart. Three such arrays

are considered, in the locations labelled '1', '2' and '3' in Figure 2.5. Only location '2' shows the individual turbines by we understand that in the other locations they would be arranged similarly.

Figure 2.5 Figure 17 showing suggested layout of possible array [2.1].



If the 200m spacing turned out to be too close, the 9km length of the Narrows could allow a spacing of up to 450m, although the high velocities seen in the narrowest parts of the Narrows are not present in all locations along its entire length.

As was mentioned in Section 2.2 it is possible that an array of this size may extract too much energy from the flow leading to adverse environmental effects. However, the large uncertainties involved in these calculations mean that, at present, this can only be regarded as a possibility and that detailed modelling work is required to answer this question definitively.

The choice of the one-behind-the-other contour-hugging layout is probably the best compromise between maximising energy capture and minimising disruption to navigation.

This layout was proposed in a report published in 2003, but it is not known if MCT or any other company has carried out further work on designing an optimum array for Strangford Narrows.

The turbines are manufactured from steel and transported to site before being installed. The pile is installed first by lowering it into a socket drilled into the seabed. The drilling and installation are carried out using a jack-up barge. Jack up barges are vessels that can raise

themselves out of the water using retractable legs standing on the seabed. Figure 2.6 shows an example of a jack-up barge; Seacore Ltd's Deep Diver that was used to install MCT's 'Seaflow' turbine in the Bristol Channel off Lynmouth.

Figure 2.6 An example of a jack-up barge; Seacore Ltd's 'Deep Diver', photographed during the installation of MCT's 'Seaflow' turbine off Lynmouth in the Bristol Channel [2.6].



While very large jack-up barges exist that are capable of operating in water up to 70m deep, these are uncommon and likely to be very expensive. Furthermore, most jack-up barges are not designed to operate in fast currents, which can exert large forces on the legs and may also induce vibrations in the whole structure from vortex shedding off the round legs. During the installation of MCT's Seaflow machine off Lynmouth special farings had to be fitted to the barge's legs to lower the drag on them and to prevent any vibrations. The top of these farings can be seen in Figure 2.6.

For these reasons, MCT has stated that the current generation of pile mounted tidal current turbines are likely to be restricted to water depths of less than or equal to 40m. There may also be an upper limit on water velocity but this has not been explicitly stated.

2.6 The 2003 study

This case study is primarily based on the results of a study into the potential for the use of marine current energy in Northern Ireland carried out in 2002-2003 by Marine Current Turbines, Kirk McClure Morton, Queens University Belfast and Seacore Ltd. The work was funded by the DTI, The Department of Enterprise Trade and Investment and Northern Ireland Electricity. A summary of the results has been published [2.1]. The conclusions of this case study are derived directly from the data presented in this report.

(Whittaker et al, 2003) [2.1] reports a number of key parameters related to a possible array, or rather three separate arrays. These are reproduced in Table 2.2 and Table 2.3.

Table 2.2 Key parameters for proposed Strangford Array, taken from Table 3 of

Location	Mean max Spring	Mean max Neap	Ratio Neap to Spring	Ratio Ebb to Flood	Water depth at LAT (m)	Distance to connect to grid (Marine equivalent km) ¹	Turbine rotor diameter (m)	Optimum turbine rated velocity (m/s)	Optimum turbine rated power (kW)	Energy capture per year per unit (MWh)
1	3.23	2.57	0.8	0.86	30	1	20	2.45	1,912	8,369
2a	2.95	2.28	0.77	0.91	30	1	20	2.3	1,582	6,865
2b	3.25	2.5	0.77	0.91	30	1	20	2.5	2,032	9,093
3	3.03	2.34	0.77	0.87	25	1	16	2.5	1,300	4,983

(Whittaker et al, 2003) [2.1]

Table 2.3 Key parameters for proposed Strangford Array, taken from Table 4 of (Whittaker et al, 2003)

	Likely time for implementation	Location (Fig 17 ²)	Mean maximum Spring velocity (m/s) ³	Turbine size (rotor diameter) (m)	Rated power (kW)	Number of systems	Gross rated power (MW)	Gross energy capture (MWh/year)	Average cost of energy (p/kWh) ⁴
Demo project	2004-5	2a	2.9	20	1,582	1	1.6	6,865	5.38
1st extension	2006	2b	3.2	20	2,032	5	10.1	45,465	3.04
2nd extension	2008	1	3.2	20	1,912	5	9.5	41,845	3.21
3rd extension	2010	3	3	16	1,308	10	10.3 ⁵	49,830	3.6
Total							31.5	144,005	
Total (excluding demo project)							29.9	137,140	

In these tables, the terms 'Mean max Spring', 'Mean max Neap' and 'Ratio Ebb to Flood' are the constants in the bi-sinusoidal formula for estimating the time variation of the velocity. This is a simplified formula that is sometimes used for initial estimates assessments of tidal-current resources where a full set of harmonic constants is not available. Box 1 explains the mathematical basis for determining tidal cycles. The use of the word 'mean' implies that the values were derived from data on a large number of spring-neap cycles derived either from field measurements or detailed numerical modelling, but (Whittaker et al, 2003) does not say over what period the averaging was done.

¹ (Whittaker et al, 2003) says: '...on-shore connection costs are such that 1km on land costs the same as 0.05km offshore so we have taken the marine cable connection distance and added 0.05km for each on-shore km to arrive at a similar connection cost measured in terms of 'equivalent marine cable'. Therefore the figures in the table above are 'marine cable equivalent distance'.

² Fig 17 of (Whittaker et al, 2003) is reproduced in Figure 1.5. This does not identify locations called '2a' and '2b', but does identify a single location labelled '2'.

³ These figures are different from those quoted in Table 3 of (Whittaker et al, 2003) and reproduced in Table 2.2 of this Case Study.

⁴ These costs are low enough to make this project highly profitable under the existing renewables obligation without further Government support.

⁵ 1308kW × 10 = 10.3MW

Box 1 The bi-sinusoidal formula

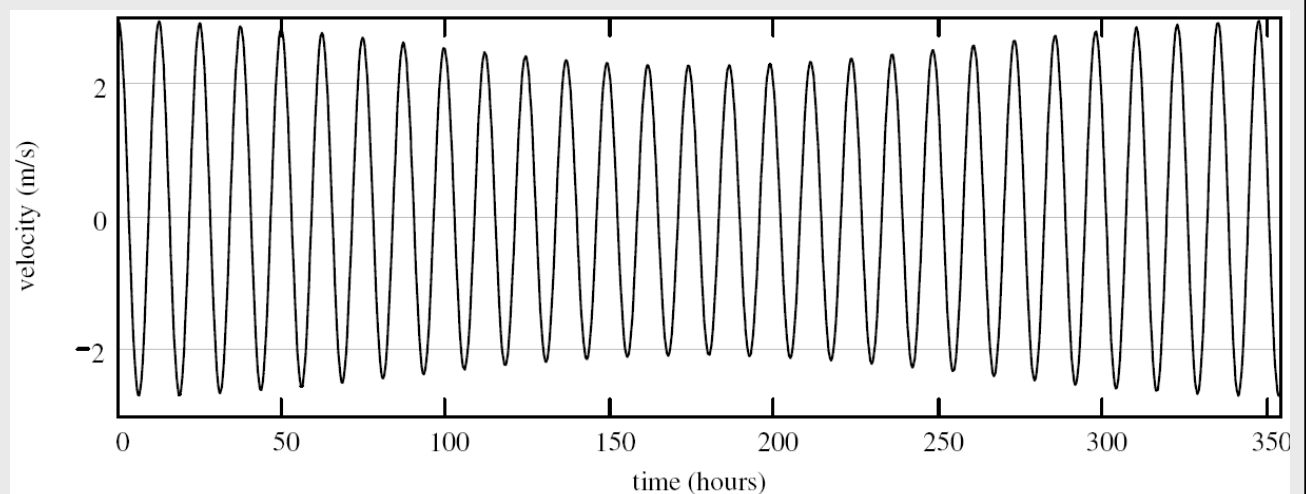
For simple, initial assessments of a tidal current resource, the following formula can be used:

$$v(t) = \frac{1}{1+\varepsilon} \left(\varepsilon + \cos\left(\frac{2\pi t}{\tau_1}\right) \right) \times \left(\frac{1}{2}(a_s + a_n) + \frac{1}{2}(a_s - a_n) \cos\left(\frac{2\pi t}{\tau_2}\right) \right)$$

where:

- τ_1 is the period of the twice-daily tide (12.4 hours)
- τ_2 is the period of the spring-neap cycle (354 hours)
- a_n mean peak neap velocity
- a_s mean peak spring velocity
- ε is a parameter that shifts the cosine curve upwards thereby making the flood velocity greater than the ebb velocity, or vice versa, depending on its value.

Because τ_1 and τ_2 are fixed, only three parameters, a_n , a_s and ε , are needed to characterise the flow regime. Approximations to a_n and a_s can be found on Admiralty navigation charts and tidal stream atlases, or can be estimated using a small number of field measurements. Using the values of these constants from Site 2a in Table 2.2 gives the following time profile of velocity over a spring-neap-spring cycle.



Real tidal currents follow a much more complex pattern than this. For example, the above formula predicts that the spring-neap pattern will repeat indefinitely whereas in real tides spring-neap cycles usually differ from each other. Also, in real tides the floods often follow an alternating pattern with a high peak then a low one then a high one again. The formula cannot model this kind of behaviour.

For accurate work, the time variation of velocity is modelled as a sum of typically ten but in some cases as many as 30 cosine functions each with a different coefficient (called harmonic constants). This requires a much larger number of experimentally determined parameters.

2.7 Energy output

The figures in Table 2.2 and Table 2.3 appear to have been derived from the ‘free-stream’⁶ velocity using the cube law formula for the power output and a bi-sinusoidal formula for the velocity. The mathematics of the cube-law formula are summarised in **Box 2**.

Energy capture from tidal currents flowing in channels like Strangford Narrows is, in fact, more complex than this. The cube-law formula comes from the wind industry, where it is used successfully to model the power output of wind turbines. There are, however, important differences between a wind and a tidal current. The Earth’s atmosphere is several km deep and a wind turbine occupies a tiny fraction at the very bottom of this. The sea, on the other hand, especially in places where tidal turbines are likely to be deployed, is relatively shallow and with a sharp boundary at the top. Tidal turbines occupy a proportionately large fraction of the distance from the seabed to the surface. Similarly in the horizontal direction the atmosphere is effectively infinite compared with the dimensions of a wind turbine. Tidal currents, on the other hand, are often constrained within narrow channels, as in this case, with fixed boundaries on either side.

These differences mean that extraction of energy from a tidal current affects not just its kinetic energy but also the distribution of hydrostatic head along the channel. This has implications for the amount of energy that can be extracted. For any given location there could potentially be significant differences between the power output calculated from the free-stream velocity using the cube-law formula and that calculated using a more rigorous analysis.

However, no detailed analysis of the energy extraction from this site using the latest theories has been carried out, and the scope of this case study, being a review of existing literature, precludes doing so as part of this project. This would in any case be a very complex and time-consuming calculation involving extensive computational modelling and field measurements.

For the purposes of this case study we will assume that the power output of the array is as given in (Whittaker et al, 2003), namely 137,140MWh/year [2.1]. This is slightly less than the amount by which Northern Ireland’s electricity demand has grown each year over the last decade.

Box 2 The cube-law formula

The energy in a tidal current is, by analogy with wind energy, usually expressed as proportional to the cube of the water velocity. The energy flux density (W/m²) is given by $\frac{1}{2}\rho v^3$ where ρ is the density of the water (kg/m³) and v is the magnitude of the velocity (m/s). The energy passing through a disc of area A is thus $\frac{1}{2}A\rho v^3$. A turbine only captures a proportion C_p of this, and so the power output of the turbine is $\frac{1}{2}C_p A\rho v^3$. C_p varies with the current velocity, having a maximum at a particular velocity for which the turbine has been optimised. This is usually the rated velocity. (Ainsworth & Thake, 2006) states that the MCT Seagen machine produces an electrical output of 1MW at its rated velocity of 2.8m/s. This would imply that $C_p = \frac{P}{\frac{1}{2}A\rho v^3} = \frac{10^6 W}{\frac{1}{2} \times 2 \times \pi \times \left(\frac{16}{2}\right)^2 \times 1025 \times 2.8^3} = 0.221$. This is roughly half the value that MCT has claimed in the past for its turbines. When the machine is installed and operating it will be possible to measure C_p experimentally and compare it with its predicted value.

⁶ (ie the velocity before any energy has been extracted).

2.8 Grid connection

The MCT has identified an existing grid connection of 11kV, 1MW capacity within 25m of the shore at the Strangford sewage pumping station [2.7].

It is assumed that the cost of this is included in the capital cost discussed below.

There is an 11kV line supplying the town of Strangford, from the 33kV substation in the village of Bishopscourt, a distance of about 7.5km [2.7]. Following the installation of the Seagen demonstration machine this 11kV line will be operating near maximum capacity and any further development would require an extension of the 33kV system. Information on the cost of extending the 33kV system is not publicly available. The cost has not therefore been included in the generation cost calculations.

2.9 Unit cost of Energy

2.9.1 Size of array

This hypothetical case study has been based on the array specified in (Whittaker et al, 2003) [2.1], consisting of 20 Seagen-style machines with varying diameters and nameplate capacities and producing an annual power output of 137,140MWh/year. As was stated in Section 2.7, it is possible that an array of this size may be sufficiently large to cause unwanted effects on sedimentation dynamics. Further investigation is needed before this question can be definitively answered. For the purposes of this case study, and in lieu of a definitive answer, it is assumed that the array will be as described in (Whittaker et al, 2003) [2.1].

2.9.2 Capital cost

The Seagen project has to date received DTI R&D grants totalling £4,266,750 representing 50% of the total project cost of £8,559,500. An array of 20 devices would not cost twenty times this amount, however. This is because the cost can be divided into a fixed element and a variable element. The fixed element would be independent of the number of devices and so for a multi-device project would be spread over a larger number of machines and so contribute less to the overall cost per MW. The fixed element would consist of detailed design, project management, procurement, geotechnical and environmental surveys, etc.

The variable element would consist of the actual manufacture and installation cost of the machines themselves and their delivery to the site.

There is no information available to determine what proportion of this £8.6 million could be regarded as fixed and which variable.

(Whittaker et al, 2003) [2.1] quotes an example calculation, apparently containing fictitious numbers for illustration purposes only. Because of this it is difficult to draw conclusions from them.

The calculation clearly assumes, however, that only the external costs (i.e. the purchase cost of the rotor, gearbox, etc and the installation contractor's charges), are included in the variable component and that the developers own costs are all in the fixed component. However, we think that a significant proportion of the developer's own costs are likely to be variable, because:

- More design effort is involved in designing a larger array.
- A larger array would be a much more complex project than a single device and would

take longer to manufacture and install, meaning that project management costs will be greater.

- The longer installation time of the project will also mean that the developer's core team will be focused on the project for proportionally longer, and their costs will be proportional to the time spent.
- The variable cost example quoted in [2.1] also does not include the cost of geotechnical and environmental survey work, which would also be greater for a larger array because of the greater seabed area involved.

For all these reasons, it has been assumed that these proportions would be reversed. Therefore, in these calculations a split of 30% fixed to 70% variable has been used.

Consequently, the estimate of the total capital cost of a 30MW array is:

$$0.3 \times £8.6 \text{ million} + 30 \times 0.7 \times £8.6 \text{ million} = £183 \text{ million}$$

This equates to £6.1M/MW (nameplate).

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. 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.

2.9.3 Grid connection cost

The capital cost of the Seagen demonstration device used in the above calculation includes the cost of connecting the machine to the local distribution network. This is to be done via Strangford sewage pumping station. However, the 11kV line that serves the town of Strangford will reach the limit of its capacity when the Seagen demonstrator is connected and to connect additional machines will require the extension of the 32kV system, whose nearest connection point is at the village of Bishopscourt about 7.5km away [2.8]. No information was available on the cost of providing this connection and so this has not been included in cost estimates.

2.9.4 Construction time

It is assumed that the array will take 2 years to build.

2.9.5 Operating costs

No information is available on the operating cost of a tidal current array. The only other full scale tidal current devices to have been installed at sea were The Engineering Business's 'Stingray' machine, which was on station for a total of about 9 weeks [2.9, 2.10], MCT's 'Seaflo' machine, which, although it has been at sea for over 2 years is only known to have actually operated for 68 days [2.6], not all of which involved actually generating power. The proponents of only other prototype device, the Norwegian Hammerfest Strøm machine, have not published any cost information.

The limited information on operating costs that is evident from these projects is unrepresentative of the way in which a fully commercial array would be operated. It has

therefore been assumed that the annual operating cost is 3% of the capital cost. This is at the lower end of the range usually assumed for marine energy projects but in this case the machines will be installed only a few hundred metres from shore, in a sheltered channel so likely to experience less extreme weather than would be expected in the open sea.

2.9.6 Plant lifetime

There is no data on which to base an estimate of the expected lifetime of a tidal current generator. A 20 year life has been assumed, as this seems to be assumed in economic studies of marine energy projects.

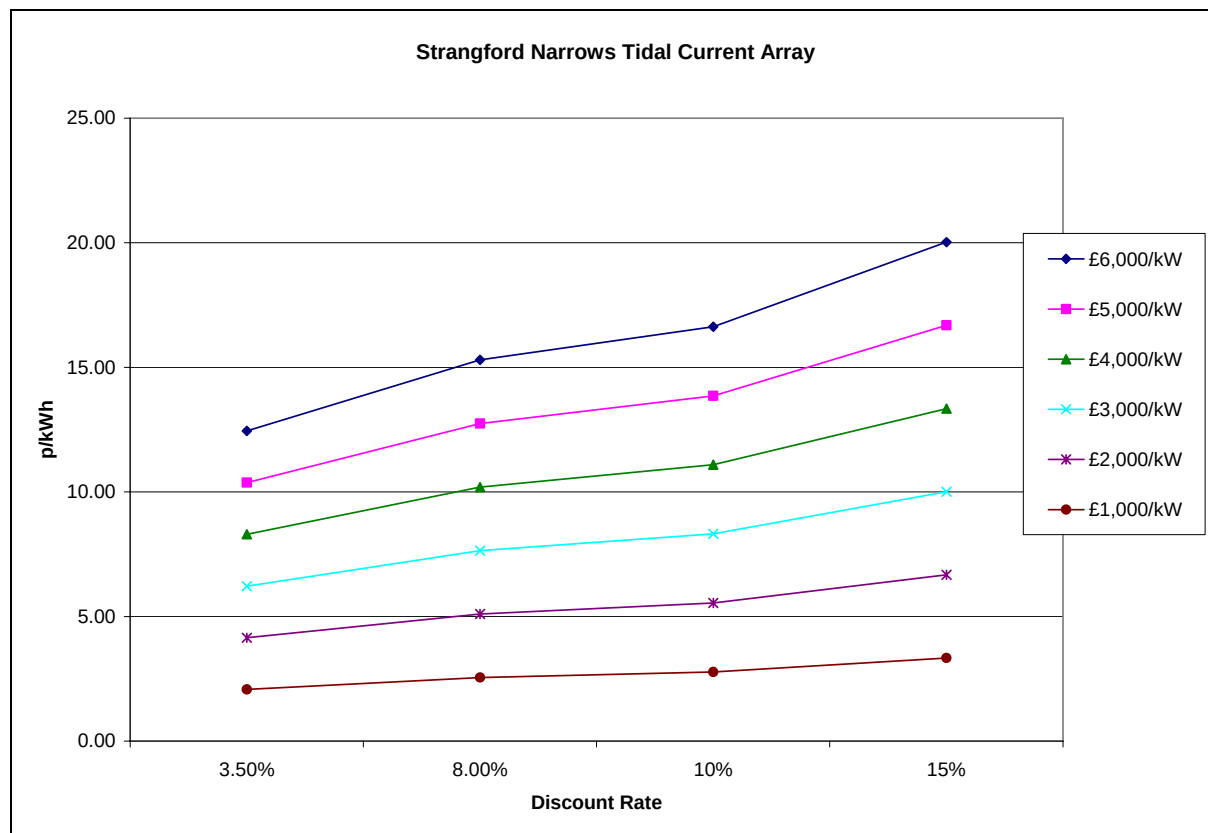
2.9.7 Cost of energy

The unit cost of energy has been calculated using a discount cash flow analysis over a technical life of 20 years (see Appendix 1). 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. The unit cost of generation over a range of discount rates is shown in Table 2.4 and graphically in Figure 2.7.

Table 2.4 - Unit cost of generation relative to capital cost and discount rate for the Strangford Narrows hypothetical tidal current array

Discount Rate →	3.50%	8.00%	10%	15%	
Cost of installed capacity					
£6,000/kW	12.45	15.30	16.63	20.02	p/kWh
£5,000/kW	10.37	12.75	13.86	16.69	p/kWh
£4,000/kW	8.30	10.20	11.09	13.35	p/kWh
£3,000/kW	6.22	7.65	8.32	10.01	p/kWh
£2,000/kW	4.15	5.10	5.54	6.67	p/kWh
£1,000/kW	2.07	2.55	2.77	3.34	p/kWh

Figure 2.7 - Unit cost of generation relative to capital cost and discount rate for the Strangford Narrows hypothetical tidal current array



Two technology assessments commissioned by the Carbon Trust have estimated projected future costs for tidal current technology [2.11, 2.12]. 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. 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.

2.10 Electricity integration

30MW is relatively small by electricity generation standards and a facility of this size would not be expected to cause significant problems if fed into the local distribution network or to require grid strengthening.

The power output of a tidal-current generator follows a regular pattern of peaks and troughs with zero power output in the troughs and the peaks occurring every 6.2 hours. This makes

it certain that some of the peaks will co-inside with troughs in demand and some of the troughs will coincide with peaks in demand.

However, during a demand trough the power consumed is still many times the output of the Strangford array and, provided that the operator offers the electricity for sale at a low enough price, it should be possible to sell all of it, even where the peak output coincides with a demand trough.

The main concern regarding the grid integration of the electricity from the array is its effect on the voltage of the local transmission system [2.8]. This could potentially be mitigated by the use of suitable power conditioning equipment.

Also, as noted in Section 2.8, the 11kV line supplying the town of Strangford is not sufficient to accommodate an array of devices and an extension of the 32kV system, whose nearest connection point is at the village of Bishops court about 7.5km away, would be required.

2.11 Embedded Carbon

The only detailed figure for the mass of any part of the Seagen machine refers to the pile, is 270 tonnes [2.7]. The volume and hence the mass of the other components of the machine has been based on the dimensions shown in Figure 2.4. Overall, it is estimated estimate that one turbine contains about 366t of steel and 0.55t of copper implying an embedded carbon emission of 598t of CO₂. Consequently, the array of 20 devices would have a total embedded carbon of $598 \times 20 = 11,960\text{t}$ of CO₂.

The proposed 20 machine array, not including the demonstration device, would generate about 137GWh/year [2.1]. Assuming an average emission factor of 0.43 kg CO₂/kWh the Strangford array would save about 58,910 tonnes of CO₂ per year. The embedded carbon would be 'paid back' in about 2.5 months.

2.12 Regional and social benefits

2.12.1 The local economy

No hard data exist on the effect of the construction of a tidal-current array on the local and regional economy. ADAS Consulting Ltd and the University of Newcastle [2.13] studied the impact of a number of UK wind, hydro and biomass facilities on their local economies. It is proposed to take the wind projects studied in this reference as representative of the effects on the local economy that would be observed if the Strangford array were built.

The authors of the ADAS study collected detailed information on:

- Income and expenditures of individuals who had gained employment as a result of the development of the renewable energy facilities.
- The initial capital expenditure involved in constructing the project.

They used this information to estimate direct, indirect and induced effects on local employment. The analysis included the effect of the initial capital injection due to the construction of the project and the continuing revenue stream due to electricity sales.

The local area was defined as that within a 30km radius of the facility.

Five wind farms were studied. Table 2.5 lists them and their characteristics.

Table 2.5 - Wind farms studied in (ADAS, 2003) [2.13]

Wind Farm	Location	Start date	Installed capacity (MW)
Harlock Hill	Cumbria	1997	2.5
Deli near Delabole	Cornwall	1991	4
Lambrigg Windfarm	Cumbria	2000	7
Hagshaw Hill Windfarm	Lanarkshire	1995	16
Carno Windfarm	Powys	1997	34
		Total	63.5

In terms of capacity, these wind farms are very small. Only one of them is comparable to the proposed Strangford tidal current array and in total they amount to about twice the capacity of the Strangford array. Table 2.6 lists the impact of the construction of these five wind farms on the local economy. This shows that around 5% of the total project cost was spent in the local area and that about 1.2 job-years per MW of installed capacity were generated in the local area.

Table 2.6 Impact of initial capital injection to build renewable energy facility - average values of all the case study sites

	Average per site	Total of all five sites
Total cost (£k)	9,520	47,600
Local expenditure (£k)	495	2,475
Percentage of local expenditure to total cost	5	5
Number of job years	15	75

If these characteristics are applied to the Strangford array, then about £9.2 million would be injected into the local economy. 1.2 job-years per MW would imply that the proposed Strangford narrows array would stimulate 36 job-years of employment during construction. In the wind example, each job-year is equivalent to £33k of the local expenditure. If it is assumed that each £33k of the £9.2M injected into the local economy by the construction of the Strangford generates one job-year then 279 job-years would be stimulated in the local economy.

Table 2.7 lists the ongoing benefits to the local economy from the continuing operation of the five wind farms studied.

Table 2.7 Ongoing benefits to the local economy from the continuing operation of the five wind farms [2.13]

	Average per site	Total of all five sites
Full-time local jobs	0	0
Part-time local jobs	2	10
Rent (£k)	27	135
Business rates (£k)	30	150
Community payments (£k)	9	45
Inputs from local firms (£k)	105	525

The study found that the continuing operation of the five wind farms would result in a total of 10 part time jobs in the local area equal to 0.16 jobs per MW. On this basis the Strangford array would create about five part-time jobs in the local area.

2.12.2 Visual impact and effect on the landscape

Figure 2.88 shows an impression of what the project's proposers think the Seagen turbine will look like from the shore. Although the turbine itself would look enormous if it were erected on land, when installed the majority of the machine is below the water level with only the top of the 3m diameter pile and the pod visible above the water line. In the picture Figure 2.8, the turbine is a considerable distance away, near the opposite shore and further along the channel. Viewed from the nearest point on the shore it would be more visually intrusive.

The proposed array would involve 20 such pods arranged in a line parallel with one shore and spaced a few hundred metres apart. This could potentially make the array more visually intrusive.

Figure 2.8 Artist's impression of visual of appearance of Seagen turbine [2.1].



2.12.3 Impact on leisure and commercial activities

Part of the reason why the arrays are configured as lines parallel to the shore is if they were arranged across the channel it would prevent the passage of craft. Each turbine will require an exclusion zone to prevent fishing lines or nets becoming entangled in the rotors.

2.12.4 Facilities for construction/maintenance programmes

The towns of Portaferry and Strangford are suitable for landing boats. The city of Belfast, with its docks and shipbuilding facilities, is accessible by sea roughly 70km around the coast.

2.13 Environmental Issues

Highlights

- Strangford Lough is a European site of international conservation importance for birds, natural habitats and species.
- Multiple national designations including a Marine Nature Reserve.
- Key environmental sensitivities/constraints include maintaining the Lough's sediment transport processes, water quality and landscape/seascape.
- Biological sensitivities include the maintenance of benthic communities, fish and shellfish, birds and marine mammals.
- Oyster farming is the most economically important fishery in the Lough.
- The Lough is a centre for tourism with water-based activities such as boating, sailing and SCUBA diving popular.
- The Lough supports a rich archaeological and cultural heritage resource.

Almost land-locked, Strangford Lough is separated from the Irish Sea by the Ards Peninsula to the east and is bounded to the south by the Lecale coast. The Narrows, an 8km long channel with a minimum width of 0.5km, connects it to the open sea. This narrow channel has extremely strong currents of up to 4m/s. The Lough is 30km long from head to mouth and up to 8km wide. For the most part, the Lough is less than 10m in depth with a deeper channel up to 66m deep extending from the Narrows up the central portion of the Lough.

The Lough's west shore has numerous islands and there are extensive areas of mudflats and sandflats mainly at the northern end, with gravel, cobble, boulder and rocky shores further south. The Lough also has areas of saltmarsh, the most extensive being in the Comber river estuary.

The Lough supports a wide range of marine habitats and communities with over 2,000 recorded species. It is important for marine invertebrates, algae and saltmarsh plants, for wintering and breeding wetland birds, and for marine mammals. This variety and richness of habitats and species has led to the Lough receiving multiple and overlapping designations for nature conservation.

Other users of the Lough include tourism particularly outdoor recreation (e.g. sailing, diving, walking, bathing, angling, and bird-watching). Shellfish aquaculture and commercial fishing are also important and archaeological evidence of fish traps form part of the Lough's rich archaeological and cultural heritage resource which dates back to the early Mesolithic.

2.14 Summary of key environmental sensitivities/constraints

Table 2.8 – Summary of key environmental sensitivities/constraints

Feature	Summary	Potential adverse factors
Seabed sediments and transport	• Bedrock and boulders predominate in the Narrows, moving through cobble, gravel and sand to extensive mudflats in the northern part of the Lough. Local variation due to the effects of shelter and currents	• Physical disruption to tidal flows may affect

Feature	Summary	Potential adverse factors
processes	around islands and the rock and boulder platforms (known as pladdies). • Prevailing southwesterly waves cause sediment erosion on the eastern shore of the Lough. The northern mudflats act as a sink for this sediment [2.14].	sediment transport.
Hydrology	• Majority of the Lough less than 10m in depth with water depths reaching 66m in central channel [2.15]. • Mean spring tidal range is 3-4m [2.16]. Extremely strong tidal currents of up to 4m/s in the Narrows reducing as the Lough widens to the north. Topography of the Narrows causes distinctive, swirling turbulence, apparent on the water surface. • Water in the southern part of the Lough similar to Irish Sea water whereas water at the northern end and in peripheral areas has different characteristics of temperature, salinity and plankton [2.14].	• Disruption of tidal flows, levels of vertical mixing and light penetration, salinity.
Water and sediment quality	• Water quality generally good, although some local effects from discharges of storm water and sewage from peripheral housing areas. • Sediment metal concentrations close to background concentrations [2.17].	• Contamination. • Disruption of tidal flows may allow accumulation of contaminants.
Landscape/ seascape	• Relevant landscape character areas include Strangford drumlin and islands, Scrabo, Ards farmlands and estates, Ballyquintin and Lecale coast and Portaferry and North Lecale [2.18]. • The Lough forms part of the Strangford and Lecale Coast Areas of Outstanding Natural Beauty.	• Visual intrusion. • Noise. • Change to landscape character.
Coastal habitats	• Relevant BAP priority habitats include saltmarsh, vegetated shingle, and maritime cliff and slope [2.19].	• Habitat loss
Intertidal and subtidal habitats and communities	• Large expanse of intertidal habitats with about 30% of the Lough's surface area intertidal [2.15]. • Lough supports a wide variety of intertidal and subtidal habitats including BAP priority habitats such as maerl beds, mudflats, saline lagoons, seagrass beds, sheltered muddy gravels, <i>Modiolus</i> beds, mud in deep water, sublittoral sands and gravels, and tidal rapids [2.18]. • Encrusting epifauna (e.g. ascidians, sponges and hydroids) on bedrock and boulders in the Narrows. • Dense aggregations of brittle stars found on gravel in the lower Lough. • Internationally important horse mussel beds in areas of moderate current and below 10m depth. These beds are highly diverse with records of over 300 associated infaunal and epifaunal species. Considerable trawling damage to these beds in the northern part of the Lough where they used to co-exist with scallops [2.18].	• Physical disturbance. • Habitat loss

Feature	Summary	Potential adverse factors
	Sea pens and brittlestars in fine sand and mud substrates with <i>Nephrops</i> in stable muds.	
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	- Sprat spawn in the Lough (May-August) and a number of species use the Lough as a nursery area including cod, haddock, herring, lemon sole and whiting [2.19]. - Species of conservation importance such as the basking shark are also present occasionally. - Exploited shellfish species include scallops, oysters, whelks, periwinkles, crabs, <i>Nephrops</i>, lobsters and squat lobsters.	- Physical disturbance to spawning grounds. - Collision risk. - Noise.
Birds	- Most important coastal site in Northern Ireland for wintering water birds (e.g. geese, ducks and waders). - Islands and surrounding lands provide valuable nesting grounds for a variety of birds including Arctic, sandwich and common terns which feed in the Lough. - Seabird visitors to the Narrows especially after winter storms may include gannets, kittiwakes and Manx shearwaters [2.14]. - Overall vulnerability to surface pollution very high for 6-8 months of the year [2.20].	- Collision risk with diving seabirds. - Disturbance during installation and maintenance activities.
Marine mammals	- Most important breeding site in Ireland for common seal. Smaller numbers of grey seal. - Both seal species distributed throughout the Lough and haul out at established sites including the shores of the Narrows. - Common seals most sensitive to disturbance during the breeding season in June/July. Grey seals breed between September and November. The seals are not restricted to the Lough and forage in the Irish Sea [2.21]. - Harbour porpoise forage in the Narrows. Bottlenose dolphin, pilot whales and killer whales less common [2.14].	- Noise. - Disturbance during installation and maintenance activities. - Collision risk.

2.15 Conservation sites and other key environmental sensitivities

Strangford Lough is designated as both a Special Area of Conservation under the Habitats Directive⁷ and a Special Protection Area under the Birds Directive⁸ (Figure 2.9 and Table

⁷ Council Directive 92/43/EEC on the conservation of natural habitats of wild flora and fauna

⁸ Council Directive 79/409/EEC on the conservation of wild birds

2.9). The Lough is also a Ramsar site under the Convention on Wetlands of International Importance.

Table 2.9 – Nature conservation sites of international importance

Map ref	Site	Area (ha)	Key features
A	Strangford Lough SAC	15,398.54	Mudflats and sandflats not covered by seawater at low tide, coastal lagoons, large shallow inlets and bays, reefs, annual vegetation of drift lines, glasswort and other annuals colonising mud and sand, Atlantic salt meadows, perennial vegetation of stony banks, common seal.
B	Strangford Lough SPA/ Ramsar/IBA ¹	15,580.79	<i>During breeding season:</i> Arctic tern <i>Sterna paradisaea</i>, common tern <i>Sterna hirundo</i> and sandwich tern <i>Sterna sandvicensis</i>. <i>Over winter:</i> Bar-tailed godwit <i>Limosa lapponica</i>, golden plover <i>Pluvialis apricaria</i>. <i>Migratory species:</i> Knot <i>Calidris canutus</i>, light-bellied brent goose <i>Branta bernicla hrota</i>, redshank <i>Tringa totanus</i> and shelduck <i>Tadorna tadorna</i>. <i>Assemblage qualification:</i> Regularly supports 70,200 wintering waterfowl. <i>Non-bird Ramsar features:</i> Supports a variety of important wetland features. Areas of fringing saltmarsh and freshwater habitats support a diversity of wetland plant species. Strangford Lough supports one of the most extensive saltmarsh areas in Northern Ireland. Supports an important assemblage of vulnerable and endangered wetland plants and animal species.

Note: ¹Strangford Loch and Islands Important Bird Area covers the same area and species as the SPA but also includes curlew.

Source: JNCC website, BirdLife International website.

Areas of Special Scientific Interest (ASSIs) represent the main form of domestic statutory protection for sites of high nature conservation value. Those present in and around Strangford Lough are highlighted in Table 2.10 and Figure 2.9.

Table 2.10 – ASSIs in and around Strangford Lough

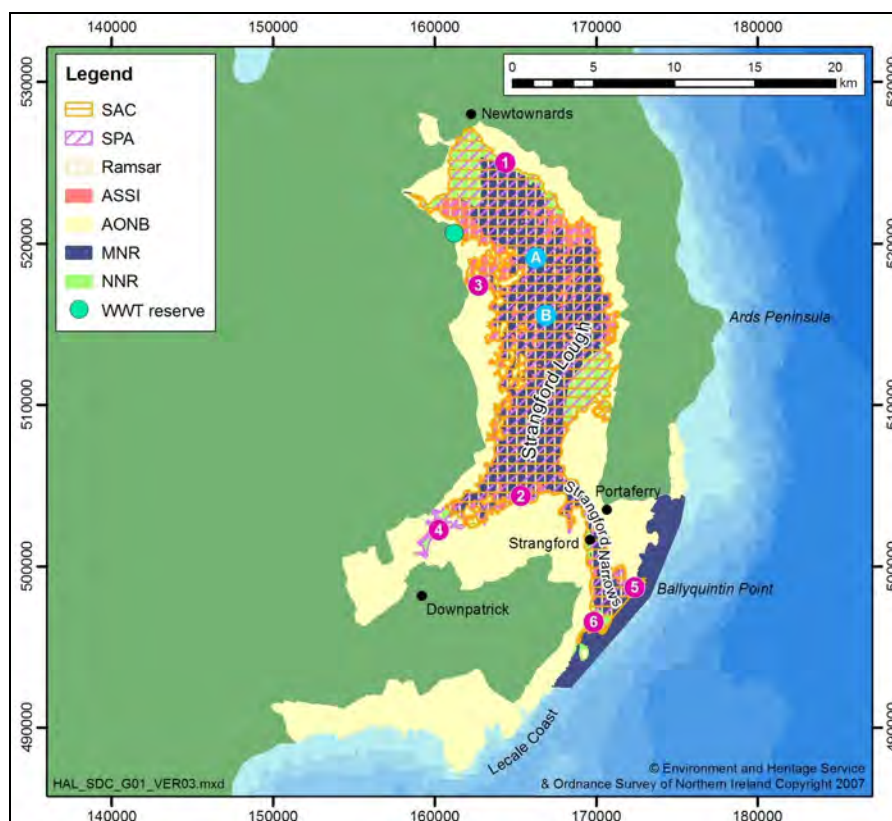
Map ref	Site	Area (ha)	Key features
1-3	Strangford Lough (Parts 1, 2 & 3)	4,107.5	Breeding seabird assemblage, breeding wader assemblage, breeding wildfowl assemblage, coastal saltmarsh, coastal vegetated shingle, common seal, intertidal mud/sand, intertidal rock, invertebrate assemblage, maritime cliff and slope, waterfowl assemblage.

4	Quoile	210.4	Fen, higher plant assemblage, purple moor-grass and rush pasture, upland oakwood.
5	Ballyquintin Point	74.1	Coastal vegetated shingle, earth science.
6	Killard	111.5	Earth science, higher plant assemblage, invertebrate assemblage, maritime cliff and slope.

Source: EHSNI website.

The whole of Strangford Lough up to mean high water mark was designated as a Marine Nature Reserve in 1995. The MNR extends seawards of the Narrows into the Irish Sea to include areas north and south of the mouth of the Lough. The MNR provides for management for nature conservation purposes and for study and research [2.22]. There are also seven coastal National Nature Reserves on or around Strangford Lough: North Strangford Lough, the Dorn, Granagh Bay, Ballyquintin Point, Killard, Cloghy Rocks and Quoile Pondage [2.18]. Castle Espie on the north west coast of the Lough is a Wildfowl and Wetlands Trust reserve [2.23].

Figure 2.9 – Conservation sites and other key features



Note: Strangford Loch and Islands IBA covers the same area as Strangford Loch SPA/Ramsar and is not shown.

The **Strangford Area of Outstanding Natural Beauty** covers much of the Lough. Partly drowned drumlin hills create a large number of islands, while, on shore, the hills form a pleasant rolling landscape. The **Lecale Coast AONB** covers the coastal area between Strangford Lough and the Mourne. The coastline is characterised by coves, dramatic headlands and secluded sandy beaches.

Important geological sites include the raised cobble beach at Ballyquintin Point and the Killard Point glacial moraine [2.18].

2.16 Other uses/users

Commercial fishing has declined rapidly in recent years. Concerns that the use of mobile fishing gear was causing severe damage to the sea bed, in particular, to the horse mussel reefs, led to a temporary total ban of dredging and trawling. Potting can still take place during the ban and vessels target crabs, whelks, lobsters and *Nephrops*. Shellfish cultivation of oysters, mussels, clams and scallops has increased in the Lough in recent years. Even before the ban on mobile fishing gear, oyster farming was, and still is, the most economically important fishery in the Lough [2.21].

The Lough is an extremely important tourist destination with outdoor recreation (e.g. walking, bathing, angling, bird watching etc.) increasingly popular. Boating and sailing activities are especially popular with a large number of vessels and clubs around the Lough [2.24]. Other water-based activities include windsurfing, jet skiing, water skiing and SCUBA diving. A regular ferry service operates about every 15 minutes between Strangford and Portaferry, transporting up to 28 cars across the Narrows [2.25].

Archaeological surveys of the intertidal zone [2.26] indicate that the Lough supports a rich archaeological and cultural heritage resource dating back to the early Mesolithic period. The survey found evidence of submerged landscapes of peat and forests indicating post-glacial sea-level rise and landscape change. Other finds included more recent fish traps, landing jetties and evidence of the region's historic reliance on boats for trade, communication and resources [2.27].

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3 Pentland Firth tidal current array

3.1 Background

Tidal current energy using tidal current 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 capture, the UK a high proportion of sites exhibiting extreme tidal currents. These extreme tidal currents are expected to be targeted for exploitation by first generation tidal 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 [3.1].

A number of different tidal current 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 2002. 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 development of a Pentland Firth tidal array, an extrapolation of MCT's Seagen technology is adopted.

The Pentland Firth is the channel that separates the mainland of northern Scotland from the Orkney Islands. The region has been described as the Saudi Arabia of world tidal energy [3.2] and is infamous with mariners for the extreme tidal currents affecting the Firth (tidal currents exceeding 7m/s have been reported [3.3]). The Carbon Trust Marine Energy Challenge identified that the Pentland Firth and approaches (encompassing the Pentland Skerries, Duncansby Head, South Ronaldsay (Pentland Firth), Hoy and South Ronaldsay (Pentland Skerries) sites) contain well over 40% of the currently recognised UK tidal current energy resource [3.4]. It is therefore sensible to assume that the Pentland Firth is a location that would be high on the agenda for large scale development when the developing first-generation TEC device technologies reach maturity. On this basis, the Pentland Firth appears an obvious candidate to examine as a hypothetical case study.

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 Pentland Firth. 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 technology was on the market development of a large tidal current array would demand detailed understanding of the existing hydrodynamic resource, and the impact of any developments on this underlying resource. The scheme would be required to meet detailed design and consent requirements compared 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 to properly inform the project design and implementation [3.5]). The case study presented here should be regarded as an initial 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. At present, there is some 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 treated as initial approximations.

3.2 The location

The Pentland Firth separates the coast of mainland northern Scotland from the Orkney Islands (Figure 3.1). The Firth connects North Atlantic Waters in the west to the North Sea in the east. The Firth is around 25km long and varies between 10 and 15km wide along its length. There are two major islands in the Firth, Stroma and Swona, with the small island formation of the Pentland Skerries mid-channel at the eastern end. In general the sea bed slopes away from the coastline fairly steeply, reaching 50-70m deep within 1-2km. The mid-channel region of the Firth is of fairly uniform depth of 70-80m. The sea bed gradient is therefore very shallow away from the immediate shelving adjacent to the coastline.

Figure 3.1 Pentland Firth (source: adapted from private communication, Alan Owen, RGU)



The dominant tidal regime in the Pentland Firth is a mixture of tidal streaming and hydraulic current (see Box 1). Tidal streaming is particularly apparent in the region of reduced cross-section between the islands of Stroma and Swona. The hydraulic current driven through the channel by phase differences at either end of the Firth explains why a relatively common tidal range of 2.5m at spring tides can produce the extreme tidal currents observed in the channel.

Tidal currents through the channel tend to follow bathymetric contours. This ensures that in large extents of the Firth, 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. However this general rectilinear flow theme does not hold true in specific regions of the Firth which are known to be subject to eddy structures (see Admiralty Chart 2162). The islands in the Pentland Firth produce significant eddy structures in their wake, extending 2-4km downstream as the tide peaks. Similarly, some of the headlands also generate major eddy structures (e.g. Brims Ness on the southern tip of Hoy). 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.

Box 1: Couch & Bryden have characterised the three mechanisms that can give rise to extreme tidal current regimes²:

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.

The University of Highlands and Islands Millennium Institute has conducted a low level review of potential developments in the Pentland Firth [3.6]. Some of the output from this review is pertinent, and the relevant findings on geology and ecology, grid integration, and navigation, shipping and fisheries are summarised in the relevant sections below.

- **Geology and Ecology:** Predominant sea-bed materials in the region are red sandstone, flagstones and conglomerates at shallow inclines. These materials are generally well suited for potential development employing a piled monopole structure. There is little unconsolidated sediment and few established benthic communities (this is not surprising given the long term scouring effect of extreme tidal currents). The lack of sediment while benefiting installation of the TEC device is a potential issue as it limits opportunities for burying undersea cables associated with any prospective development. Any impact of development on the existing benthic communities is a potential environmental concern which would have to be investigated in the Environmental Impact Assessment (EIA) required to obtain necessary development permissions from the Crown Estate (the nominal landowner) and other relevant legislative bodies. A clear pre-requisite of any development would be detailed mapping of local seabed characteristics of prospective sites to assist in site selection, development of drilling strategies and design of the monopole structure. Orkney and the northern tip of Caithness on either side of the Pentland Firth are maritime coastal areas of considerable ecological interest. The region contains a number of candidate Special Areas of Conservation (cSAC) under the EU Habitats Directive, as well as a number of Special Protection Areas (SPAs) under the EU Birds Directive.

- Grid integration: 33kV power lines depart from Dunnet undersea to Orkney and overland to Thurso. Thurso has a 132kV line which in turn links to the 275kV line at Dounreay.
- Navigation, shipping and fisheries activity: Trawl fishing is restricted in the Pentland Firth due to the relatively low numbers of fish and the difficulties of working in energetic tidal currents. Similarly, areas with strong currents in close proximity to shore are unsuited for safe marine travel. However, the Pentland Firth has one of the highest traffic shipping densities in Scottish waters as vessels transit between the east and west coasts of the UK and with Atlantic traffic en-route to and from the Balkans and Russia. Any potential impact on ferry connections between the mainland and Orkney Islands would also require investigation as these ferry crossings form part of the lifeblood of the Orkney communities. Any surface piercing TEC device would, therefore, require a clear exclusion zone for mariners. Such exclusion zones would also impact recreational sailors.

3.2.1 Site selection

A number of publications provide guidelines towards conducting site selection [3.1, 3.7–3.9]. 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 to determine the suitability of the site. For this analysis the following criteria were identified as being key to identifying a suitable site:

1. Spring tidal peak velocity greater than 3+ m/s, which relates to the *theoretically available resource*.
2. Area of bathymetry suitable for locating a minimum of 50 turbines (acceptable depth range 25-45m), which relates to the *technically available resource*.
3. It is envisaged that any spare capacity on the existing 33kV inter-connect between the Orkney Islands and the mainland will be taken up by wind energy projects already underway or at an advanced development stage. Therefore, due to the exorbitant costs of undersea cabling, only sites on the mainland side of the Firth are considered for this study. This is an impact related to consideration of the *practically available resource*. If the Orkney Islands are to be fully exploited as a renewable energy resource (wind, wave and tide), this issue will need to be addressed.
4. Consideration of potential impact on shipping lanes which also impacts on the *practically available resource*.

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 (eg grid accessibility, competing use (MOD, shipping lanes, etc.), environmental sensitivity).

Applying the first criterion does not narrow the search down significantly. The second criterion however has a major impact on limiting the available site locations. Only three locations meet the second criterion, the first off of Duncansby Head, the second in the inner sound between Stroma and the mainland, the third to the south of South Ronaldsay. The first two locations have a similar impact on the final criteria, whereas the South Ronaldsay site is filtered out of the search by the third criterion. The Duncansby Head location (see Figure 3.4) was eventually selected as the preferred development site as it has a larger tidal resource, characterised by maximum spring and neap tidal velocities of 4.15m/s and 1.95m/s respectively.

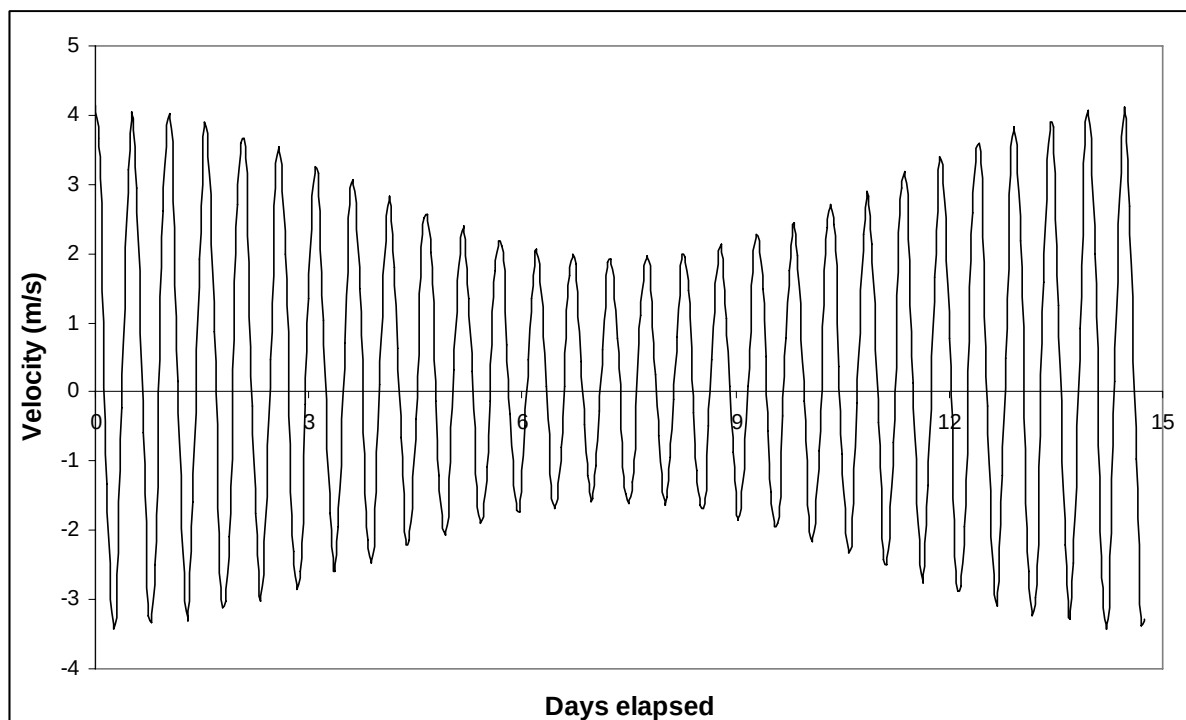
3.2.2 Resource analysis

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 Energy & Environment is developing a protocol for the DTI's Marine Renewable Deployment Fund programme, which incorporates a methodology for such analysis [3.10, 3.11]. However, in this case, no site specific data are 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 Duncansby Head has been modelled using a simple bi-sinusoidal formula operating on the parameters shown in Table 3.1 obtained from three corroborating sources [3.12-3.14] (see Figure 3.2). The data available in the referenced material support 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 3.1 – Key parameters characterising the Duncansby Head site tidal current resource

Mean max Spring velocity	Mean max Neap velocity	Ratio Neap to Spring	Ratio Ebb to Flood
4.15m/s	1.95m/s	0.47	0.83

Figure 3.2 – Velocity variation for a typical Spring-Neap cycle from a bi-sinusoidal simulation at the chosen site off of Duncansby Head.



3.3 The technology

This case study has been based on MCT Ltd's 'Seagen' machine designed for deployment in Strangford Narrows [3.15]. A further report conducting scoping studies based upon the Seagen concept focussed on the future development of an array of tidal devices in Strangford Narrows provided further details of scaled up device performance [3.16]. This

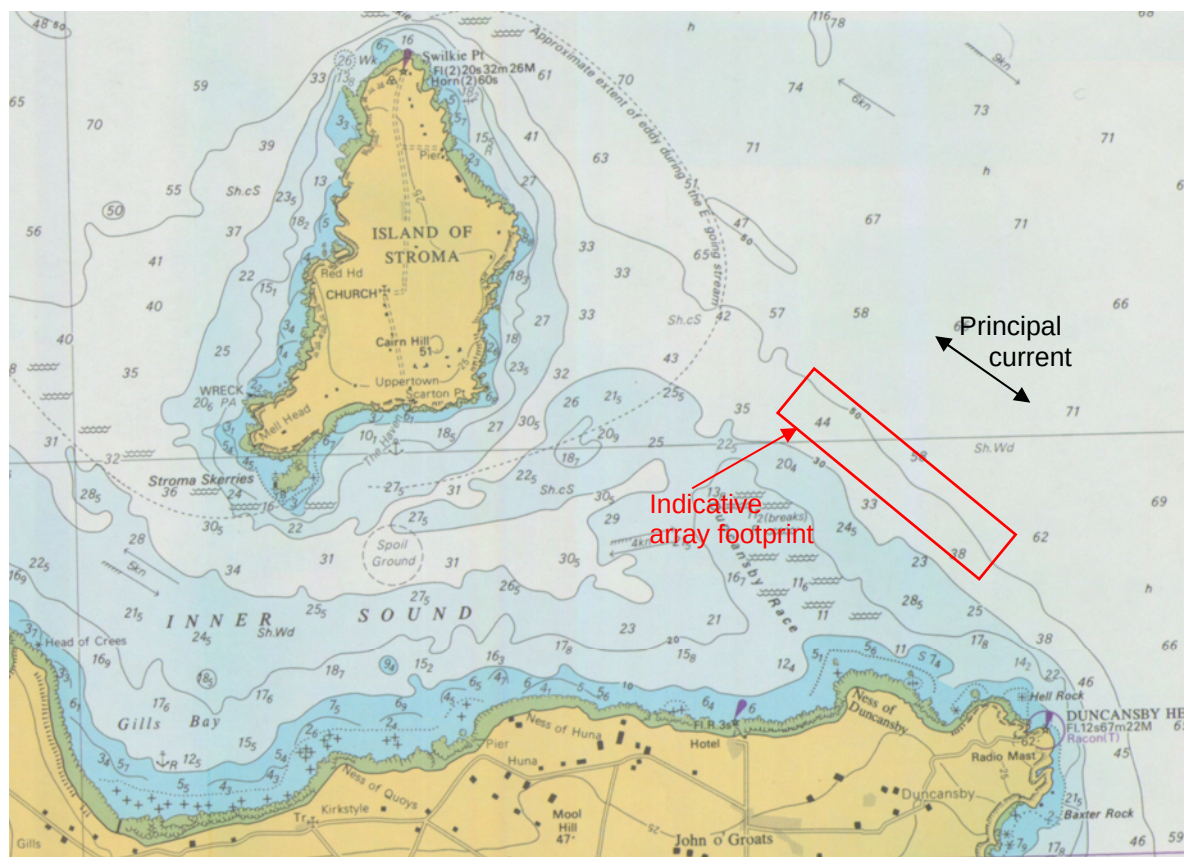
has proved useful in enabling this study to perform similar operations as detailed in the following section.

3.4 The proposed array

The concept for this case study suggested the development of a 200MW installed tidal current array. The Pentland Firth is, as already outlined, recognised as one of the world's most energetic tidal current regions. However, as further explored in Section 2.2, first-generation TEC device technology will only be able to exploit a very limited subset of the theoretically available resource due to technical restraints, most significantly depth limitations. The preferred site identified lies to the north of Duncansby Head.

The array footprint is indicated on Figure 3.4. The shape of the footprint is constrained by shelving of the bathymetry in the area. The downstream extent of the array was constrained during the design process in an attempt to reach 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, as detailed in Section 3.4.1.

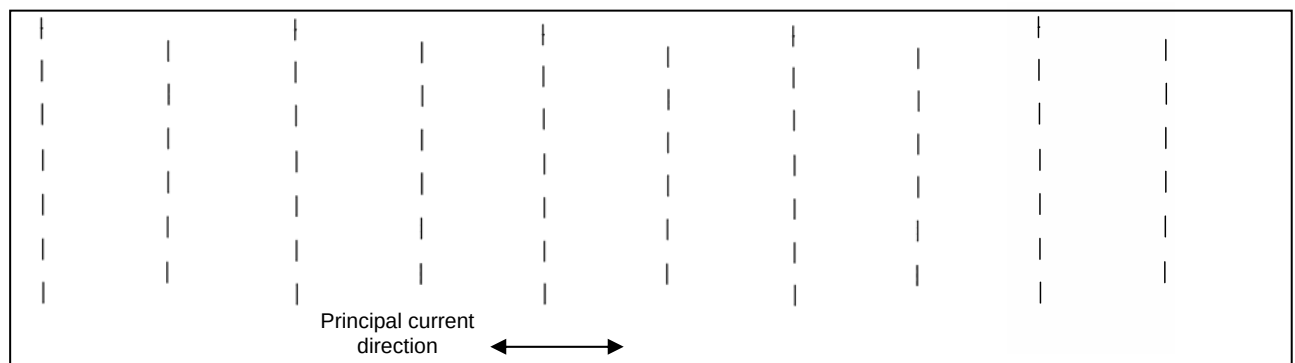
Figure 3.4 Duncansby Head site (source: Admiralty Chart 2162, scale 1:50,000).



The width of a Seagen device is taken as being 43m. The spacing between devices orientated in the direction of the flow is selected as one device width laterally and six device widths in the downstream direction (258m). The devices are 'staggered', so the effective length between one device and the next device directly behind it is twelve device widths (516m). 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 very inefficient when considering cost, as connecting all the devices to the local substation becomes excessively 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 Duncansby Head site, shelving of the bathymetry limits the width of the array. The lowest astronomical tide (LAT) in the region is + 0.4m above Chart Datum. Assuming a minimum clearance of 5m 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 20m turbine is 29m. This provides 4.4m of clearance between the sea surface at LAT and turbine swept area. The other extreme of installation depth is limited by provision of the necessary equipment to install the device (typically a jack-up rig as used in the oil and gas sector), and the position of the turbine in the water column with respect to the peak resource velocity (typically in the upper half of the water column). The cost of hiring a jack-up rig varies significantly typically correlated with the price of oil and gas. This has proven to be a limiting factor in the deployment of pre-commercialisation prototype TEC devices. However, it is realistic to assume that this will not be as major a concern for the development of a large facility. For instance, the mobilisation and transport costs for a jack-up rig are a large component of the cost when deploying only one device. The impact of this aspect on budget will be significantly reduced when shared between multiple devices. It has therefore been assumed for this analysis that TEC device deployment will be limited more by advantageous positioning in the water column. Maximum deployment depth has therefore been set at 46m, envisaging that the turbine will be mounted at the mid-point of the depth of the device installation. Consequently, for the Duncansby Head site, the width of the array to 7 devices to stay within the specified depth limits (29-46m). The relative position of the devices is therefore as indicated in Figure 3.5, with 5 rows of 7 devices interspersed with 5 rows of 6 devices for a total of 65 installed Seagen-type devices. Therefore, the length of the array is 2,322m. To meet the brief of investigating a 200MW installed capacity facility it is therefore obvious that the TEC device technology employed will have to be rated at about 3MW.

Figure 3.5 Relative positions of the 65 3MW rated Seagen devices in the proposed array



3.4.1 Array effects

It is well understood that extracting energy from the tidal system will have some effect on the local flow conditions [3.17, 3.18]. Understanding 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. To provide some insight into the potential significance of array effects on the available resource, some simple generic numerical model experiments were conducted. It is important to acknowledge the limitations of this analysis, and to advise that the results are taken only as being indicative rather than definitive. Some of the output from this analysis is presented in Figures 3.6 and 3.7. The results presented are stream-wise cross-sections taken through the centre of the model domain, which is coincident with the centre of the array (see Figures 3.5 and 3.7). 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 3.6 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

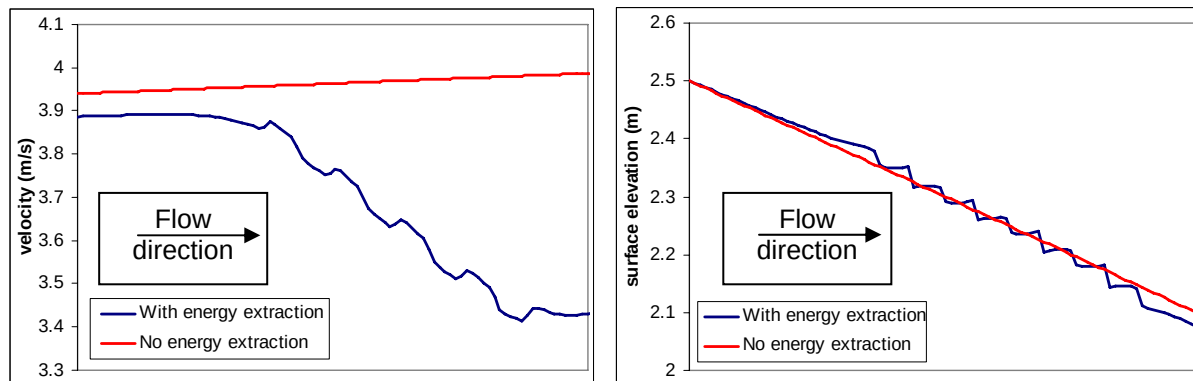
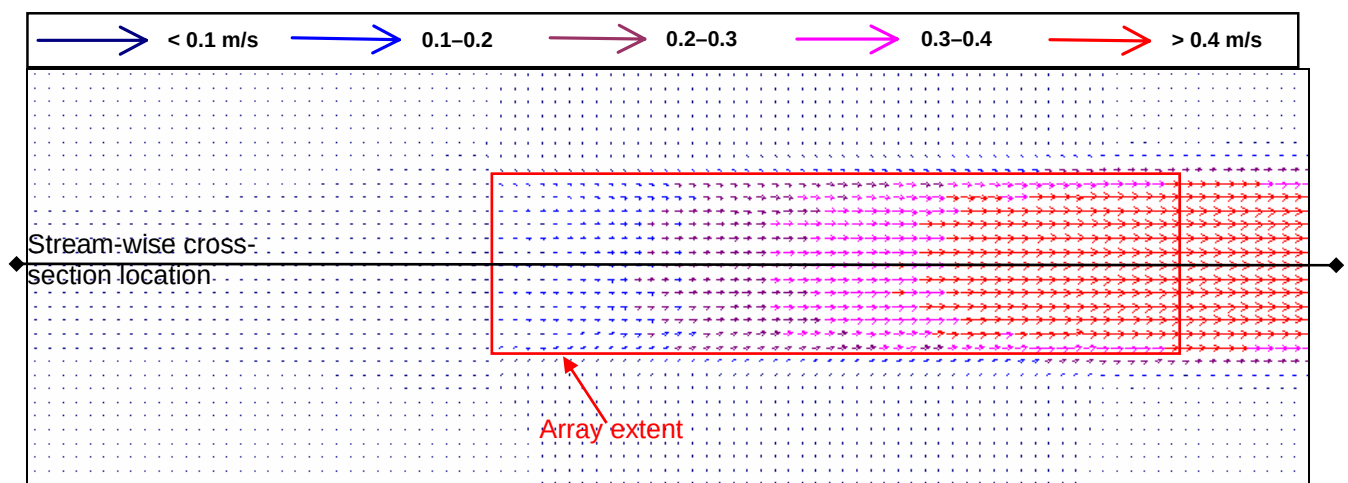


Figure 3.7 Modelled residual current velocity at high water spring tide peak between no extraction and with extraction (i.e. with extraction result subtracted from the no extraction case) by the array outlined in Figure 3.5 in a highly idealised domain.



In summary, the results demonstrate that operation of the array has 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 tidal current device 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 devices in the array by about 12-14% 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 favourable 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. For the Pentland Firth, the width of the channel cross-section is 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 1-2km if the typical effect of an island on flow development in the Firth is to be used as a benchmark).

3.5 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 TEC device technologies would require the long-term testing of multiple devices. The DTI Marine Renewable Deployment Fund (MRDF) programme has been established to support this further stage of pre-commercial technology development. 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 therefore a 5 to 10-year window. It is therefore logical to assume that some technology development would continue during this period. This is factored into the analysis presented as enabling the deployment of a scaled-up version (3MW installed capacity) Seagen-type TEC technology. This thinking follows the approach presented in a report for government by Marine Current Turbines Ltd. and associated partners [3.15].

There are two simple mechanisms for increasing the installed capacity of a TEC device; either to increase the rated velocity, or increase the performance surface of the device by increasing the swept area of the device by extending 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. The compromise approach of increasing both parameters in line with consideration of local factors has therefore been taken in scaling the technology up to produce a 3MW device (see Table 3.2). It was necessary to adopt a particular value for the coefficient of performance of the device 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 [3.15, 3.16]. To enable comparison between this case study and the accompanying Strangford Narrows case study, a value of 0.404 was adopted. It is acknowledged that more in depth analysis than was conducted as part of this case study would enable fine-tuning of device performance to local conditions. In particular, it has not been possible to take account of the array effects detailed in the preceding section. Data from testing of a full-scale operational Seagen device would also enable significant improvement on the reliability and veracity of the figures presented.

The proposed array has been identified as containing 65 installed devices, and the tidal current resource in the region has been characterised in Section 3.2.2. Assuming that the generic Spring-Neap velocity variation in Section 3.2.2 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 3.2. In practice, it is to be expected that a range of devices would be deployed across the array. For instance, taking account of the array effects discussed in Section 3.4.1, 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 try 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.

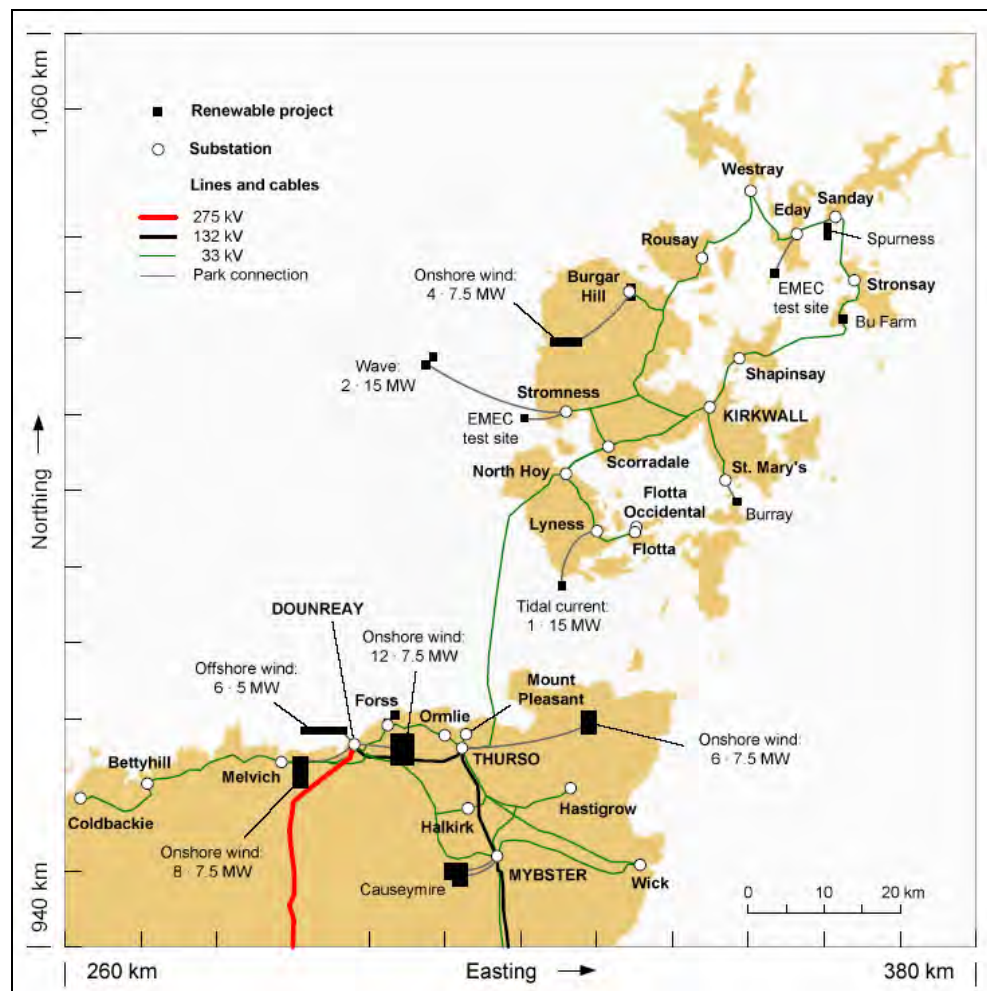
Table 3.2 Characteristics of the Seagen-type device and array proposed for deployment.

Number of rotors	2
Diameter of rotors (m)	20m
Area of rotors (m ²)	628.318m ²
Assumed density of water (kg/m ³)	1,025kg/m ³
Start up velocity (m/s)	0.75m/s
Turbine rated velocity (m/s)	2.85m/s
Device rated power at turbine rated velocity (kW)	3,011.5kW
Number of devices in the array	65
Installed capacity of the array (MW)	195.75
Coefficient of performance, Cp	0.404
Energy capture per year per device (GWh)	9.796GWh
Nominal energy capture per year by the array (GWh)	636.74GWh
Load factor of the array	37.13%

3.6 Grid connection and electricity integration

It is suggested that for the 200MW Pentland Firth tidal farm case study, the following grid implications are considered.

Figure 3.8 Electricity network in the region of the Pentland Firth (Source: Scottish Executive (2006) 'Matching Renewable Energy with Demand').



3.6.1 Offshore cabling

In conjunction with the findings of Granger and Jenkins [3.19] and in the absence of proven 132kV offshore transformers, a 33kV system is suggested to link the individual TEC devices together (each TEC having its own 33kV transformer). Groups of TEC devices would be linked together having multiple 33kV links to the shore.

3.6.2 Onshore cabling

A new substation would be required on shore to convert the 33kV to 132kV to take the power from shore landing point to Thurso. There is no transmission capability to accept this power. Therefore, it is proposed that a new 132kV power line would have to be installed from the shore landing point of the farm to Thurso. This line would be subject for approval by the normal consenting process for new power lines.

The proposed 132kV power line extension would ensure the transmission of the power from the TEC array to Thurso and would form a third easterly arm to compliment the two existing

132kV lines that presently feed Thurso from Dounreay in the west and Mybster from the south (see Figure 3.8).

With the new lines connected to Thurso, the power from the TEC farm could then be directed both south to Mybster 132kV or west to Dounreay 132kV where there is a 400MW 275kV line which is a present only lightly loaded. The capacity within these two 132kV lines is not known but it would appear sensible to direct the bulk of the power to the Dounreay 275kV lines where there is know capacity. This option may required an upgrade to the present 132kV line from Thurso to Dounreay

3.6.3 Overall capacity

The present power systems linking the Thurso area with the south is 600MW, comprising of the Dounreay line 400MW and the Thurso line comprising of 2x100MW lines heading south via Mybster. It should be noted that there is minimal generic demand in the area, hence the bulk of the power that is produce would be required to be exported. Additionally there are at present numerous wind farms at various stages of planning and consenting that will be competing for the transmission capacity.

Finally, the proposal above to take the power from the TEC farm to the 275kV line to allow export of power to the south will only allow the export as far a Beaulay. The proposed upgrade to the Beaulay – Denny line is well documented in other investigations [3.20] and hence will not be covered in this study.

3.6.4 Costing

The following indicative costing has been conducted to cover the following:

- The subsea cable that interconnects the TEC farm and link it the shore.
- The new overland line from the shore point to Thurso
- Associated sub stations and switchgear.

The Scottish Executive [3.21] suggests the 'Technology Type Voltage (kV) Cost function (£/MW) Distance weighting costing method' as detailed in Table 3.3.

Table 3.3 Grid connection cost functions [3.21].

Technology	Type	Voltage (kV)	Cost function (£/MW)	Distance weighting
Onshore wind	MVAC	33	$18,730 + d * 1.25 * 4,440$	10 for water and natural heritage areas, 1 elsewhere
	HVAC	132 & 275	$18,730 + d * 1.25 * 1,080$	
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 different renewable technologies have been presented in the literature [3.22]. Using the offshore wind calculations the following costing can be estimated.

Table 3.4 Cable costings for the hypothetical Pentland Firth case study

	Distance (km)	Cost (£/MW)	Weighting	Total cost (£)
Land calculation	30	33,901,000	0.3	10,170,300
Sub-sea calculation	16.5	22,932,250	1	22,932,250
				33,102,550

Using the offshore wind, tidal current calculations it can be seen from Table 3.4 that a total transmission infrastructure cost of £33.1 million is required to facilitate this TEC development. Within the land calculation the 30km accounts for the new overhead lines from the shore landing point to Thurso, while in the subsea calculation the 16.5km accounts for three 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 from Thurso to Dounreay.

3.7 Unit cost of Energy

There is a lack of evidence in the public domain to base the cost of developing a hypothetical case study. In particular the cost related to project development, device production and device installation. 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 could be questioned. 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 [3.23]. Consequently, the generating costs calculated here should be regarded as indicative. Significant uncertainties remain however and future large scale cost reductions are not necessarily guaranteed. .

3.7.1 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 but is slightly higher than was assumed for the Strangford Narrows case study. This is because, although the array lies relatively close to shore, and is partially sheltered from extreme weather events compared with an open sea location, it is still in an offshore location rather than an inland waterway, the current is faster and the water is deeper.

3.7.2 Plant lifetime

As with almost everything else about tidal current energy technology, there is limited data on which to base an estimate of the expected lifetime of such a plant. A 20 year technical life has been assumed.

3.7.3 Decommissioning

Little or no discussion of decommissioning strategies for marine renewable technologies lies in the public domain. It is suggested that as this particular site has been identified as a primary location within the Pentland Firth for deployment of TEC 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 TEC devices that have reached their design life. It is likely that the standard approach would be for the devices to be salvaged, recycled or reused as deemed appropriate.

3.7.4 Cost of energy analysis

The unit cost of energy has been calculated using a discounted cash flow analysis based on the estimated capital and operating costs and the energy generated over the technical life of the project. An explanation of the methodology is set out in Appendix 1.

In section 3.5 the electrical output of the array was projected to be 636.74 GWh/year. In order to conduct this analysis certain assumptions are required, the details of which follow:

3.7.5 Capital cost

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 demonstration 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. It must be stressed that this capital cost is based on the first single full-scale demonstrator device and therefore not necessarily representative of costs which could be achieved with commercial development particularly on the scale envisaged in this case study. 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.

3.7.6 Construction Time

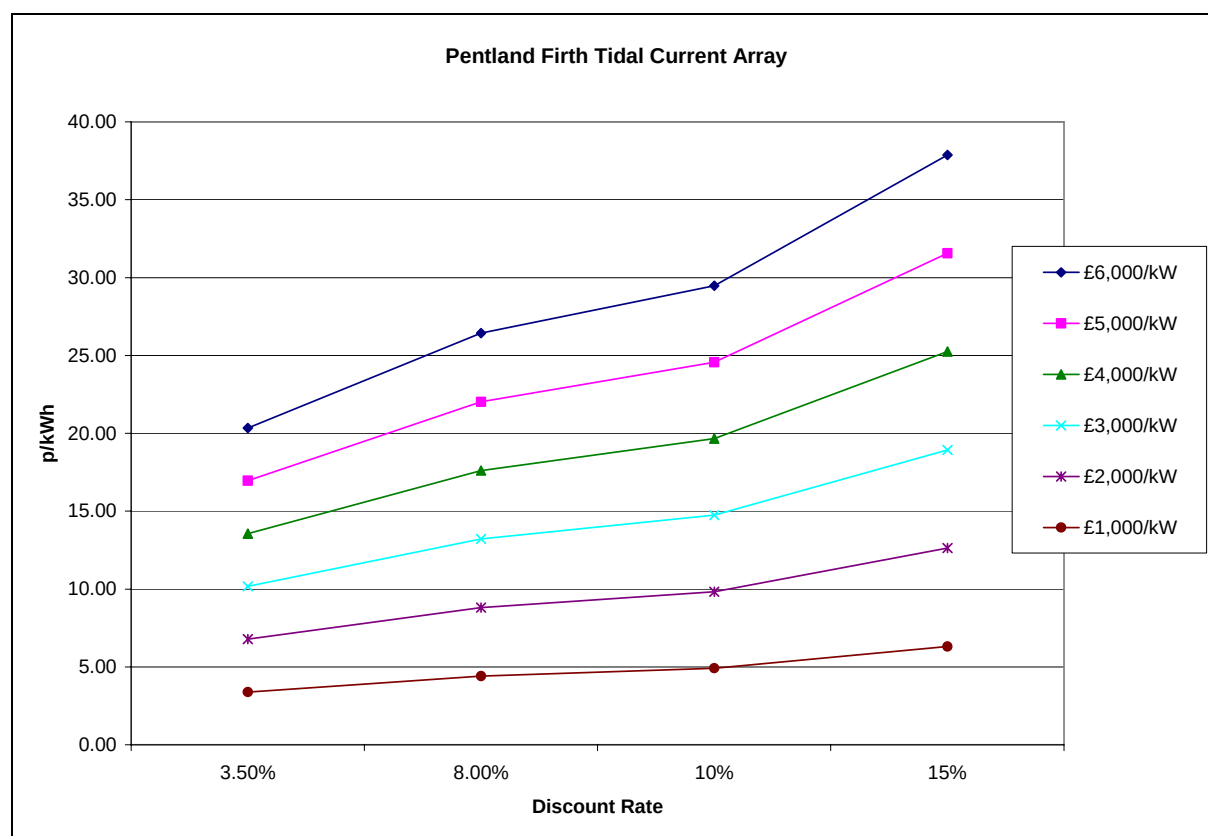
There is limited information to rely on to inform a decision on how long construction of a large TEC device array will take. We have therefore assumed that the project would be developed in stages. Our assumption is that the first stage would be completed in 36 months and includes installation of all the supporting infrastructure including all grid issues detailed in section 3.6, and the first tranche of 33, 3MW installed capacity devices, which would be installed between months 18 and 36 of the construction program, and commence operation at the end of year 3. The second tranche of 32 devices is assumed to be installed by the end of 54 months at which time the facility becomes fully operational.

3.7.7 Unit Cost of Generation

Based on these considerations the cost of energy over a range of discount rates and capital costs are shown in Table 3.5 and Figure 3.9.

Table 3.5 - Unit cost of generation relative to capital cost and discount rate for the Pentland Firth hypothetical tidal current array

Discount Rate →	3.50%	8.00%	10%	15%	
Cost of installed capacity					
£6,000/kW	20.34	26.42	29.48	37.87	p/kWh
£5,000/kW	16.95	22.02	24.56	31.56	p/kWh
£4,000/kW	13.56	17.62	19.65	25.25	p/kWh
£3,000/kW	10.17	13.21	14.74	18.94	p/kWh
£2,000/kW	6.78	8.81	9.83	12.62	p/kWh
£1,000/kW	3.39	4.40	4.91	6.31	p/kWh

Figure 3.9 - Unit cost of generation relative to capital cost and discount rate for the Pentland Firth hypothetical tidal current array

Two technology assessments commissioned by the Carbon Trust have estimated projected future costs for tidal current technology [3.24, 3.25]. 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. 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.

3.8 Carbon balance

The only detailed figure for the mass of any part of the Seagen machine refers to the pile, is 270 tonnes [2.7]. The volume and hence the mass of the other components of the machine has been based on the dimensions shown in Figure 2.4. Overall, it is estimated estimate that one turbine contains about 732 tonnes of steel and 2.35t of copper implying an embedded carbon emission of 1,198t of CO₂. Consequently, the array of 65 devices would have a total embedded carbon of $1,198\text{t} \times 65 = 77,870\text{t}$ of CO₂. It has been assumed that the quantity of steel used in the monopile has been doubled compared with the 1 MW devices that would be deployed in Strangford Lough because of the necessity to support a larger 3MW structure.

The proposed 65 machine array, not including the demonstration device, would generate about 636.74 GWh/year. Assuming an average emission factor of 0.43 kg CO₂/kWh the Strangford array would save about 273,798 tonnes of CO₂ per year. The embedded carbon would be 'paid back' in about 3.4 months.

3.9 Regional and social benefits

3.9.1 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 in the local area and 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 area thus limiting the local benefit.

However, there will 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.

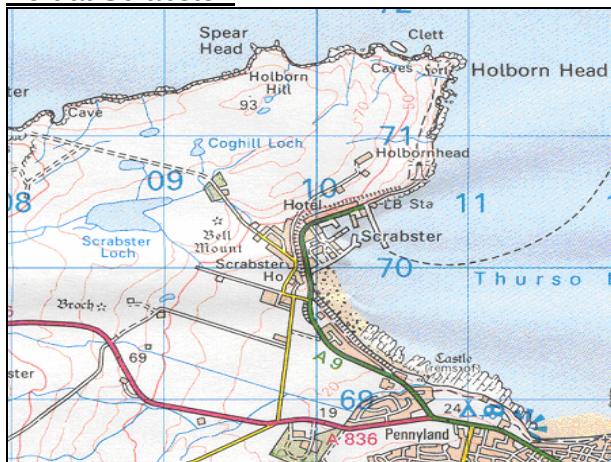
3.9.2 Community benefit

It is unclear what the position would be with regard to whether or not 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 TEC array projects could facilitate this type of local payment.

These local payments are an incentive to gain community buy-in to having a project in their area. As there are significant differences in the visual impact of TEC devices compared to Wind turbines, it is unclear if this model will transfer and if community buy-in is significant to the success of a project. However, it would seem that some local incentive would be required where there was direct negative impact on other users of the sea space, such as fishing, shipping and leisure craft.

3.9.3 Port availability

Although there are numerous small harbours in close proximity to the location proposed in this hypothetical case study, the main ports of Wick and Scrabster are the only two in the area (both about 30km from the site) suitable for deployment and maintenance operations, and are displayed below.

Port at Wick:Port at Scrabster:

The utilisation of these two ports during the installation and operational phases of the TEC farm would help facilitate direct economic benefit to the area.

3.9.4 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 [3.26, 3.27]. In the case of tidal current energy generation, early work suggests that this is not considered to be nearly as significant a concern [3.28].

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 TEC 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 0.09-0.88 metres dependent upon the various assumptions made during the analysis [3.29]. As first generation technologies are expected to be deployed in water depths circa 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 [3.28]. The impact of changes to the wave climate would be a more immediate concern for TEC device 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.

3.10 Environmental Issues

Highlights
• The coastline and waters of the Pentland Firth are used by large numbers of seabirds, and a variety of marine mammals. • The nature and ecological significance of tidal rapids communities is poorly documented. • Areas of highest tidal flow exhibit a tide-swept seabed, and are likely to be of limited importance to demersal fish and benthic species. • A variety of international and national conservation sites are present on the coastline of the firth, primarily due to the presence of important breeding seabird colonies. • The area experiences a high volume of shipping traffic. • Surrounding inshore waters are used for a variety of recreational activities.

The Pentland Firth is a channel of water off the northeast coast of the UK which separates mainland Scotland from the Orkney Islands and links the northern North Sea with the northeast Atlantic (Figure 3.10). Additionally, the firth provides a route to Scapa Flow, a sheltered basin amongst the southern Orkney Islands. This geographic setting makes it an important shipping route, characterised by fast flowing tidal streams and a rugged cliff coastline. It is also an important area for nature conservation, with several internationally and nationally important conservation sites present.

The firth is approximately 10-13km wide and 20km in length from Dunnet Head and Tor Ness in the west to Duncansby Head and Old Head in the east. There are two islands of appreciable size within the firth, Stroma and Swona, lying approximately 5km northwest and 9km north of Duncansby Head respectively. The smaller Pentland Skerries are an extensive group of islets and rocks lying centrally in the eastern approach to the firth. Water depth is typically 60-70m in the main channel between Stroma and Swona, where very high tidal current velocities may be experienced [3.30].

3.11 Summary of key environmental sensitivities/constraints

Table 3.6 – Summary of key environmental sensitivities/constraints

Feature	Summary	Potential adverse factors
Seabed sediments and transport processes	• Areas of highest tidal flows are predominantly bedrock outcrops swept clean of mobile sediments, and may feature fields of cobbles and boulders [3.31, 3.32]. • The seabed of southern Scapa Flow is dominated by muddy sandy gravel [3.33]. • Extensive areas of active sand waves exist in the western and eastern approaches to the firth [3.34]. • Beach and cliff erosion, accretion and longshore drift are generally minor [3.31, 3.33].	• Physical disruption of tidal flows may affect sediment transport and erosion processes.
Hydrology	• Waters are oceanic/shelf in character, influenced by waters from both the northern North Sea and north-east Atlantic, and remain fairly well mixed throughout the year [3.35]. • The firth exhibits a tidal range of 2-4m on spring tides, with peak spring tidal flows of >4m/s in the centre of the firth [3.30].	• Physical disruption of tidal flows. • Changes in mixing within the water column.
Water and sediment quality	• Water is predominantly of good quality [3.31]. Very few rivers drain into the area and coastal development is limited. • Irradiated particles exist on the seabed at Dounreay, which may occasionally be mobilised into the water column [3.36]. • A large oil terminal exists on the island of Flotta in Scapa Flow.	• Contamination.
Landscape/seascape	• Predominantly rural. • Old red sandstone cliffs dominate the coastline, with some small inlets and sandy coves. • Strong tidal flows with eddies and races. • Protected landscapes include the Hoy and west mainland National Scenic Area (NSA) on Orkney.	• Visual intrusion. • Noise. • Change in landscape character. • Increased coastal traffic.

Feature	Summary	Potential adverse factors
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Coastal habitats	- Coastal habitats present include maritime cliff and slopes, maritime heath, stony bays, littoral sediment and rock, sand dunes, grassland, machair, vegetated shingle and saltmarsh [3.37, 3.38]. - Several of these habitats are addressed by LBAPs.	- Physical disturbance. - Habitat change. - Noise.
Intertidal and subtidal habitats and communities	- Limited information is available on the benthos in the centre of the firth, where tidal flows are greatest. - The firth is characterised by the Priority BAP habitat 'tidal rapids', characterised by marine communities rich in diversity, nourished by a constantly renewed food source brought in on each tide [3.37]. - The north Caithness coast shows intertidal communities typical of an exposed rocky shore [3.39].	- Physical disturbance. - Habitat loss. - Habitat change.
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	- Areas of highest tidal flows are unlikely to provide suitable habitat for spawning or nursery grounds of commercially important fish or shellfish. - More sheltered waters in the wider area are known to support seasonal spawning grounds for herring, lemon sole, sandeels and sprat; nursery grounds for haddock, saithe, lemon sole, sandeel and sprat; and commercially important populations of shellfish [3.40]. - Atlantic salmon and lamprey are likely to pass through the area. - Basking sharks are occasionally sighted during summer months [3.41].	- Physical disturbance to spawning grounds. - Collision risk. - Noise.
Birds	- Extensive sea cliff habitat and islands support several breeding bird populations of international and national importance, including large assemblages of diving seabirds which feed within the waters of the firth and beyond. - Seabird vulnerability to surface pollution is classified as very high for 9 months of the year [3.42].	- Collision risk with diving seabirds. - Disturbance during installation and maintenance activities.

Feature	Summary	Potential adverse factors
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Marine Mammals	• Harbour porpoise, white-beaked dolphin and minke whale are commonly sighted, with several other cetacean species occasionally sighted [3.31, 3.43]. • Seals are common, with several breeding sites for grey seals and haul-out sites for common seals present, primarily on the islands [3.31, 3.33].	• Noise. • Collision risk. • Displacement from foraging grounds and/or migration routes.
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3.12 Conservation sites and other key environmental sensitivities

Within the area, there are four sites designated as Special Protection Areas (SPAs) for avian features under the EC Birds Directive⁹ and one as a Special Area of Conservation (SAC) for habitat and species features under the EC Habitats Directive¹⁰ (Table 3.7). All of these sites overlap with Important Bird Areas (IBAs) – non-statutory sites recognised as supporting internationally or nationally important numbers of birds (BirdLife International website) (Figure 3.10).

National and local conservation sites in the area include 10 Sites of Special Scientific Interest (SSSIs), 7 Geological Conservation Review sites (GCRs), 1 National Scenic Area (NSA), 1 RSPB reserve, 1 Scottish Wildlife Trust (SWT) reserve and 2 Preferred Conservation Zones (PCZs) (Figure 3.10). The majority of these sites are designated for avian features, primarily breeding seabirds, and overlap with international conservation sites. Other important features include extensive cliffs and other coastal habitats, coastal plant species and geological features.

The coastline of the firth is covered by the Orkney and Caithness Local Biodiversity Action Plans (LBAPs) which work towards delivering the national Biodiversity Action Plans¹¹ (BAPs) for a variety of habitats and species of conservation interest. Nationally important BAP species likely to be present in the area include basking shark, common skate, otter and several species of birds, cetaceans, and fish [3.37].

Table 3.7 – International conservations sites

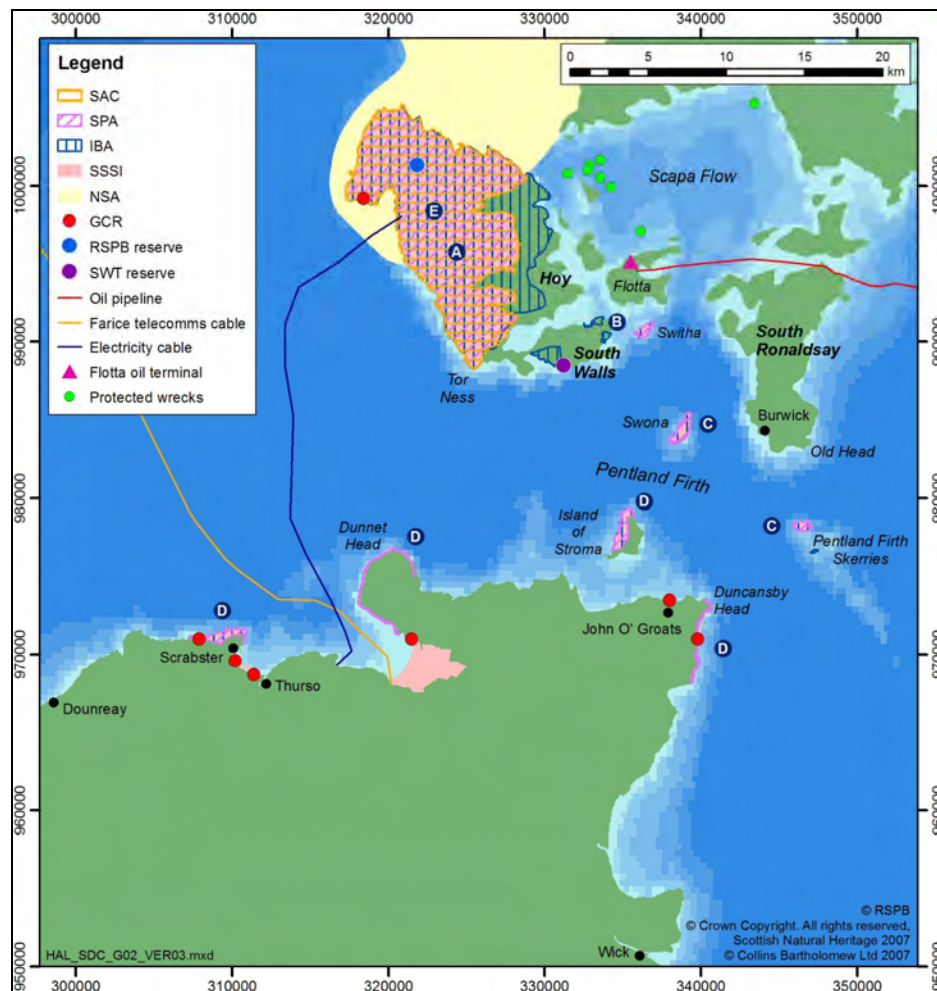
⁹ Council Directive 79/409/EEC on the conservation of wild birds

¹⁰ Council Directive 92/43/EEC on the conservation of natural habitats of wild flora and fauna

¹¹ The UK Biodiversity Action Plan is the UK's response to the *Convention of Biological Diversity*

Map ref	Site	Area (ha)	Key Features
A	Hoy SPA	9,500	<i>During breeding season:</i> Peregrine <i>Falco peregrinus</i>, red-throated diver <i>Gavia stellata</i>, great skua <i>Catharacta skua</i> <i>Assemblage qualification:</i> Regularly supports 120,000 seabirds during the breeding season
B	Switha SPA	57	<i>Over winter:</i> Barnacle goose <i>Branta leucopsis</i>
C	Pentland Firth Islands SPA	171	<i>Breeding:</i> Arctic tern <i>Sterna paradisaea</i>
D	North Caithness Cliffs SPA	558	<i>During breeding season:</i> Peregrine <i>Falco peregrinus</i>, Guillemot <i>Uria aalge</i> <i>Assemblage qualification:</i> Regularly supports 110,000 seabirds during the breeding season JNCC recommended boundary extension to 1km offshore of mean low water [3.44].
E	Hoy SAC	9,500	Vegetated sea cliffs of the Atlantic and Baltic coasts, natural dystrophic lakes and ponds, Northern Atlantic wet heaths with <i>Erica tetralix</i>, Alpine and Boreal heaths, blanket bogs, European dry heaths, petrifying springs with tufa formation (<i>Cratoneurion</i>), alkaline fens, calcareous rocky slopes with chasmophytic vegetation

Source: JNCC website.

Figure 3.10 – Conservation sites and other key features

Notes: Letters refer to sites described in Table 3.6. PCZs not shown on map. Orkney PCZ covers south and west coast of Hoy and South Walls.

3.13 Other uses/users

The coasts of the Pentland Firth are predominantly rural, with Thurso being the largest conurbation in the region (population ca. 8000) [3.45, 3.46]. Shipping activity is high in the area, with up to 5,500 vessels annually (Faber Maunsell & METOC 2006). Busy ferry routes operate between the Scottish mainland and the Northern Isles, and oil related traffic (including laden tankers) moving to and from the Flotta oil terminal is frequent in Scapa Flow. Recreational, fish farm service craft and diving support boats also operate in the area. Currently, no vessel traffic separation scheme is in operation in the main channel of the firth between Stroma and Swona [3.47]. The waters off the coast of Hoy have recently been identified as a Marine Environmental High Risk Area (MEHRA) due to their environmental sensitivity and high levels of shipping activity [3.47].

While the wider area experiences high levels of fishing effort, particularly with static gears [3.40], this effort is likely to be concentrated in shallower, more sheltered waters, away from areas of highest tidal flows. Scrabster is the main port in the area, where 22,000 tonnes of fish and shellfish from 160 vessels were landed in 2005 [3.48]. Several marine fish and shellfish farms exist in sheltered waters around the southern islands of Orkney [3.49, 3.50].

There are no recently active marine disposal sites, oil and gas or renewable energy infrastructure within the Pentland Firth [3.51, 3.52]. A telecommunication cable lies

immediately to the west of the firth, extending north from Dunnet Bay; an oil pipeline extends west from the Flotta oil terminal, and an electricity cable runs from near Dunnet Bay to the west coast of Hoy. The firth is within a large RAF training area covering much of northern Scotland.

14km west of Thurso lies the Dounreay site, a former nuclear energy research centre currently being decommissioned. Currently, it is estimated that there are approximately 10,000 irradiated particles (ca. 1mm in diameter) on the seabed around the site's disused effluent outfall [3.36]. A 2km radius fishing exclusion zone exists around this outfall. Some particles have been detected on nearby beaches.

There are numerous charted and uncharted wrecks in the Pentland Firth and surrounding waters. Within Scapa Flow, 9 wrecks are listed as protected: 2 under the Protection of Military Remains Act and 7 designated as Maritime Scheduled Ancient Monuments (Figure 3.9) [3.53]. Additionally, a German submarine wreck is located at 70m depth in the eastern approach to the firth [3.54]. Mesolithic sites of archaeological interest have been observed on Orkney and the north Caithness coast [3.55].

Scapa Flow is a popular area for motorised water sports, windsurfing and diving. The north Caithness coast, particularly around Thurso, is a popular location for surfing. Walking, climbing and wildlife watching frequently take place on the north Caithness coast and to a lesser extent on the Orkney coast [3.45].

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4 Liverpool Bay tidal-energy lagoon

4.1 Background to lagoon concept

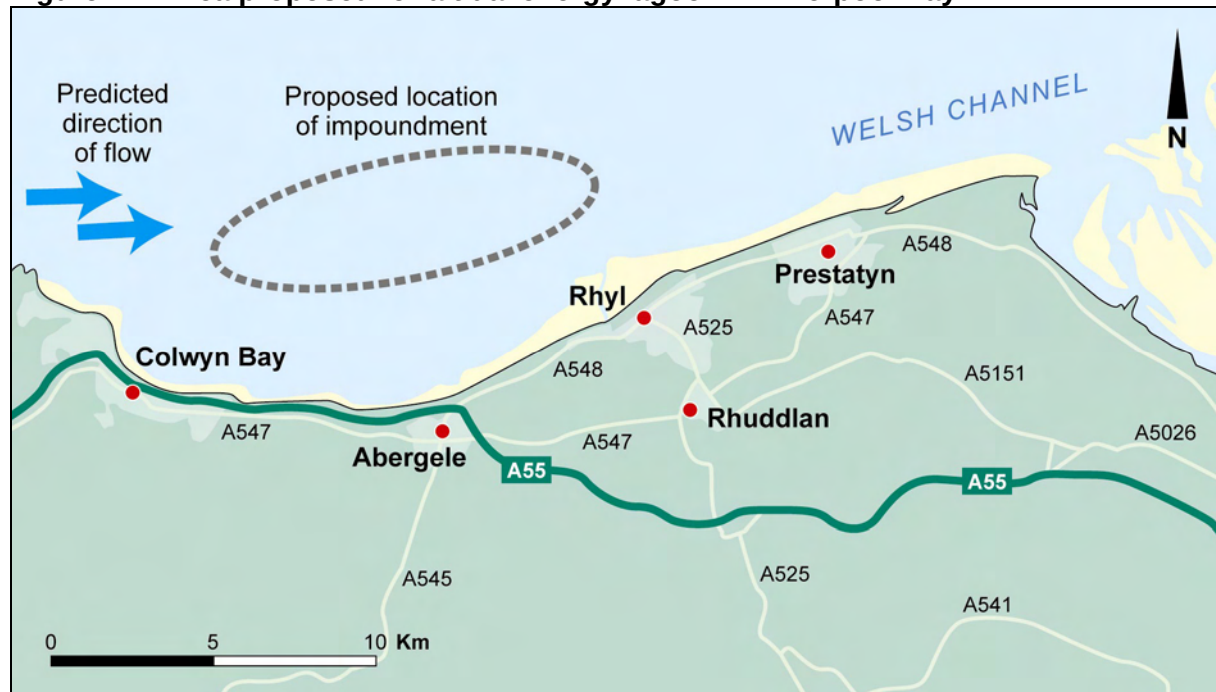
The concept of tidal-energy lagoons has been proposed as an alternative to barrages that form a permeable barrier across an entire estuary. Both systems exploit tidal energy by restraining large volumes of water within an impounded basin. The flood tide is allowed to flow through a series of sluices or water passages containing turbines. At high water, the sluices and entrances to turbines are closed. As the tide on the seaward side of the structure recedes, a head, or difference in water levels on either side of the barrier, develops. When the difference is sufficiently large, water is allowed to flow through the turbines that generate electricity.

Proponents of tidal-energy lagoons have argued that estuaries can remain unconstrained avoiding some of the environmental effects caused by complete closure. It has also been argued that lagoons can be built at lower cost with sand-filled embankments in comparatively shallow water [4.1]. In deeper water, embankments become less suitable and more expensive because of the amount of material required. Consequently, tidal energy lagoons would need to be built on intertidal coastal areas or along the edge of estuaries with high tidal ranges.

In contrast, most tidal-energy barrages would be constructed from concrete caissons that are prefabricated in docks or purpose-built yards. Once completed, these large concrete structures would be floated to the barrage site and carefully sunk on to prepared foundations. The advantage of this construction technique is that it allows the progressive closure of an estuary and is usually a cheaper alternative to embankment in deeper water. For example, a combination of a barrage lagoon or a multi-lagoon system for the Severn Estuary has been considered [4.2]. This configuration would enable power generation over longer periods of a day because adjacent systems could be operated on either the flood or ebb tide [4.3].

During the 1980s, most commercial and research interest in the UK focused on the development of large tidal energy barrages across the Severn and Mersey [4.3, 4.4]. Despite detailed assessments of both estuaries, none of the schemes investigated was sufficiently economic to progress to full-scale development. More recently, there has been renewed interest in the development of tidal energy from lagoons, principally by Tidal Electric Limited (TEL) [4.5]. The company has promoted the construction of tidal lagoons in coastal waters with a high tidal range. TEL has advocated a 60MW site for Swansea and a 430MW site for Liverpool Bay. More recently, a smaller 340MW lagoon concept has been proposed for Liverpool Bay [4.6].

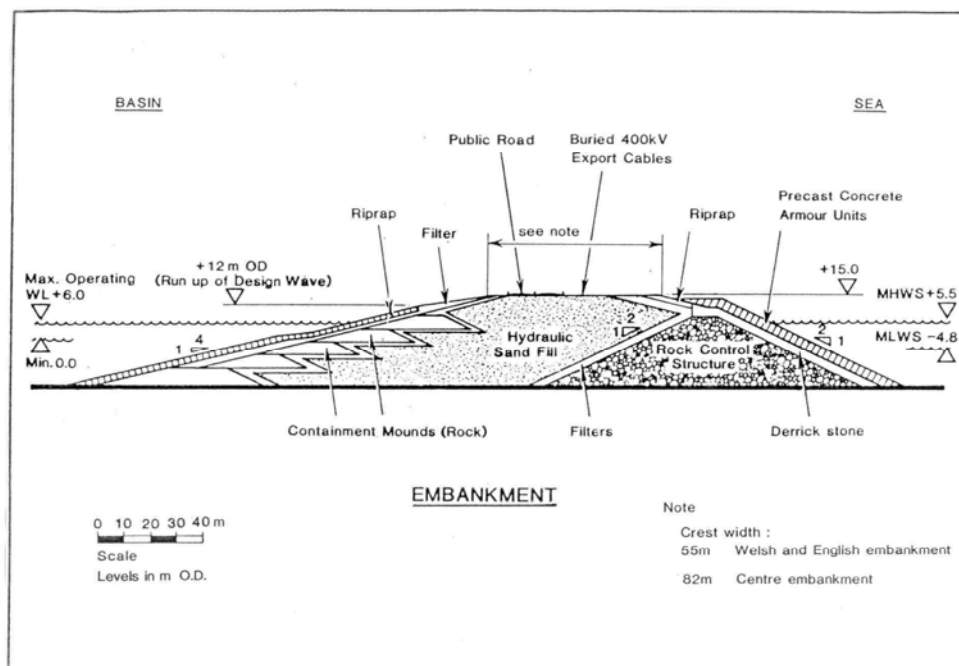
This case study is based on a 340MW scheme proposed by Evans et al [4.6]. This case study summarises the energy potential, cost and value of energy for a Liverpool Bay tidal-energy lagoon which could be located in the general area depicted in Figure 4.1. It also evaluates the embedded carbon and carbon savings that the scheme could offer as well as its potential economic benefits and environmental impacts.

Figure 4.1 Area proposed for a tidal energy lagoon in Liverpool Bay

4.2 Lagoon design and cost

The scale of Liverpool tidal-energy scheme is mentioned in a number of briefings [4.7, 4.8]. However, there are few specific details of the proposed design or exact location.

The construction of a tidal-energy lagoon could be achieved by creating a large protected bund filled with pumped sand that is dredged locally and dumped to form an embankment. While this material is abundant and comparatively cheap, it is vulnerable to scouring action by waves and tidal currents. Consequently, an initial rock bund is required to protect the sand fill on the seaward side of the structure. The sand fill is stabilised on the basin side by dumping successive layers of broken rock, known as quarry run. The inner core of the embankment is then covered by a protective layer that is shielded by rock armour. The function of this outer layer is to dissipate wave energy and maintain the integrity of the embankment. This technique has been advocated for other proposed tidal energy schemes such as the Severn and Duddon [4.9, 4.10]. The resultant embankment profile is illustrated in Figure 4.2.

Figure 4.2 Cross section of embankment proposed for the Severn barrage

There is very limited information on the scale of the Liverpool Bay lagoon or its position. Evans et al have proposed a lagoon with an area of 60km^2 impounded by 34km of embankment in a rectangular configuration ($12\text{km} \times 5\text{km}$) [4.6]. The proponents have also proposed a novel construction method that would use a series of progressively smaller sand-filled geotextile bags stacked on top of each other to form an embankment. The turbines, generators and switch gear would be housed in concrete structures, although it is not clear whether these would be built in situ or prefabricated elsewhere.

4.2.1 Power-house design and cost

Evans et al have proposed an offshore lagoon with an installed capacity of 340MW [4.6]. They have not provided any details of the power house structure, but have assumed that low head double regulated turbines would be used. It is not clear whether the design would include sluices or rely solely on the flow of water through the turbine chambers on each tide. Evans et al have suggested that a scheme of this size would have 20 turbines. By implication each would have an installed capacity of 17MW .

The size of the turbines, and the related power house design, are constrained by the depth of water. There must be sufficient depth of water to prevent cavitation during turbine operation, which can result in damage to the runner blades and loss of energy. It is possible that a smaller number of large turbines could be used if there is sufficient depth of water, as this size of turbine would suggest; however, without published details of the scheme it is not possible to comment on the viability of the turbine size or the likely dimensions of the power house.

The costs for the 340MW scheme proposed by Evans et al are also presented in Table 4.3 for comparison. These estimates have been inflated from 2004 to 2006 using the COPI index [4.11]. It should be emphasised that the cost categories are those used by Evans et al

with the exception of cable connection to the grid, which is not specifically identified or included by the authors.

4.2.2 Electrical connection

A scheme with a rated capacity of 340MW would need to be connected into the national transmission system (i.e. 132 or 275kV) at a suitable substation. The closest substation for a scheme with this generation capacity is Birkenhead or possibly Lister Drive on Merseyside a distance of about 43km [4.12]. It has been assumed that there would be no constraints imposed by a connection of this magnitude, but this may not necessarily be the case. The route also assumes that a subsea cable would be used through the entire length of the cable route from the lagoon to the shore. It is possible that the subsea could be laid to the closest landfall and a new dedicated 132kV link constructed to the nearest suitable substation. This route would need to avoid the Dee estuary and the urban areas of Merseyside and Chester. Consequently, the most suitable connection point would be Capenhurst.

The cost of a subsea cable connection over a distance of 43km has been based on methodology developed for estimating connection costs for marine renewables [4.13]. The technology-related cost function (£/MW) includes a distance weighting depending on the technology, the transmission voltage and the type of terrain or sea bed of the cable route (Table 4.2). The estimated cost of connection at the substation has not been included.

Table 4.2 Grid connection cost functions [4.13]

Technology	Type	Voltage (kV)	Cost function (£/MW)	Distance weighting
Onshore wind	MVAC	33	$18,730 + d * 1.25 * 4,440$	10 for water and natural heritage areas, 1 elsewhere
	HVAC	132 & 275	$18,730 + d * 1.25 * 1,080$	
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.

Table 4.3 Capital cost breakdown for the Liverpool Bay tidal energy lagoon

Capital item	£million (340MW scheme proposed by Evans et al).
Caisson construction (Power House)	1.63
Embankment	444.41*
Turbine generators	86.71
Construction labour	11.92
Cable connection to 275kV GSP	75.59 #
Project management, feasibility, planning and approval	43.36
Total capital cost	663.61

*Costs include dredging, rock armour, quarry run (waste rock), road transport, placement and geomembrane bags)

connection costs based on methodology developed for marine renewables developed by the Scottish Executive [4.13]

4.3 Energy output

The 340MW lagoon proposed by Evans et al assumed two-way (ebb and flood generation). The calculated energy output is based on one mean tide and takes no account of the variability between spring and neap tides. It is also not clear whether due consideration has been taken of the depth constraints imposed by the necessity to avoid cavitation. Evans et al estimate that a 31.5% load factor could be achieved equivalent to 938GWh/year [4.6]. This figure is significantly higher than other tidal lagoon or barrages schemes with the exception of the estimated energy output for the Swansea Bay lagoon by its proponents, Tidal Electric. Without a more detailed analysis, this figure should be treated with some caution.

4.3.1 Unit cost of energy

The unit cost of generation has been estimated using a discount cash flow analysis of the scheme (see Appendix 1). A constant annual energy output of 938GWh, although in reality this value 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 four years has been assumed with one year for preconstruction. 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 4.4.

Table 4.4 Unit cost of generation for the Liverpool Bay tidal-energy lagoon

Discount rate	3.5	8	10	15
Liverpool Bay unit cost (340MW Evans et al) p/kWh	3.11	6.80	8.64	13.75

4.4 Carbon balance

To estimate the carbon life-cycle balance, the embedded carbon used to manufacture the key materials (i.e. concrete, steel and copper) was estimated from the quantities of these materials used to build the 340MW lagoon (see Appendix 2). As there are no detailed designs for the power house the volume of concrete has had to be assumed by comparison with other tidal energy schemes. The volume of concrete must therefore be viewed as an approximation. The amount of rebar (re-enforcement steel rods used in the concrete structure) was based on the average density of this material in three different tidal energy barrage schemes (Mersey [4.4], Duddon [4.10] and Wyre [4.14]). The estimated quantities of steel and copper used in the turbine generators was based on the quantities of these materials, per MW installed, used for these components in the proposed Mersey barrage [4.4]. The development study for the Mersey scheme included a detailed assessment of these materials, which provides a reliable benchmark for comparison with other proposed projects that use comparable turbines.

The embedded carbon in the cable connection has assumed a 43km length of 132kV cable. In addition, the amount of carbon required to deliver the volume of sand in the embankment has also been estimated. This estimate has assumed that a cut and suction dredger fitted with a 2MW diesel and pump would be used. A drive chain with this capacity could deliver an estimated 1,000m³/hour. Assuming an efficiency of 40%, a diesel engine would emit an estimated 6,196t of CO₂ to emplace the volume of sand in the embankment. A full explanation of the methodology used to estimate CO₂ emissions related to dredging and pumping is presented in Appendix 2. The embedded carbon required to supply plant, materials and labour to the site has not been estimated. Therefore, the overall figure presented in Table 4.5 should be regarded as a lower limit. The range in values represents

the total embedded carbon for the scheme assuming minimum and maximum carbon conversion factors for steel and concrete.

The carbon savings assume that each kWh generated would displace 0.43kg of CO₂. In reality, the savings would fluctuate as energy output varies with different tides. Therefore, the annual savings should be viewed as an average. It is also assumed that the volume of the impounded reservoir does not contract with time. Sediment accumulation within the basin may progressively limit the volume of water and therefore energy output and carbon saving.

Table 4.5 Embedded carbon and carbon savings produced by the 340MW Liverpool Bay tidal-energy lagoon.

	Minimum estimated value of CO ₂ (t)	Maximum estimated value of CO ₂ (t)
Total volume of concrete (m ³)	320,000	320,000
Total mass of steel (t)	78,051	78,051
Total mass of copper (t)	163	163
Pumping CO ₂ (t)	6,769	6,769
Estimated embedded CO ₂ (t)	198,261	263,307
Estimated carbon savings of technical life of 120 years (t) and assuming 0.43kgCO ₂ /kWh	48,410,914	48,410,914
Carbon payback period (months)	6	8

4.5 Decommissioning

Detailed proposals for decommissioning have not been assessed for either barrages or lagoons. TEL, the developers of the Swansea Bay tidal energy lagoon, has suggested that the mechanical and electrical components could be removed, and the remaining structure left in place. However, consent procedures may well stipulate that complete removal is necessary. This would necessitate complete removal of the concrete caissons possibly by in-situ destruction and then removal of the broken concrete. The embankment would require removal of the rock armour layers and protective layering and possibly the internal rock bund. Once exposed, the sand core would be dissipated by waves and currents. A full environmental impact would be necessary, particularly to determine the effects of sediment transport and distribution within Liverpool Bay following removal of the protective embankment shield.

Disposal of the re-inforced concrete and rock armour may well demand disposal in a landfill site or as a recycled foundation material.

The Countryside Council for Wales (CCW), the statutory authority responsible for landscape and environmental consents in Wales, has stipulated that decommissioning must form part of the full environmental impact assessment (EIA) for the smaller Swansea Bay tidal-energy lagoon [4.15].

Tentative cost estimates for decommissioning the Swansea Bay tidal lagoon suggest complete removal could be as high as the original construction cost. A bond accrued through the life of the scheme may be necessary to fund decommissioning.

4.6 Regional/social impacts and benefits

4.6.1 Employment

Employment estimates for large-scale tidal-energy projects vary widely. The smaller Duddon scheme (100MW) estimated 1,200 at the peak of construction, whereas the larger Mersey barrage (700MW) would require 2,000 at the peak of construction [4.4, 4.10]. Direct employment for a scheme on the scale of the Liverpool Bay could employ between these two estimates although not necessarily within close proximity to the construction site.

Building a large offshore structure in Liverpool Bay would not necessarily benefit those communities closest to the site, although there would be some benefit to those commercial port facilities such as Mostyn, Rhyl, and Connah's Quay that are closest to the construction site. If caisson construction was used it would require large dry-dock facilities. Other tidal energy projects have reviewed suitable facilities for this purpose including Loch Kishorn, Hunterston and Ardyne Point on the west coast of Scotland. Cammell Laird on Merseyside and Inchgreen Scott Lithgow on Clydeside would be suitable for steel fabrication. It is possible that a purpose-built caisson fabrication facility could be built on Merseyside. This was proposed as a viable option for the Mersey barrage [4.4].

4.6.2 Landscape/seascape impacts

The visual impact of a large offshore structure will be evident when viewed from a distance of 6km. Its impact will become more striking at low tide when the full height of the embankment becomes apparent, although the structure will become less visible as the flood tide progresses. Because the maximum visible section is only about 3.0m at high water, the structure will appear as an offshore reef or island from the shore.

CCW has issued specific guidance on the landscape and seascape impacts of the Swansea Bay tidal energy lagoon [4.15]. They have stipulated that a visual impact assessment will need to illustrate the proposed scheme with a series of photomontages from a selection of view points. They have also stressed that these images need to include navigation hazard warning markers. The effects of changing light conditions throughout the day, and the difference impressions at high and low tide also need to be taken into account.

4.7 Environmental issues

Highlights

- The coastline and waters of Liverpool Bay are used by large numbers of seabirds, and to a lesser extent a variety of marine mammals.
- Biological sensitivities include benthic communities, fish, birds and marine mammals.
- There are a many coastal and marine international and nationally important sites of conservation within Liverpool Bay.
- The coastline is relatively densely populated and there are numerous other uses of Liverpool Bay, including shipping, tourism, oil & gas developments, offshore windfarms, and fisheries.

Liverpool Bay lies in the eastern Irish Sea between north-east Wales, Cheshire, Lancashire and Merseyside and is noted for its large tidal range of some 10m [4.16]. A potential offshore tidal impoundment site in Liverpool Bay is situated between Colwyn Bay and Rhyl on the north coast of Wales. Much of the coastline between Rhyl and Colwyn Bay is vulnerable to

flooding from the sea. The study area extends along the north coast of Wales eastwards from Conwy Bay to the border with England in the Dee Estuary.

The north coast of Wales is primarily low and sedimentary with few rocky headlands; with the exception of north Anglesey and the Ormes Heads (both of which lay just outwith the study area). Long sandy beaches, sand dunes, two shallow estuaries and shallow offshore sand banks are the primary features. The coast is also much influenced by a well developed tourist industry, the Mersey Estuary outflow and the presence of many industrial activities in Liverpool Bay and the nearby Merseyside area.

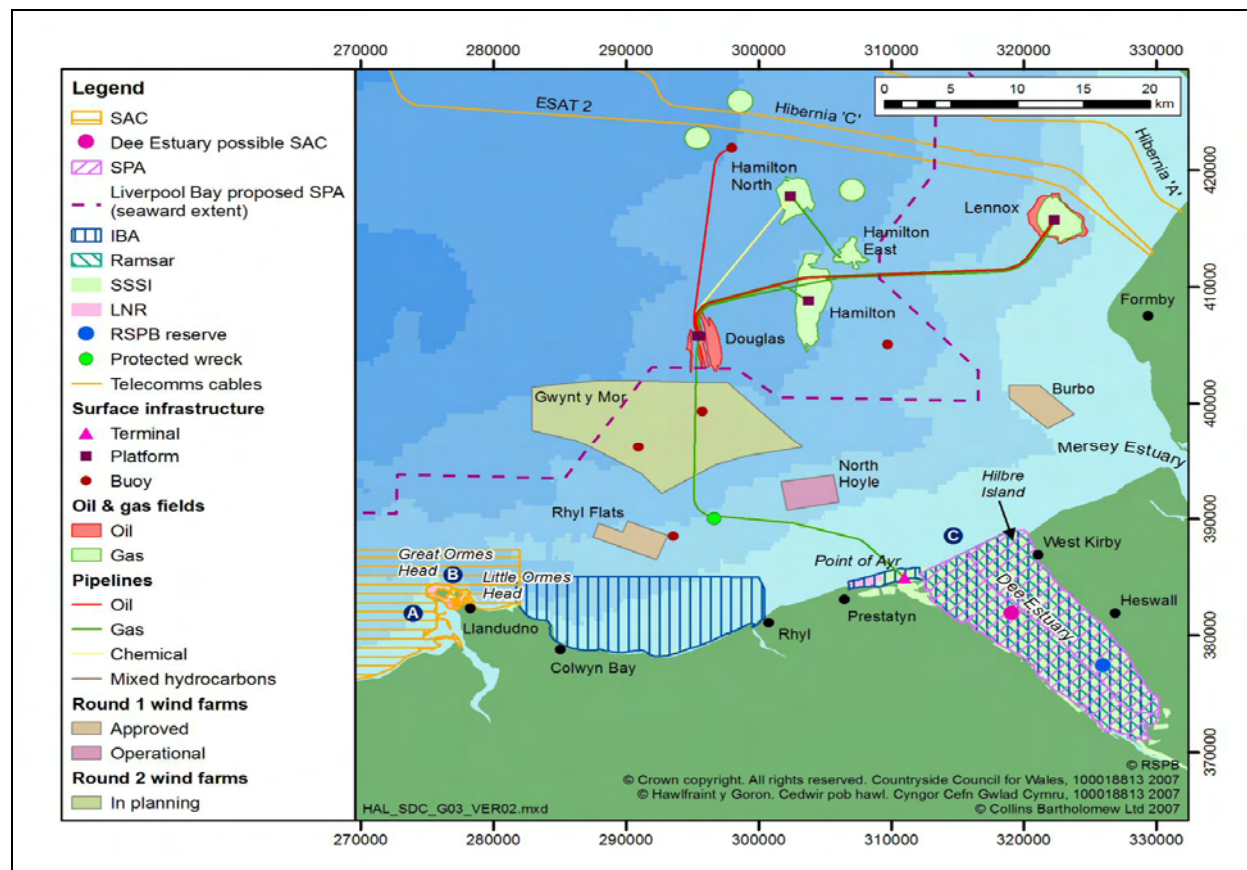
4.8 Summary of key environmental sensitivities/constraints

Table 4.6 – Summary of key environmental sensitivities/constraints

Feature	Summary	Potential adverse factors
Seabed sediments and transport processes	- Seabed consists primarily of sand with varying amounts of silt and clay. - The varied tidal regime and orientation of the coastline relative to the prevailing winds, results in complex sediment circulation. - Waves and tidal currents strong enough to initiate significant transportation of sediment in the bay, resulting in large sand waves in some areas [4.17]. - Longshore drift is an important component of the development of the system [4.18] with net sediment transport from west to east along the coast.	Physical disruption to tidal flows may affect sediment transport.
Hydrology	- Tidal heights around Liverpool Bay vary with a difference in spring tidal range at open coast sites of about 1.5m. - Inshore tidal streams are parallel to the North Wales coast with max. current speeds between 0.75 and 1.0m/s. - Waves are generally wind generated locally or longer period swell waves that have propagated into the Irish Sea [4. 19].	Disruption of tidal flows, levels of vertical mixing and light penetration, salinity.
Water and sediment quality	- Large stretches of the coastline are heavily urbanised and industrialised. There are large nutrient inputs from waste disposal and agricultural run-offs. - The nature of some phytoplankton blooms occurring in Liverpool Bay	- Disruption of tidal flows may allow accumulation of contaminants. - Re-suspension of contaminated sediments.

Feature	Summary	Potential adverse factors
	and associated coastlines can affect some beaches in North Wales [4.20].	Contamination.
Landscape/seascape	- The study area comprises one national seascape unit, extending between Great Ormes to the Dee Estuary, subdivided into six regional seascapes: Colwyn Bay, Vale of Clwyd, Clwydian Hills, Western Dee, Eastern Dee, and Northern Wirral. - Unspoiled landscape/seascape important factors to Welsh tourism (20% of holiday visits are to this coastline). - Designated landscapes include the Clwydian Range and Anglesey AONB, Snowdonia National Park and the Great Orme Heritage Coast. - Historic landscapes include the Creuddyun and Conwy, the Vale of Clwyd and Denbigh Moors.	- Visual intrusion - Noise - Habitat loss - Change to landscape character - Effects on tourism/recreation due to development and through alterations to the physical environment.
Coastal habitats	- Extensive areas of shingle present along the North Wales coast [4.19]. - Sand dunes are an important feature and dunes at Talacre and Gronant represent the last surviving complex of north facing dunes in Wales east of Anglesey. - Priority BAP habitats include sand dunes, and coastal vegetated shingle	- Loss of existing flood protection value of natural features such as dunes. - Habitat change due to changes in wave exposure.
Intertidal and subtidal habitats and communities	- Strongly dominated by infauna in sandy sediments. - Some epifauna present, but these are relatively minor components of the invertebrate communities. - The thumbnail crab <i>Thia scutellata</i> is an infrequently recorded species known from the area. - Important estuarine habitats present in the Clwyd, Dee and Mersey Estuaries.	- Physical disturbance. - Habitat loss. - Habitat change due to changes in wave exposure. - Changes in species composition.
Fish & shellfish	- Cod (January to April), whiting (February to June), plaice (December to March), sole (March to May) and sprat (May to August) spawn in the area [4.20]. - Nursery grounds for plaice and sole. - Important area for elasmobranchs including basking sharks and rays.	- Physical disturbance, particularly to migration routes. - Electromagnetic field (EMF) disturbance. - Habitat loss

Feature	Summary	Potential adverse factors
	- Commercially exploited shellfish species (Crustacea and Mollusca) are present. - Scallops occur offshore in the eastern Irish Sea [4.19].	- Collision risk. - Noise.
Birds	- The north coast of Wales and the Dee Estuary important for wintering and passage wildfowl and waders. - Liverpool Bay is important for non-breeding common scoter and red-throated diver. The potential area covers where the main aggregations of wintering common scoter have been recorded off Welsh coast. - Other species of interest are breeding populations of fulmar, cormorant, shag, kittiwake and auk species. - Bird vulnerability to surface pollution is highest during the summer months of July to August, when breeding seabirds and moulting scoter are present, and during the winter months of Dec-March, when wintering scoter and divers present.	- Disturbance during construction & maintenance. - Collision risk with diving seabirds. - Loss of feeding habitat due to changes in benthic communities - Loss of marine wintering areas
Marine mammals	- Most common species are harbour porpoise (BAP priority species) and grey seal. - Haul-out sites for grey seal present along the north coast of Wales. Highest concentration at the mouth of the Dee Estuary and on Hilbre Island - Mink whale, long-finned pilot whale, Risso's dolphin, bottlenose dolphin, and common dolphin are occasionally seen.	- Noise - Disturbance to feeding, migration and breeding behaviour - Collision risk

Figure 4.3 – Conservation sites and other key features

Notes: Letters refer to sites described in Table 4.7

4.9 Conservation sites and other key environmental sensitivities

There are several conservation sites of international importance in the vicinity, including the seacliffs at Great Ormes Head (which lie just to the west of the study area), the Dee Estuary Special Protection Area (SPA)/IBA and Ramsar and Dee Estuary draft Special Area of Conservation (SAC), the proposed Liverpool Bay SPA, and the Menai Strait and Conwy Bay SAC. Table 4.7 provides an overview of these sites and lists the qualifying species of the SPA and SAC (Wild Birds and Habitats Directives).

Table 4.7 – Nature conservation sites of international importance

Map ref	Site	Area (ha)	Key features
A	Menai Strait and Conwy Bay SAC	26482.67	Sandbanks which are slightly covered by sea water all the time, mudflats and sandflats not covered by seawater at low tide, reefs, large shallow inlets and bays, submerged or partially submerged sea caves
B	Great Ormes Head SAC	302.62	European dry heath, semi-natural dry grasslands and scrubland habitat on calcareous substrates (<i>Festuco-Brometalia</i>)
C	Dee Estuary SPA/Ramsar/IBA	13076.29	<i>During breeding season:</i> Common tern <i>Sterna hirundo</i>, little tern <i>Sterna albifrons</i> <i>On passage:</i> Sandwich tern <i>Sterna sandvicensis</i> <i>Over winter:</i> Bar-tailed godwit <i>Limosa lapponica</i> <i>Migratory, on passage:</i> Redshank <i>Tringa totanus</i> <i>Migratory, over winter:</i> Black-tailed godwit <i>Limosa limosa islandica</i>, curlew <i>Numenius arquata</i>, dunlin <i>Calidris alpina</i>, grey plover <i>Pluvialis squatarola</i>, knot <i>Calidris canutus</i>, oystercatcher <i>Haematopus ostralegus</i>, pintail <i>Anas acuta</i>, redshank <i>Tringa totanus</i>, shelduck <i>Tadorna tadorna</i>, teal <i>Anas crecca</i> <i>Over winter assemblage:</i> Waterfowl <i>Non-bird Ramsar features:</i> Extensive intertidal mudflats and sandflats with large expanses of saltmarsh, plus a variety of other internationally important intertidal, subtidal, coastal and wetland habitats.
D	Liverpool Bay (pSPA)	197504.24 (under discussion)	Proposal for inshore SPA in Liverpool Bay for large aggregations of red throated divers <i>Gavia stellata</i> , and common scoter <i>Melanitta nigra</i> being developed jointly by CCW and EN.
E	Dee Estuary (pSAC)	15754.93 (under discussion)	Estuaries, mudflats and sandflats, <i>Salicornia</i> and other annuals colonising mud & sand, Atlantic salt meadow, annual vegetation of drift lines, fixed and shifting dunes, river lamprey <i>Lampetra fluviatilis</i> , sea lamprey <i>Petromyzon marinus</i> .

Source: JNCC Website

Along this section of coast there are also many Sites of Special Scientific Interest (SSSI). To the west lies Great Ormes Head SSSI and the Aber Afon Conwy SSSI and Little Ormes Head SSSI which each contain coastal and intertidal habitats of national importance.

The North Wales Coast IBA stretches from Little Orme's Head to Rhyl extending approximately 6km seawards and supports important populations of wildfowl. This area also includes the SSSI at Llanddulas Beach and, at the mouth of the Dee Estuary, Gronant Dunes and Talacre Warren SSSI and National Nature Reserve (NNR), both of which are notable for coastal sand dunes. Such designations highlight the characteristic soft shoreline of the region and its importance for wildlife.

The Dee Estuary SPA/IBA and Ramsar site is an area of significant ecological importance especially for seabirds and waders. The Estuary is also proposed as an SAC (primarily for sandflat, mudflat and saltmarsh communities), but has not yet been included on the list of candidate sites. The Royal Society for the Protection of Birds (RSPB) owns, leases or has management agreements for a total of 4,715 hectares of the estuary and a Dee Estuary Strategy is in place. A number of SSSIs are found within the estuary and the small tidal island of Hilbre, is designated as a Local Nature Reserve (LNR). The island attracts birds such as oystercatchers and curlews in the autumn and is a haul out site for grey seal. Several intertidal, coastal and riverine/estuarine habitats, along with many species of invertebrates, fish, birds, mammals and plants in the study area are the subject of local biodiversity action plans (LBAPs) which contribute to national biodiversity action plans (BAPs).

4.9.1 Sedimentation issues

The impact of a large offshore structure on the scale envisaged for a tidal energy lagoon in Liverpool Bay would need careful assessment. One of the key concerns raised by CCW over the Swansea Bay lagoon is the potential impact on sedimentary processes [4.15]. Predicting sediment movement is important not only because of potential changes to intertidal habitat, but also coastal processes. To predict changes to sediment erosion, movement and accretion a sediment transport model would need to be developed over an extensive area of Liverpool Bay. The model would need to be linked to a hydrodynamic model that predicts water flows over different tidal ranges and related current strengths. CCW has also indicated that an EIA would need to include an assessment of potential coastal processes at all stages of development including construction. The EIA would also need to take account of climate change, particularly sea level rise and increasing storm frequency and intensity.

Changes to substrate linked to lagoon construction and operation could potentially affect inshore fisheries and benthic fauna. Consequently, surveys of these habitats would be a requirement. CCW has expressed concern over the potential loss of habitat especially intertidal feeding areas frequented by waders and wildfowl. Any EIA must also take account of dredged areas as well as the permanent loss of habitat caused by the large lagoon footprint [4.15].

4.10 Other uses/users

Within the Irish Sea oil and gas production is centred in the Liverpool Bay area with the Douglas and Lennox fields producing some 1.69 million tonnes of oil in 2004. The Irish Sea has a great potential for wind and tide energy and the Liverpool Bay area was included as one of the three strategic areas around England and Wales identified in November 2002 in the DTI's Future Offshore Consultation for offshore wind development. Several windfarm development applications are currently being considered for the Liverpool Bay area.

The Point of Ayr gas processing terminal in North Wales receives natural gas from the Douglas and other fields via pipeline. One of the nine major UK oil refineries is located at Ellesmere Port. A sewage pipeline extends from North Wirral 3km into Liverpool Bay.

Liverpool Bay is an important UK resource for coastal tourism and leisure. The area attracts a high number of people for a wide range of land- and water-based activities, including bird watching, yachting, walking, golf, diving, surfing, angling, and sailboarding. Tourism in Merseyside generated £604 million spending in the local economy. The tourist industry supports 21,800 jobs in the region, of which 74% are directly related to tourism [4.21]. The value of seaside tourism to Wales in 2001 was estimated at £0.9 billion [4.22].

There are a number of significant port facilities along Liverpool Bay. The Mersey River provides access to several facilities, including the Port of Liverpool and the Manchester Ship Canal and Port of Manchester. Lying on the Welsh coast of the Dee Estuary is the port of Mostyn Docks. A significant proportion of the shipping that uses these port facilities passes close by or through the Liverpool Bay area. The Queens Channel is an important shipping route in the area with an estimated 12,340 vessels passing through, corresponding to an average of 34 vessels per day. The main fishing along Liverpool Bay is undertaken by small commercial vessels based at local ports and harbours, including Hoylake, Chester, Mersey Estuary, Mostyn, Rhyl, Connah's Quay and Conway. In total, there are 12 marinas in NW England and North Wales with approximately 2,000 berths [4.21].

The northern Irish Sea and Liverpool Bay are an area of interest for military activity, with submarine, surface vessel and aircraft exercising in the region [4.19].

Fishing remains an important industry in the region in terms of employment and local economy. Beam trawlers, gill netters and demersal trawlers all operate in the Liverpool Bay area. The principal fishing effort is by otter trawling, which predominantly targets *Nephrops* with by catch of cod, whiting and plaice [4.19]. From April to December, a shrimp fishery is pursued between the Dee and Duddon estuaries. A number of other shellfish fisheries operate to the nearshore, including mussels, Manila clam and oyster cultivation and cockle harvesting. The river Dee is important for rod catches of salmon. Mariculture in Liverpool Bay is limited to shellfish production within the Conwy Estuary.

There is one area licensed for dredging in Liverpool Bay (licensed for sand), called Hilbre Swash. However, extraction only takes place in relatively small area within the licensed area.

There are numerous important prehistoric sites on land around Liverpool Bay and there may be some sites in shallow water.

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5 Mersey tidal-energy barrage

5.1 Background to the Mersey barrage

This case study summarises the proposed development of a tidal-energy barrage across the Mersey Estuary. The Mersey has a mean spring tidal range of about 8.0m with an extensive intertidal area and a narrow mouth where the estuary enters Liverpool Bay. These characteristics highlighted the possibility that a site near the mouth of the estuary could be a potentially good site for a tidal-energy barrage. Not only could the scheme generate up to 0.5% of the UK's electricity demand in 1990 from a renewable source, it could also offer a second road crossing between Liverpool and Birkenhead, and help to stimulate regional regeneration. Although the amount of electricity generated would be about 8.6% of the energy from a Severn barrage (on the Cardiff Weston line), the Mersey attracted significant attention and support from the UK Government and industry that culminated in a detailed development study published in 1993 [5.1].

The Mersey barrage was first proposed by the former Merseyside County Council in 1981. The underlying interest from this urban authority and its successor led to the formation of the Mersey Barrage Company, a consortium of construction and engineering companies, and local interest including the Mersey Docks and Harbour Board. During the late 1980s and early 1990s, the Mersey barrage project evaluation received significant public and private-sector backing. This level of support culminated in a detailed study summarising the results of about six years of evaluation that forms the basis of this case study. In addition to the energy capture and related renewable energy benefits, this case study also focuses on the impact of the proposed barrage on shipping activities. The Mersey Estuary has a number of important commercial port facilities, notably the Stanlow oil refinery and petrochemical complex. The owner, Shell, was particularly concerned because it imports crude oil at a dock near the entrance to the estuary and exports refined products from the refinery further upstream. Considerable effort was expended at the time simulating ship movements to predict the impact on shipping.

Merseyside has suffered from industrial decline and the barrage was also viewed as a potential catalyst for regional regeneration. The case study also examines the non-energy benefits, most of which would have come from employment and a new road crossing.

5.2 Renewed interest in the Mersey

Interest in tidal energy from the Mersey Estuary has been recently revived. A new study co-sponsored by Peel Holdings, (owner of the Mersey Docks & Harbour Company and Liverpool John Lennon airport), and the Northwest Regional Development Agency (NWDA), has been commissioned to look at a number of different tidal energy options [5.2].

The study team will assess seven different technology options:

- A tidal energy lagoon constructed in Liverpool Bay consisting of an enclosed embankment with a power house consisting of sluices and turbines. The proponents have stated that this option could be developed in combination with any of the other options.
- An array of tidal current turbines positioned within a central area near the mouth of the Mersey Estuary. The type of tidal current turbine technology has not been specified.

- A tidal fence consisting of vertical axis turbines housed in submerged cells built across the estuary. Each cell would be positioned between a series of partially dammed sections spanning the estuary. Tidal flow between each dammed section would be accelerated by the artificial constrictions increasing the power output of the turbines.
- A constrained channel with tidal current turbines concentrated in a single central section. The estuary would be partially blocked by two sections of embankment built out from each side to form a narrow channel. The concept is also designed to accelerate water through a narrow channel to increase energy output.
- A water wheel zone consisting of a series of large diameter water wheels housed either within a barrage crossing the entire estuary or in a series of separate sections.
- A tidal energy barrage consisting of sluices and turbines housed within a structure which could be completely closed at high water to form a head of water. Water would be allowed to flow back through the turbines to generate power.
- Tidal gates consisting of compact turbines positioned in the base of sluices. Water would be allowed to flow through these sluices on the flood tide which would then be closed at high water. The sluices would be opened on the ebb tide allowing water to generate power by flowing back through the turbines.

A summary of the pre-feasibility assessment has been published [5.2]. Initial estimates of power outputs from the different technical options are presented in Table 5.1.

Table 5.1 Initial estimates of power outputs from potential tidal energy options for the Mersey.

Option	Rated Power (MW)	Annual Energy Output (GWh/year)
Tidal Lagoon*	350	650
Tidal barrage with 28, 8m diameter turbines*	700	1,200
Central Reservation i.e. 120m wide, 1.5km long array of 150 8m diameter tidal current turbines	20	40
Constrained Channel i.e. 500m wide and 300m long 150 8m diameter axial flow stream turbines.	50	100
Tidal Fence with 49 vertical axis turbines	35	80
Tidal Gate using 1400, 1-1.5m diameter turbines	380	700
Water Wheel 28m diameter, 25-30m long water wheels each with 24 blades	200	500

* estimates do not include additional energy from pumping at high water (see Section 5.5 for an explanation of power generation that incorporates pumping at high water)

The next stage of this appraisal will include modelling to determine power output; preparation of outline designs, their estimated costs and construction programme. The study will also include modelling to determine changes to hydraulic flow and sediment movement, environmental impacts and the potential for associated economic development.

5.3 Development of the Mersey barrage scheme

The estuary's importance for shipping and as a habitat for large numbers of migratory birds were two key factors that had to be taken into account from the very start of the Mersey barrage scheme conceived in the early 1980s. The potential for regional regeneration from direct employment during construction, and from a new road crossing, were also recognised as significant additional benefits that needed to be investigated. This case study looks at the development of a barrage across the Mersey and why the preferred Stage 3 alignment was selected. The case study also explains how the barrage could be constructed and the amount of electricity it would generate.

The impact on shipping would be significant, largely because of the presence of the Stanlow petrochemical complex. The installation relies on the importation of crude oil from a terminal at Tranmere and the export of refined products from the lower reaches of the Manchester Ship Canal. Garston docks would also have been affected. The assessment of ship movements caused by changes to hydraulic (water) flows, and ship movements through locks, were both investigated in some detail.

The first proposal for a Mersey barrage was made by the former Merseyside County Council in 1981 which commissioned a desk study by Marinotech North West published in 1983. This was followed by another study carried out jointly between Marinotech North West and Rendel Parkman, which reported in 1985. The study re-examined the economic case for the project and concluded that the scheme was worth further investigation. At this point, Merseyside County Council was disbanded under local government reorganisation. However, before its demise, the Council encouraged the formation of the Mersey Barrage Company (MBC) to promote the scheme. The MBC was a consortium of construction companies led by Tarmac and Costain and local interests including the Mersey Docks and Harbour Board. The members of the MBC are listed in Section 5.11.

In 1986, a jointly funded project was initiated by the MBC with the former Department of Energy. These new studies were split into two stages. Stage I (late 1986 to 1988) was completed in 1988, at a cost of £0.8 million, with 59% funding from the MBC and 41% from the Department of Energy [5.3]. This included hydraulic and energy modelling together with a preliminary examination of the geotechnical conditions, socio-industrial benefits and likely effects on shipping, and the ecology of the estuary.

One of the primary objectives of Stage I was to determine a clear preference for an alignment. The 1983 report had considered three possible locations for the barrage:

- Line 1 near the entrance to the estuary between New Brighton and Langton Lock.
- Line 2 located in the middle of the narrows between Seacombe Promenade and Trafalgar Dock.
- Line 3 upstream of the Narrows, between Rock Ferry and the former Herculaneum Dock.

The 1983 study concluded that Line 2 was the least favoured and this was subsequently excluded from further investigation. No clear preference emerged between the other two alignments during Stage I studies and the decision was deferred to the next Stage, although it became apparent that the downstream position, Line 1, posed considerable difficulties for shipping. A more favourable location 800m upstream, identified as 1A, emerged as a more suitable alternative.

A preliminary geotechnical study was undertaken to determine whether there were any insurmountable geological features that would preclude barrage construction. The investigation included bathymetric and geophysical surveys over a 200m wide strip across the estuary at each proposed alignment. The survey showed good foundation conditions for

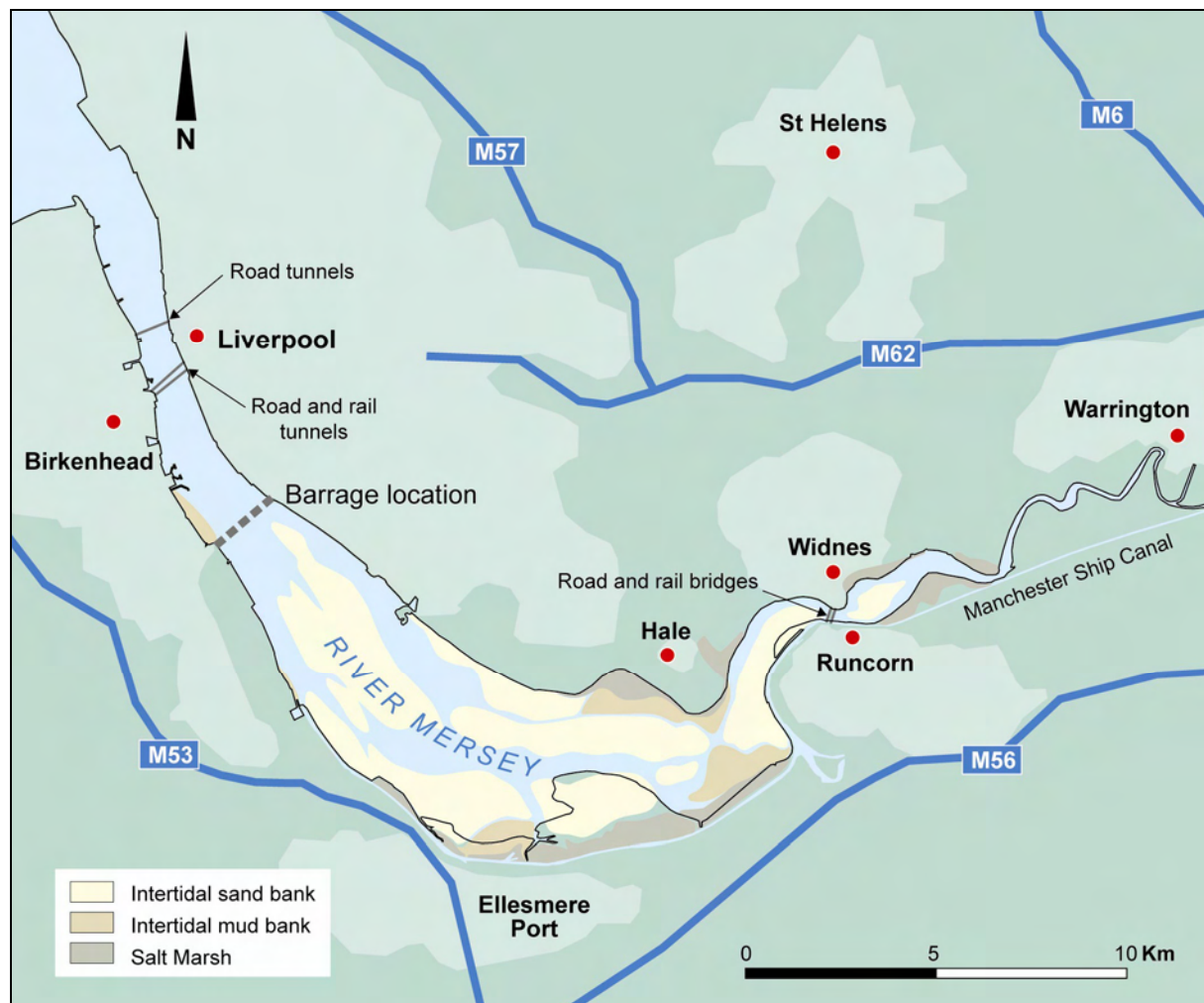
a possible barrage in the area of Line 1A, but more complex conditions near Line 3 where a deep buried glacial channel was discovered infilled with a thick deposit of boulder clay interspersed with sand and gravel.

On completion of Stage I, a second phase of study was initiated in 1988 at a cost of £1.74 million co-funded between the MBC and the Department of Energy [5.4]. A detailed engineering review was undertaken to determine the most suitable method of construction, its cost and the timescale of the project, which would lead to a decision on the most suitable alignment. Other aspects investigated in this phase of work included energy modelling using improved mathematical techniques, sedimentation, regional impact and a reassessment of the environmental effects based on updated estimates of water level changes.

During Stage II, the MBC selected Line 3 as this would, on balance, yield electricity at the most economic cost. The alternative location near to the mouth of the estuary at Egremont, Line 1A, was rejected because although the amount of electricity generated and the regional benefits would be greater at this location, the capital costs would be significantly larger. The main element of cost difference between the two schemes would be the requirement for a large ship lock at Line 1A that would cost £200million (1989 prices), to allow super tankers access to the Tranmere Oil Terminal, which is the supply point for the Stanlow Refinery.

5.4 Stage III barrage design and cost

The selection of a preferred alignment further upstream extended the length of the barrage and meant that it would have to be constructed on a less compact substrate. However, the Line 3 alignment avoided the necessity for a large ship lock to accommodate supertankers (Figure 5.1). More detailed modelling of the energy output revealed that a substantial increase in forecasted energy output could be achieved by including a greater number of turbine generators within the design and the incorporation of flood pumping.

Figure 5.1 Barrage location of the Stage III alignment

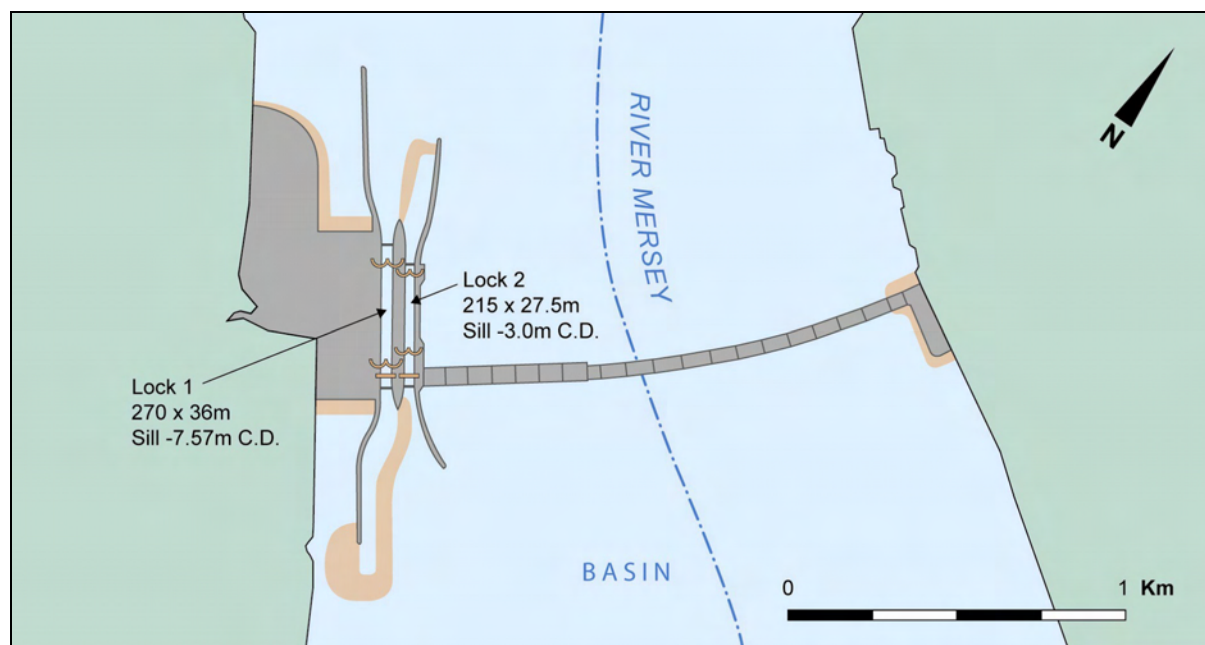
The MBC accelerated its work on the 3B alignment to verify the design, cost estimation and energy output [5.1]. The main objective of this phase of work was to refine the cost and energy yield estimates to a point where the consortium would be confident in submitting a proposal to build a barrage based on firm construction prices. This phase also investigated shipping, regional non-energy benefits, sedimentation and the first major phase of environmental monitoring.

An extensive geotechnical site investigation centred on Line 3 was instigated in the autumn of 1990 that included drilling a number of new boreholes across the estuary and a complementary geophysical survey to evaluate the foundation conditions. Data from each of these surveys were combined to compile a three-dimensional perspective of the underlying sediments and, in particular, the buried glacial channel. Laboratory tests on core samples together with in-situ testing provided information on foundation conditions, which were crucial to the revised design criteria for the barrage.

By the middle of 1991, the preferred location for the barrage had been selected (New Ferry to Liverpool Garden Festival site). Energy studies and engineering designs were both well advanced, which showed that the barrage would take an estimated 5.5 years to construct and cost £966 million, at 1991 prices. The barrage would have an installed capacity of 700MW and comprise 28, 8m-diameter pit turbine generators each with a generation capacity of 25MW. These would be housed in a series of caissons located on the New Ferry side of the estuary (see Figure 5.2). In contrast to earlier configurations, the sluices would be of the open-weir type which, although hydraulically less efficient than venturi sluices, offer

a more cost-effective solution in view of the less favourable foundation conditions revealed by the geotechnical survey. The revised estimate for the annual energy output at this stage was 1.39TWh/year, a reduction of about 6% on the previous assessment during Stage II.

Figure 5.2 Detail of the Stage III alignment. The turbine-generator section is housed in the section adjacent to the two ship locks. The remainder of the barrage consists of sluices.



A breakdown in construction costs for the Stage III alignment is presented in Table 5.2. The categories shown in this Table were the principal divisions used by the MBC to calculate the total capital cost of the project including design, management and environmental studies. Unlike smaller tidal energy barrages, the caissons would be prefabricated in a purpose-built site, and classified as temporary works adjacent to the barrage alignment. Completed caissons would be floated out from this site and winched into position on neap tides. Accommodation works include the construction of access roads, upgraded flood defences, diverted pipelines and modifications to existing watercourses that flow into the Mersey Estuary. All these costs, including mechanical and electrical equipment, have been inflated to 2006 prices using the All New Construction Price Index (COP1). The operation and maintenance cost for the barrage was based on a planned and costed operation programme for the barrage and the locks. This value has been inflated using the Private Industrial index.

Table 5.2 Capital and operating costs for the Stage III Mersey tidal energy barrage

Capital, operating costs and energy output	£million
Civil engineering	
Temporary works (caisson fabrication site)	165.61
Caisson construction	178.42
Rock blanket and scour protection	50.88
Other works	9.77
Accommodation works	98.73
Embankment (reclamation)	31.34
Lock Insitu construction	139.33
Total for civils	674.08

Mechanical & Electrical plant and equipment	
Turbines, gearboxes and generators	360.38
Sluice gates stop logs, fish pass	69.75
Mechanical and electrical services	87.44
Switch gear	20.55
Cables on barrage	41.61
Power and control cables on barrage	57.62
Transmission	26.11
Total for M&E kit	663.47
Non construction costs including preconstruction design, consent and environmental studies	32.01
Detailed design and management costs	53.58
Site construction: engineering and management costs including commissioning and compensation.	88.45
Total project cost	1511.59
MW installed	700.00
£/kW installed 2006	2159.41
O&M	20.50

5.4.1 Electricity integration

Output from the Mersey barrage could be fed directly to the 132kV Manweb substations in close proximity to the barrage or directly into the 275kV National Grid system which terminates in Birkenhead. The latter option may also provide a more economic proposition than connection to the Manweb distribution system.

5.5 Energy output

During Stage 3, the MBC also refined its predictions of energy output. In principle, tidal energy barrages operate in a similar way to that of conventional lower-head hydroelectric power stations built across large rivers such as the Rhône and the Danube. Provided there is sufficient head (difference in water level) water will flow from one side to the other through large turbines to generate electricity. However, in a tidal barrage the flow into the impounded basin during the flood tide and the flow during the outward (ebb) generation phase have to be accurately predicted. Moreover, as ebb generation progresses, the head and, therefore, flow conditions vary adding to the complexity of calculating power output. The MBC developed complex mathematical models that allowed improved simulation of hydraulic flows and enabled it to predict, with better accuracy, the energy output on each tide. The models were also used to predict the velocity of water flowing into and out of the estuary. The ability to model hydraulic (water) flow is not only important for predicting energy output over a range of different tides, but also the conditions that ships would experience as they approach or leave locks. Improved hydraulic modelling also revealed the effects of a channel seaward of the barrage that extends out into Liverpool Bay. If the barrage were built, this channel would impede the flow of water away from the barrage during ebb generation with a consequent restriction in energy yield. This phenomenon has been predicted for other tidal energy barrages such as the Loughor, Wyre and Duddon, which have long channels extending from the mouth of each estuary into the open sea.

The concept of tidal energy from barrages studied by the MBC and other groups, including the Severn Tidal Power Group, has concluded that the most efficient and economic mode of operation is to restrict generation to the ebb tide. However, it has also been recognised that immediately preceding, and at, high tide, the barrage turbines can be used in reverse to pump water into the impounded basin increasing the volume of water. This mode of operation (flood pumping) can increase the amount of energy output by as much as 13% depending on the state of the tide. It must be stressed that the additional energy derived from flood pumping is governed by site-specific conditions (see Appendix 3 for a more detailed explanation).

The MBC evaluated turbine designs that would be suitable for a low, variable-head tidal regime and flood pumping. The work concluded that a three-bladed turbine, also used for pumping, would be marginally more efficient in comparison with a four-bladed turbine for the operational heads that would be experienced. A three bladed design would also offer cost and material savings by reducing the 'hub-to-tip' ratio [5.5].

The hydraulic studies that were used to refine the energy yield calculations have been calibrated against the Rance barrage with field data supplied by Electricité de France. An initial comparison of the MBC two-dimensional energy model results with the Rance data for a typical spring tide, has shown a difference of less than 2%. Improvements in energy modelling coupled with an optimised three-bladed turbine design revealed an increase in the predicted energy yield from 1.38 to 1.45TWh/year.

5.5.1 Unit cost of energy

The unit cost of energy for the Mersey barrage was calculated using a standard discounted cash flow analysis. It assumes a technical life of 120 years with major turbine and generator refurbishment every 40 years. The unit cost of generation assuming an average annual output of 1.45TWh and 2006 prices are shown in Table 5.3.

Table 5.3 Unit cost of generation for the Stage III Mersey tidal energy barrage

Discount rate (%)	3.5	8	10	15
Mersey unit cost (p/kWh)	5.82	12.27	15.79	26.52

5.5.2 Carbon balance

The quantity of embedded carbon has been estimated for the Stage III Mersey barrage (Table 5.4). The quantities of material used are included in the Stage III and IIIA report [5.1]. In addition to the volume of concrete, the report includes details of the steel used, not only for the turbines, but also the associated mountings, providing a reliable benchmark for estimating steel quantities in other tidal energy schemes that use pit turbines. The maximum and minimum quantities of embedded carbon are based on the highest and lowest factors for embedded carbon for steel and concrete.

Table 5.3 Embedded carbon and carbon emissions saved over the technical life of the Stage III Mersey tidal energy barrage

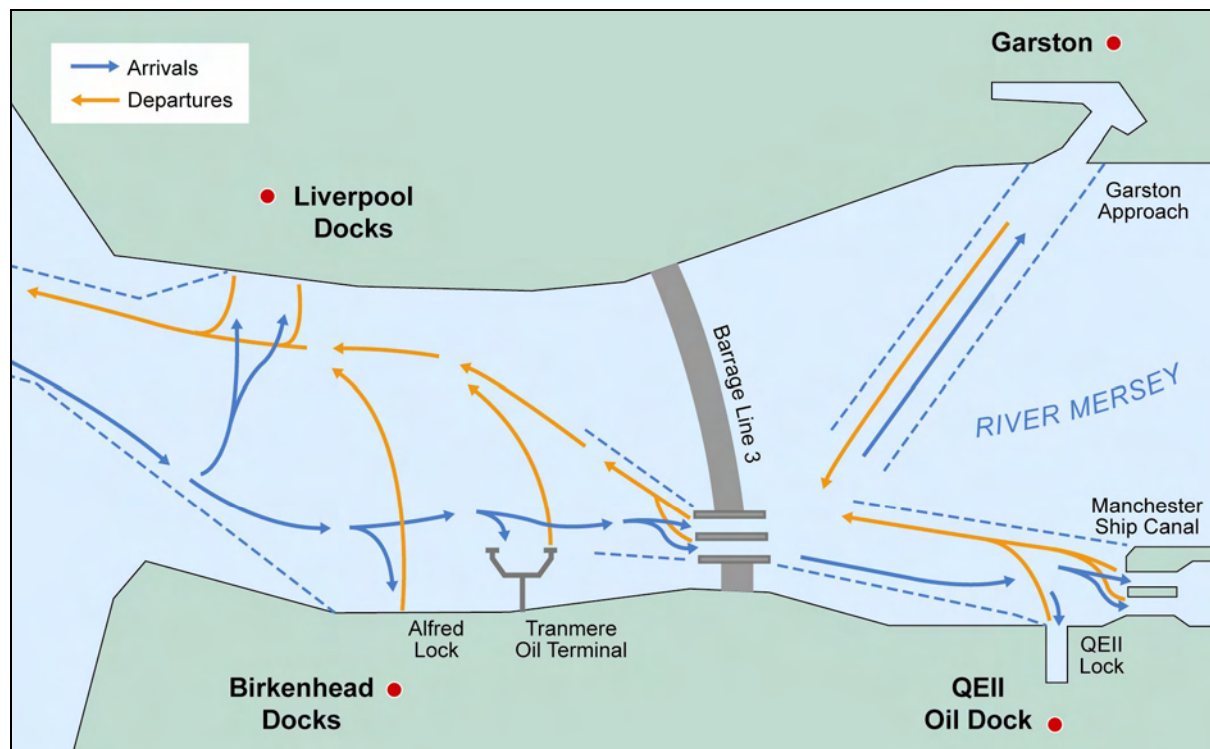
	Mersey barrage
Total volume of concrete (m ³)	1,030,000
Total mass of steel (t)	103,342
Total mass of copper (t)	215
Estimated embedded CO₂ (t)	
Minimum	374,803
Maximum	566,424
GWh/year	1,450
CO ₂ /year displaced (t/GWh)	623,500
CO ₂ saved over technical lifetime (t)	74,820,000
Carbon payback minimum (months)	7
Carbon payback maximum (months)	11

5.6 Regional and non-energy benefits

5.6.1 Shipping

The preferred alignment for a Mersey barrage was strongly influenced by the requirements for shipping. Vessels that would need to access Garston, Eastham Locks, the QEII Oil Lock and the Manchester Ship Canal would need to pass through a lock. The barrage would also induce a change in current strength and direction, and water levels that would need to be evaluated to ensure that shipping operations would not be adversely affected. The docking of very large crude carriers (VLCCs) at the Tranmere jetties would also be affected.

During the Stage 3 development stage, the MBC commissioned a study to simulate ship movements. The model incorporated the conditions predicted by the hydraulic model. Therefore, it was possible to predict the transit time for different ships and whether they would be subject to adverse risk. Different configurations of the barrage, including the position of ship locks, were evaluated to determine the optimum conditions for shipping. Two locks adjacent to the Bromborough shore offered the most favourable design. A new channel would need to be dredged to enable ships to reach Garston Dock on the opposite shore (see Figure 5.3).

Figure 5.3 Shipping movements used in the MBC shipping traffic simulation model

To determine the effects to shipping, the MBC developed a shipping traffic model based on 1990 ship movements. The model anticipated 7,153 arrivals to Merseyside port's docks that would be affected by the barrage. The model anticipated 14,306 ship movements in this single year. Ships must arrive up to four hours either side of high water. The locks were designed to accommodate the largest vessels that can enter Garston (152m x 19m) and the New Ferry Lock (270 x 36m equivalent to 39,000 deadweight tonnes (DWT)) at the entrance to the Manchester Ship Canal. Both locks would have large lead-in jetties to shield vessels as they approached or left the locks.

The ship movement simulations were based on six ship sizes

- A 323,000DWT VLCC laden to 180,000DWT (The largest ship that can berth at the Tranmere oil terminal).
- 39,000DWT product carrier (the largest ship that can use the QEII Oil dock).
- 7,500DWT general cargo vessel (The widest ship that can enter Garston Dock).
- 7,500DWT general cargo/container vessel with deck cargo.
- 4,500DWT coaster.

A series of simulations were run for each type of vessel. These enable the conditions experienced by each type of ship as it approached the locks to be predicted. The model also determined the extent of the safe operational limits. The work also established that ships could still navigate through a 300m gap during the final closure stages of the barrage. The overriding conclusion from these simulated ship movements was that the provision of two locks would be an acceptable balance between the additional construction cost and the increased operating costs for shipping companies.

The studies also revealed that VLCCs docking at the Tranmere Oil Terminal would be affected by the operation of the barrage. Arrival of a VLCC at high water may require flood pumping to be restricted. By combining the estimated transit times for ships passing through the locks, with the annual shipping traffic, the MBC was able to predict the net annual

additional shipping costs. They were also able to predict the operational costs for the barrage. The total increased costs were £1.5 million/year at 1992 prices. Voyage times to and from upriver posts would be extended, on average, by 40 minutes. The existing number of tugs and pilots would be adequate although maintenance dredging will increase by as much as 60% of pre-barrage conditions.

5.6.2 Valuation of non energy benefits and impacts

During the Stage 3 development phase of the Mersey barrage, the MBC commissioned further work to value the non-energy benefits and the negative impacts of the barrage. The results are summarised in Table 5.5 at 1992 prices.

Table 5.5 Value of non energy impacts from the Stage III Mersey tidal energy barrage

	Lowest NPV estimated (£million)	Highest NPV estimates (£million)
Amenity and blight	-0.8	16.2
Leisure	4.8	8.5
Tourism	1.9	8.4
Road crossing	92	200
Flood control	0.4	1.0
Loss of intertidal habitat	-8.0	-21

- The amenity and blight caused by barrage construction and operation was determined by the effect on property values. The two values represent the changes, with and without a road crossing.
- The primary benefit from leisure was estimated from the value of water sports.
- The value of tourism depends on the estimated number of visitors. The lower estimate assumed 200,000/year. The upper limit assumed 500,000/year.
- The value of the road crossing assumed a three-lane road link with lifting bridges across the locks. The upper limit assumes unrestricted road access, whereas the lower limit assumes that road traffic would be disrupted by ships passing through the locks.
- The benefits from flood defence upstream of the barrage are based on actual flood damage and the probability of such incidents occurring in the future.
- There would be some permanent loss of intertidal area. The cost of this impact is based on the provision of an equivalent area of new intertidal habitat.

In addition to these benefits, the number of jobs created at the peak of construction would be about 2,000 in the Merseyside area with a similar number across the UK. This estimate assumed that much of the generation equipment would be manufactured within the UK. This may not necessarily be the case now.

There would be an estimated 600 additional jobs related to the running and maintenance of the barrage once it became fully operational.

5.7 Environmental Issues

Highlights

- The large tidal range of the Mersey estuary is an important factor determining its physical and biological characteristics.
- Seabed sediments are generally mobile with low benthic species diversity.
- Intertidal sand and mudflats of the inner estuary support internationally important numbers of water birds throughout much of the year.
- Much of the estuary is developed and there is a legacy of pollution of water, sediments and biota although there have been significant improvements of recent.
- Tourism is important, and the coastline and waters of the estuary are used for a variety of recreational activities.

The Mersey estuary is a large tidal inlet in northwest England, close to the border with north Wales. At a length of 46km, it is one of the largest estuaries in the UK and receives drainage from an extensively urbanised catchment area of approximately 5,000km², including the cities of Liverpool and Manchester [5.6]. From the upper to middle reaches, the inner estuary gradually widens to a maximum width of 5km before narrowing to about 1km at the Mersey Narrows and flowing into the outer estuary which forms part of Liverpool Bay. Extensive areas of intertidal sand and mudflats exist in the upper and middle estuary, and also around the mouth of the estuary where a more natural coastal landscape remains. These intertidal and coastal habitats support international important populations of water birds, primarily over winter, and receive multiple conservation designations.

The estuary is an important and busy shipping route, with large volumes of traffic passing through the estuary to Manchester via a ship canal. Several large industrial sites are located along the banks of the estuary, and the area has historically received environmentally damaging quantities of organic effluent and contaminants. Recent initiatives, coupled with changing industrial practices, have led to improved water quality. However, given the long-term legacy of pollution and the repository held in fine sediments, chemical impacts and resultant biological effects are sometimes detectable. Consequently, the estuary remains one of the most contaminated in the UK [5.5].

5.7.1 Summary of key environmental sensitivities/constraints

Table 5.6 – Summary of key environmental sensitivities/constraints

Feature	Summary	Potential adverse factors
Seabed sediments and transport processes	• The wide shallow inner estuary has extensive intertidal sand and mud flats and large areas of saltmarsh on its southern margin [5.7]. • Tidal currents sufficiently strong to prevent accumulation of fine sediments in the Narrows and the channel floor is largely bare rock with some gravel and mud deposits. • Large area of intertidal sand and mud banks in outer estuary through which navigation channels are maintained by dredging between the training banks	• Physical disruption to tidal flows may affect sediment transport. • Alteration of estuary profile.

Feature	Summary	Potential adverse factors
	[5.7]. • Training scheme has resulted in considerable changes in sediment deposition patterns. Fine sediments, once carried into the estuary, tend to oscillate with the ebb and flow and can only escape into Liverpool Bay during exceptionally wet weather and large spring tides [5.6].	
Hydrology	• Mean spring tidal range of 8-10m [5.8] with maximum tidal current velocities of ca. 2.2m/s in the Narrows. • The strong tidal currents weaken upstream as the estuary widens, leading to deposition of sand and mud which form extensive banks at low tide. • Tidal currents dominate but density currents (especially in the Narrows) also important in moving bed material into the estuary [5.7]. • Mean annual significant wave height of <0.6m at estuary mouth [5.8].	• Disruption of tidal flows, levels of vertical mixing and light penetration, salinity. • Alteration of tidal prism. • Change in level of wave exposure
Water and sediment quality	• Decades of industrial effluent and sewage disposal have led to severe pollution of the estuary although recent initiatives have led to considerable improvements in water quality [5.9]. • Once associated with fine sediments, contaminants tend to be dispersed over a large area due to the high energy conditions in the estuary [5.6]. • Relatively high levels of contaminants found within shellfish and fish from the Mersey estuary [5.10].	• Contamination. • Re-suspension of contaminated sediments. • Disruption of tidal flows may allow accumulation of contaminants.
Landscape/ seascape	• The urban growth and built-up landscape of the Merseyside Conurbation character area is dominant on the north of the Mersey Estuary and extends to Birkenhead in the south. • Mersey Valley character area is estuarine in character with intertidal mud/sand flats and low exposed cliffs. Substantial industrial development [5.11].	• Visual intrusion. • Habitat loss. • Increased coastal traffic. • Change to landscape character.
Coastal habitats	• Priority coastal habitats listed on relevant LBAPs (North Merseyside and Cheshire) include coastal saltmarsh, sand dunes, and coastal and floodplain grazing marsh (UKBAP website).	• 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	• Limited range of benthic communities present due to the extensive modification of the estuary [5.12]. • Greatest variety found on the mobile sandbanks of the outer estuary characterised by amphipods and polychaetes with bivalve-dominated communities in	• Physical disturbance. • Habitat loss. • Habitat change due to changes

Feature	Summary	Potential adverse factors
	deeper water and dense aggregations of sand mason worms <i>Lanice conchilega</i> in areas of high tidal streams [5.12]. • Low diversity of species in the Narrows, where tidal streams are strong, and from the mobile sandflats of the middle estuary [5.13]. • Muddy sands of the inner estuary support dense populations of invertebrates notably lugworm <i>Arenicola marina</i>, ragworm <i>Nereis</i> spp. and bivalve molluscs, including cockle <i>Cerastoderma edule</i> and Baltic tellin <i>Macoma balthica</i>. The mud snail <i>Hydrobia ulvae</i> and sandhopper <i>Corophium volutator</i> also abundant (Langston <i>et al.</i> 2006). Mudflats listed as a priority habitat on the Cheshire LBAP. • Physical characteristics of the sediment, salinity and tidal flow, rather than pollution appear to be the major determinants of communities [5.6].	in wave exposure.
Plankton	• Long phytoplankton growth season lasting 6 to 7 months. Diatoms abundant throughout the growth season, dinoflagellates peak in summer [5.6]. • The flagellate <i>Phaeocystis pouchetii</i> reported to be very abundant (Langston <i>et al.</i> 2006). • Little information on zooplankton but CPR data indicates that larvaceans common [5.14].	• Harmful algal blooms.
Fish and shellfish	• Fish community historically impoverished, but since improvements in water quality, estuary now hosts a wide range of fish species [5.6]. • Over 40 fish species officially recorded as being present in the estuary, most common include sprat, herring, whiting, goby, pipefish, flounder and plaice [5.15]. • Potential spawning area for sprat (May-August) and nursery area for herring, plaice, sole and whiting [5.16]. • Migratory fish recorded include sea trout, eels, sea and river lampreys, and Atlantic salmon [5.17]. Allis and twaite shad listed on the Cheshire LBAP. • Mussels and cockles commercially exploited from production areas at the mouth of the estuary [5.18].	• Physical disturbance, particularly to migration routes. • Electromagnetic field (EMF) disturbance. • Habitat loss • Collision risk. • Noise.
Birds	• The intertidal flats and saltmarshes provide feeding and roosting sites for large populations of water birds. During the winter, the site supports ducks and waders, and during the spring and autumn migration periods, it is particularly important for wader populations moving along the west coast of Britain [5.6]. • Concern about the status of bird populations in the Mersey estuary with high alerts triggered for 6 out of the 12 water bird species evaluated. Potential reasons for the decline in numbers include pollution,	• Physical disturbance. • Habitat loss. • Noise.

Feature	Summary	Potential adverse factors
	disturbance, erosion and saltmarsh encroachment [5.19]. Overall sensitivity to surface pollution at the mouth of the estuary is very high, particularly over winter [5.20].	
Marine mammals	- The Mersey estuary is relatively unimportant for cetaceans with harbour porpoise (listed on the Cheshire LBAP) and bottlenose dolphins the most frequently recorded from nearshore areas of Liverpool Bay. - No major seal breeding sites but a large number of grey seals regularly use the outer area of the Dee Estuary for feeding and, at low water, haul out close to Hilbre Island. Common seals are only occasionally recorded (Natural England - Natural Areas - website). - Otters are listed on the Cheshire LBAP.	- Physical disturbance. - Habitat loss. - Noise.

5.8 Conservation sites and other key environmental sensitivities

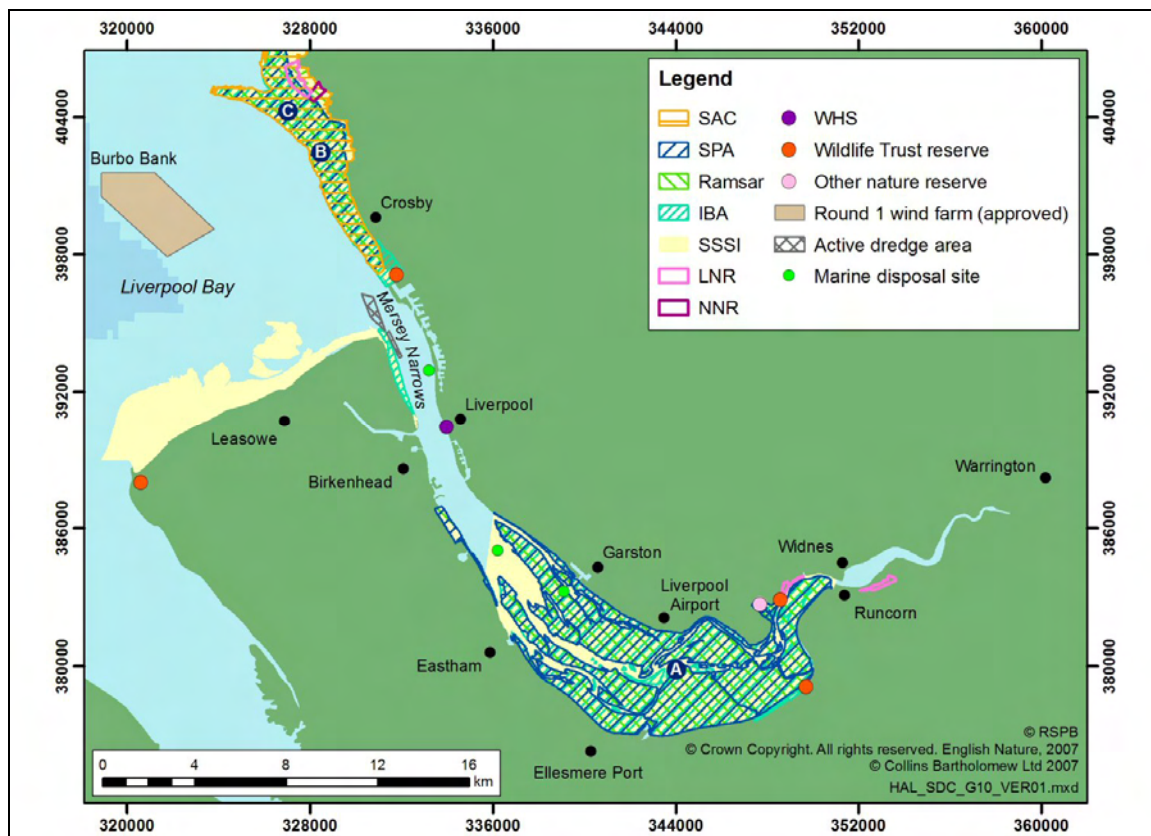
The majority of the estuary is designated a Special Protection Area (SPA) for avian features under the EC Birds Directive¹². The estuary is also identified as a Ramsar site under the Ramsar Convention¹³, and an Important Bird Area (IBA) – a non-statutory site recognised as supporting internationally or nationally important numbers of birds (BirdLife International website) (Figure 5.4). The north Wirral coastline is also a possible SPA and Ramsar site (pSPA/pRamsar), while all the waters of Liverpool Bay below mean low water to approximately 10-20km offshore are also a pSPA. The coastline north of the mouth of the estuary is designated a Special Area of Conservation (SAC) for habitat and species features under the EC Habitats Directive¹⁴, and an SPA/IBA/Ramsar (Table 5.7). Additionally, parts of Liverpool docks are a World Heritage Site (WHS)¹⁵ due to cultural features of international importance.

¹² Council Directive 79/409/EEC on the conservation of wild birds.

¹³ The Convention on Wetlands of International Importance, especially as Waterfowl Habitat.

¹⁴ Council Directive 92/43/EEC on the conservation of natural habitats of wild flora and fauna.

¹⁵ World Heritage Sites are designated under the Convention concerning the protection of the world cultural and natural heritage, adopted by UNESCO in 1972.

Figure 5.4 – Conservation sites and other key features

Notes: Only central location shown for WHS. Liverpool Bay pSPA covers all marine areas shown in map up to existing SPA boundaries, Mersey Narrows and North Wirral Foreshore pSPA covers similar area to SSSI along Wirral foreshore. Entrance to Manchester ship canal is at Eastham.

Table 5.7 – International conservations sites

Site	Area (ha)	Key features
Mersey Estuary SPA/Ramsar/ IBA	5,033	<i>Over winter:</i> Golden plover <i>Pluvialis apricaria</i>, dunlin <i>Calidris alpina alpina</i>, pintail <i>Anas acuta</i>, redshank <i>Tringa totanus</i>, shelduck <i>Tadorna tadorna</i>, teal <i>Anas crecca</i> <i>On passage:</i> Redshank <i>Tringa totanus</i>, ringed plover <i>Charadrius hiaticula</i> <i>Assemblage qualification:</i> Regularly supports 99,000 waterfowl over winter
Ribble and Alt Estuaries SPA/Ramsar/ IBA*	12,361	<i>Breeding:</i> Common tern <i>Sterna hirundo</i>, ruff <i>Philomachus pugnax</i>, lesser black-backed gull <i>Larus fuscus</i> <i>Over-winter:</i> Bar-tailed Godwit <i>Limosa lapponica</i>, Bewick's swan <i>Cygnus columbianus bewickii</i>, golden plover <i>Pluvialis apricaria</i>, whooper swan <i>cygnus cygnus</i>, black-tailed godwit <i>Limosa limosa islandica</i>, dunlin <i>Calidris alpina alpina</i>, grey plover <i>Pluvialis squatarola</i>, knot <i>Calidris canutus</i>, oystercatcher <i>Haematopus ostralegus</i>, pink-footed goose <i>Anser brachyrhynchus</i>, pintail <i>Anas acuta</i>, redshank <i>Tringa totanus</i>, sanderling <i>Calidris alba</i>, shelduck <i>Tadorna tadorna</i>, teal <i>Anas crecca</i>, widgeon <i>Anas penelope</i> <i>On passage:</i> Ringed plover <i>Charadrius hiaticula</i>, sanderling <i>Calidris alba</i> <i>Assemblage qualification:</i> Regularly supports 301,000 waterfowl over winter, regularly supports 29,000 seabirds during the breeding season
Sefton Coast SAC	4,564	Embryonic shifting dunes, shifting dunes along the shoreline with <i>Ammophila arenaria</i> (white dunes), fixed dunes with herbaceous vegetation (grey dunes), dunes with <i>Salix repens</i> ssp. <i>argentea</i> (<i>Salicion arenariae</i>), humid dune slacks, Atlantic decalcified dunes (<i>Calluno-Ulicetea</i>), petalwort, great crested newt
Liverpool – Maritime Mercantile City WHS**	887	Includes three historic dock areas of conservation importance.
Mersey Narrows and North Wirral Foreshore pSPA/pRamsar	2,089	<i>Over winter:</i> Redshank <i>Tringa totanus</i>, turnstone <i>Arenaria interpres</i>. <i>Assemblage qualification:</i> Regularly supports 20,000 waterfowl over winter.
Liverpool Bay pSPA	197,504 (under discussion)	<i>Non-breeding:</i> Red-throated diver <i>Gavia stellata</i>, common scoter <i>Melanitta nigra</i>

Source: JNCC website, UNESCO website, BirdLife International website

*Notes: *Only the open coast in the southern arm of the Ribble and Alt Estuaries SPA/IBA/Ramsar is within the study area, therefore not all species listed will be present within the area of interest. **WHS area includes buffer zone and features other than historic docks.*

Coastal national and local conservation sites in the area include 5 Sites of Special Scientific Interest (SSSIs), 1 National Nature Reserve (NNR), 3 Local Nature Reserves (LNRs), 4 Wildlife Trust reserves and 1 other non-statutory reserve (Figure 5.4). These sites are designated for coastal/estuarine habitats and species, particularly birds, and geological features. Many sites overlap with international conservation sites.

5.8.1 Environmental studies carried out by the Mersey Barrage Company

During Stage III and IIIA, substantial monitoring studies were carried out to improve the understanding of the likely environmental changes that a barrage might induce. Studies on sedimentation, water quality, fisheries and migratory bird populations, and other aspects of the estuarine ecosystem were investigated [5.1]. This work complemented preliminary assessments carried out during Stages I and II [5.3, 5.4].

The Stage III and IIIA studies concluded that the overall effects on water quality including dissolved oxygen levels and traces of contaminants would be beneficial. Other changes to phytoplankton, invertebrate and fish populations could be affected by the barrage because of the reduction in the present intertidal area. However, observations during the most recent phase of field work during the early 1990s reveal that the existing estuarine ecosystem, including invertebrate and fish populations, is currently undergoing substantial change as improvements are made to the estuary's water quality [5.1].

5.8.2 Sedimentation

Considerable emphasis was placed on sedimentological work because of the implications for navigation within the estuary and Liverpool Bay and the wider environmental significance of possible changes in sedimentation. Field measurements, which have included continuous silt monitoring and sand-flux measurements, were used to validate a series of sediment transport models applied to the 3E barrage alignment to determine the extent of changes that it would induce. Separate 2-D transport models for coarse, non-cohesive sand and cohesive mud were used. In addition, the most recent phase of work, Stage IIIA, incorporated a 3-D, layered, transport model to establish the significance of gravitational circulation [5.1].

Modelling and field measurements have been supplemented by a bathymetric survey carried out in 1990 that revealed a slight change in bed level and, therefore, the volume of sediment within the estuary since the last major survey in 1977. Consequently, this survey has confirmed that the estuary is broadly in equilibrium with no major net loss or gain of sediment.

Sediment transport models, based upon the 3E alignment, suggest sand deposition patterns would change significantly causing an increase in maintenance dredging requirements of 35-60% downstream of the barrage. Upstream, sand movement would decrease, which would lead to a reduction in dredging of 15% and 30% in the Eastham and Garston channels respectively. Results from the 2-D mud-flow model indicate that an increase in siltation would about double compared with the present 'open-river' conditions, equivalent to 1.2 million dry tonnes of deposited silt. Application of 3-D sediment transport modelling has indicated that operation of the barrage would greatly diminish the effects of gravitational circulation, which would lead to a 75% reduction in the silt flux compared with the existing 'open-river' conditions. Estimated silt deposition rates based on 3-D modelling upstream of the barrage suggest lower accretion rates comparable to levels currently observed.

It should be stressed that predictions based on models would require further refinement and validation from extensive field records, notably sand-flux measurements and wave-induced movement in Liverpool Bay. The long-term conditions would also need to incorporate the interaction of flow prediction, siltation rates and extrapolation of bed-level changes.

5.9 Other uses/users

Land use is almost entirely urban around the middle to lower reaches of the estuary, and agricultural and urban in the upper reaches. Major industrial sites on the banks of the estuary include Ellesmere Port, Runcorn, Widnes, Eastham, Liverpool airport and several docks along the Liverpool and Birkenhead waterfront. Historically, the estuary has received large inputs of domestic and industrial effluents, and a variety of contaminants including heavy metals and synthetic chemicals [5.6]. Several initiatives and new legislation have dramatically improved water quality over recent decades; however, an abundance of industrial and domestic consented discharges currently enter the estuary throughout its course [5.6].

There are no pipelines, communications cables or oil/gas infrastructure in the waters of the Mersey estuary [5.21]. Several actively producing oil and gas fields, including the Lennox, Douglas and Hamilton fields, and their associated infrastructure lie in the Irish Sea approximately 20-25km from the mouth of the estuary [5.22]. An oil refinery is located on the shore of the estuary near Eastham. The estuary overlaps with a non-authoritative airspace control area, and there is a small MOD rifle and grenade range on the coast north of the mouth of the estuary [5.23]. A 30 turbine wind farm (Burbo Bank) has been approved for construction approximately 9km offshore from the mouth of the estuary [5.24].

The commercial ports of Liverpool, Garston and Manchester dealt with 5,252, 138 and 1,875 vessel movements respectively in 2005. Vessels to and from Manchester used the Manchester ship canal which enters the estuary at Eastham, and were dominated by tankers and cargo vessels of up to 20,000 deadweight tonnes (DWT). Traffic at Liverpool included 142 tankers of over 100,000DWT [5.25]. Three main ferry routes sail between Liverpool/Birkenhead and Irish ports, transporting approximately 650,000 passengers each year [5.25]. When considering the level of shipping activity and sensitivity of the environment, the DfT [5.26] identified the waters around the mouth of the Mersey estuary as a low-medium risk area.

Fishing activity is fairly low within the Mersey estuary, and is limited to a few boats trawling for shrimps, occasional recreational charter boats and bait digging [5.27]. A greater level of activity takes place around the mouth of the estuary and surrounding coast, where trawlers target whitefish (including plaice, sole, rays and whiting) offshore from Leasowe and Ainsdale, and nets and long-lines are set along the coast to the north for bass, mullet, cod and whiting [5.27]. Additionally, shallow subtidal and intertidal waters along the coast around Formby are exploited by vehicle-towed trawls and push nets for shrimp, along with occasional hand-gathering of mussels and cockles [5.27].

There are two small Crown Estate licensed dredging areas at the mouth of the estuary [5.28]. Additionally, 261,700 tonnes of dredged material from the Mersey estuary and Liverpool Bay area was deposited amongst 3 different sites within the estuary in 2004 [5.29].

The Mersey estuary and surrounding area is regarded as a region of archaeological importance, due to the presence of existing finds and the potential it holds for future discoveries. Human and animal footprints dated to the Neolithic or Early Bronze Age have been discovered in the intertidal zones near Formby [5.30]. Several areas are likely to comprise relics of prehistoric landscapes dated to the Palaeolithic and of coastal

communities dated to the Mesolithic [5.31]. Several Scheduled Ancient Monuments are present along the coast of the area [5.32].

Tourism and recreational activities in the estuary and adjacent coastal areas consist of wildlife watching, walking, visiting areas of cultural heritage, angling, sailing, rowing, canoeing, canal boating, water skiing, windsurfing and golf [5.7].

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5.11 The Mersey Barrage Company Subscribers

Alfred McAlpine plc
Allied Steel and Wire Limited
Barclays Bank plc
BICC Cables Limited
Blue Circle Industries plc
Brown and Root Vickers Limited
Cammell Laird Shipbuilders Limited
Castle Cement Limited
Costain Civil Engineering Limited
HBM Civil Engineering Limited
Littlewoods Organisation plc
Liverpool Pilots' Association
Manchester Trading Company Limited
Manweb plc
Mersey Docks and Harbour Company
Northern Engineering Industries plc
Ocean Marine Limited
Royal Insurance (UK) Limited
Shell (UK) Limited
Tarmac Construction Limited
Trafalgar House Corporate Development Limited
Trinity International Holdings plc
University of Liverpool

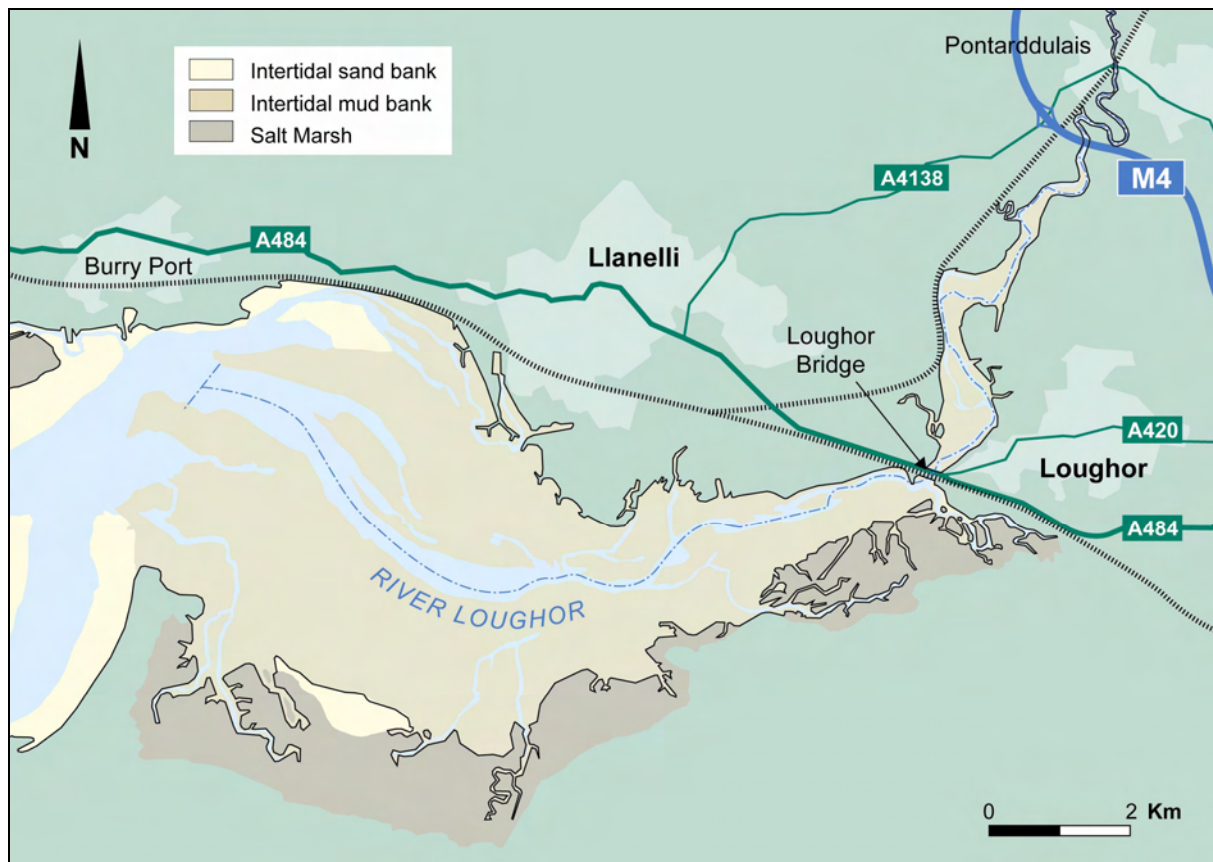
6 Loughor tidal energy and amenity barrage

6.1 Background to the Loughor barrage scheme

The Loughor estuary extends from Burry Point at the entrance to the Carmarthen Bay to Pontardulais. There is a natural constriction where the A484 and a railway line cross the river. With an annual mean spring tide of 3.9m, the upper estuary had been identified as a potential site for a small tidal-energy barrage [6.1]. Moreover, an impoundment structure built across the estuary at its narrowest point would offer the lowest capital cost option for creating a permanent impoundment. Local interests represented by the Loughor Marine Lake Consortium (see Section 6.9), which comprised local authorities and a variety of regional agencies, were interested in promoting the amenity and tidal energy potential of the locality. In 1987, the Consortium commissioned a feasibility study [6.2] at a cost of £65,000 to investigate the potential for a combined amenity and tidal energy barrage.

The natural constriction at Loughor Bridge broadly dissects the estuary into two separate sections. The surface area of the lower estuary at high water spring tide (HWST) is considerably larger (41.4km^2) than the upper estuary (2.4km^2) (Figure 6.1). At low water, the corresponding water area is greatly reduced to 3.6km^2 and 0.4km^2 respectively leaving most of the intertidal completely exposed. Most of the sediment within the estuary comprises loose unconsolidated sand that has the potential to accumulate within an impounded basin. Close observation of the tidal cycle has revealed a pronounced flood tide with high discharges and strong currents followed by a prolonged highly non-sinusoidal ebb-flow pattern. Consequently, the proposed design had to take account of these conditions to maximise energy output while minimising sediment movement. The presence of a railway bridge at the preferred alignment precluded the use of caissons in favour of in-situ construction adding further complexity to the scheme.

Figure 6.1 Loughor Estuary. The proposed barrage would be built across the narrows immediately upstream of Loughor Bridge.



The local authority and other local interests were interested in the concept of a barrage at a narrow point across the estuary because the impounded basin could also be used as a marina. This case study concentrates on how a tidal-energy barrage could form part of an amenity facility. The case study compares continuous year-round operation with restricted operation to accommodate marina use during the summer and the environmental impacts.

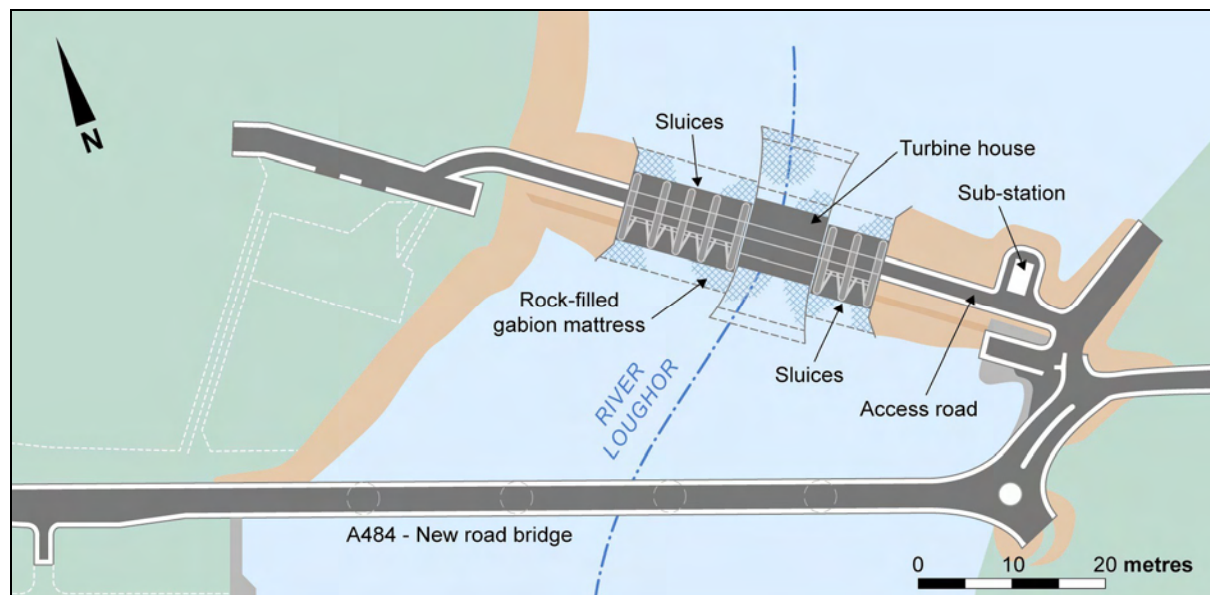
6.2 Loughor barrage design and cost

Preliminary designs and cost estimates were developed for a barrage with variable configurations of sluices and turbines. Combinations of between three and five turbines of 2.75m runner diameter and 1.25MW capacity and either four or six gated sluices were considered. The preferred alignment would be immediately upstream of the old A484 road bridge at a narrow and accessible point in the estuary.

Figure 6.2 is a plan of the proposed layout. The turbines would be housed in a central compound flanked by two sections of sluices. Closure would be completed with two short sections of embankment. Building a structure in situ would require the use of temporary coffer dams created with interlocking sheet piling. The two sluice sections would be built first, to maximise the flow through the narrows during construction. The turbine section would then be constructed before the addition of the embankment stages. This sequence allows maximum flow through the estuary as each successive stage is completed. Once each sluice section is built, radial gates can be installed so that the flow can be controlled once complete closure has been achieved. Gabion scour protection would need to be added on either side of the barrage to limit the erosive power of the currents on each tide. The feasibility study estimated that construction could be completed in three years.

The turbine size is governed by the depth below the impounded basin, which must be sufficiently low to prevent cavitation or the formation of air bubbles. If the depth of the turbines is insufficient relative to the basin level, air bubbles can form on the surface of the turbine blade. This phenomenon not only reduces energy capture it can also damage the surface of the turbine blade. Larger turbines could be used at this location, but this would require excessive dredging to ensure operation below cavitation depth.

Figure 6.2 Detailed plan of the proposed Loughor barrage.



To minimise sediment flow into the basin, and to prevent excessive scour immediately downstream of the barrage, different combinations of sluices and turbines were evaluated. Increasing the number of turbines improves energy yield, but at the expense of increasing downstream scour and erosion. The optimum barrage design would comprise four turbines and four sluices with an installed capacity of 5MW, which would take three years to build at a cost of £13 million (mid-1988 prices). This configuration would generate about 15GWh/year and scour about 1m from the downstream channel. Protection of the river bed on either side of the barrage would, therefore, be an additional requirement. If the depth of scour exceeded 1m there could be a potential threat to the railway bridge.

The breakdown of costs for the different components of the barrage are presented in Table 6.1. The categories are the subdivisions used by the consultants who undertook the barrage feasibility study. These costs have been inflated to 2006 using the COPI index.

Table 6.1 Capital and operating costs for the Loughor barrage

	£million
Civil engineering	
In-situ construction	8.85
Sheet pile cofferdams	4.17
Total for civils	13.03
Mechanical & Electrical plant and equipment	
Turbines, gearboxes and generators	2.64
Sluice gates stop logs, fish pass	2.31
Mechanical and electrical services	1.32

Total for M&E kit	6.27
Non construction costs including preconstruction design, consent and environmental studies	4.12
Total project cost	23.41
MW installed	6.00
£/kW installed 2006	3,902.48
O&M	0.18

6.2.1 Electricity integration

The power output would be suitable for direct connection to the United Utilities' 11kV distribution system. The most suitable connection point would be to the east of the barrage.

6.3 Energy output

The Loughor Marine Lake Consortium was interested in exploring the option of a dual-purpose barrage combining amenity and power-generation facilities. In contrast to tidal energy schemes investigated elsewhere, this case study shows how the value of energy can be offset if some of the capital investment can be attributed to another non-energy use such as amenity. The tidal energy potential and its value were calculated assuming that power generation would be restricted to maintain a high water level for amenity purposes between April and September. The unit cost of generation calculated for this amenity barrage assumed that 54% of the capital cost was attributed to the amenity value of the scheme and offset from the total capital cost, thus reducing the capital investment that was attributed to the power generation component of the scheme. Under this scenario, the annual energy output was also reduced by 36% from 15.14GWh/year to 9.7GWh/year with the imposition of a seasonal operational restriction during the summer months. The estimated unit costs of energy were also calculated for an optimised year-round power generation scheme assuming that the full capital cost was exclusively attributed for this purpose. On the basis of these assumptions, a tidal energy barrage on the Loughor would be more economic if it were operated without a seasonal restriction (see Table 6.2). However, in comparison to most other barrage schemes, the project is less economic irrespective of the mode of operation.

A further option of restricted power output throughout the year was also considered. Under these circumstances, the amount of electricity generated would depend on the minimum impounded water level. Table 6.2 summarises the amount of power that could be generated assuming different impoundment levels and relative to unrestricted generation. The example assumes a configuration of four turbines and four sluices.

Table 6.2 Annual energy output (GWh/year) from the Loughor amenity barrage with impounded water restricted throughout the year and between April and September

	3.5m OD	3.0m OD	2.5m OD	Unrestricted water level
Restricted output year round(GWh/year)	4.3	8.3	12.0	15.1
Output expressed as a percentage of unrestricted output	28	55	80	100
Restricted output April – September (GWh/year)	9.7	11.7	13.6	15.1
Output expressed as a percentage of unrestricted output	64	77	90	100

6.3.1 Unit cost of generation

The unit cost of generation was performed under two scenarios. The first assumed year-round operation and, therefore, power generation on each tide. The full capital cost of the barrage was also discounted. In the second scenario, 54% of the capital cost was attributed to the amenity component of the barrage and, therefore, deducted from the total capital cost. However, the amount of energy generated is lower. In this example, the economic value of electricity is marginally higher if the barrage has a dual function and assuming that the capital cost attributed to the amenity value could be separately accrued to the project's total cost.

Table 6.3 Unit cost of generation for the Loughor tidal energy barrage

Discount rate:	3.5	8	10	15
Loughor unit cost p/kWh (all year)	6.98	14.5	18.14	27.93
Loughor unit cost p/kWh (winter only)	7.03	13.55	16.74	25.31

6.3.2 Carbon balance

The quantities of construction materials estimated from the feasibility study were used to calculate the embedded carbon (Table 6.4). The quantity of steel for the turbines and generators was estimated by comparing the weight/MW installed for the Mersey barrage. Both schemes used pit turbines. The range of values reflect the maximum and minimum values for embedded carbon used to manufacture steel and concrete.

Table 6.4 Embedded carbon and saved carbon emissions for the Loughor tidal energy barrage

	Loughor barrage
Total volume of concrete (m ³)	34,420
Total mass of steel (t)	4,020
Total mass of copper (t)	4
Estimated embedded CO₂ (t)	
Minimum	13,444
Maximum	19,916
GWh/year	15.4
CO ₂ /year displaced (t/GWh)	6622
CO ₂ saved over technical life time	794,640
Carbon payback minimum (months)	24
Carbon payback maximum (months)	36

6.4 Regional issues

Construction of the Loughor barrage would offer a limited number of local jobs; however, this was not estimated as part of the feasibility study. Comparison with other small scale barrage schemes suggests that for a barrage on the scale of the Loughor the number would be minor. However, unlike other barrage schemes the impoundment structure would be built entirely insitu which would demand a committed work force permanently on site, but possibly only as many as 200.

The estimate of permanent staff required to operate the Wyre barrage was 17 full time staff [6.3]. However, this number includes personnel required to operate ship locks and possibly bascule bridges. The Loughor barrage would probably need only six full time staff because it has no locks or associated transport function. However, as many as 20 additional jobs could be created with a new leisure facility created by the impoundment based on the estimate for the Wyre [6.3]. This added benefit could be worth as much as £300,000 to the local economy. The value of the leisure function could depend on whether year round energy generation becomes the primary objective of a barrage or whether the scheme is design for seasonal power generation combined with recreational uses. Power generation would impose some restrictions because of the necessity to include an exclusion zone near the barrage.

The barrage could also have some negative impacts on the local economy. It is possible that it could affect migratory fish entering the River Loughor and therefore indirectly lower the value of game fishing. The Loughor estuary is also a designated area for cockles and mussels (see section 6.5). The former invertebrate relies on uncontaminated sediment and could be affected by changes in sedimentation induced by a tidal energy barrage.

6.5 Environmental issues

Highlights

- Shallow estuarine waters, large tidal range, extensive mudflats, salt marshes and sand dunes systems, including the most extensive area of saltmarsh in Wales.
- Fairly well developed northern shore and undeveloped, rural southern shore. High scenic value reflected in the Area of Outstanding Natural Beauty (AONB) and Heritage Coast designations covering the southern half of the estuary.
- Extensive areas of intertidal sediment support one the largest cockle fisheries in Britain.
- Conservation interest centred on coastal habitats and large numbers of birds attracted to the sediment flats including internationally important numbers of oystercatcher and pintail. The Burry Inlet SPA/Ramsar is the most important area for wildfowl and waders in south west Wales.
- Several species of nationally and internationally protected fish including sea lamprey, river lamprey and twaite shad migrate through the area.

The Loughor Estuary (also known as Burry Inlet or Burry Estuary) is at the mouth of the river Loughor. It separates Carmarthenshire from the north coast of the Gower Peninsula. The southern shore is largely rural and undeveloped; in contrast, the north coast is more developed including the conurbations of Llanelli and Pembrey.

The Loughor Estuary is a drowned river valley formed at the end of the last ice-age. It is a shallow, muddy/silty estuary with strong tidal streams and frequently shifting sandbanks. The southern shore has the largest continuous area of saltmarsh in Wales (2,200ha) and there are extensive sand dunes at the mouth of the estuary.

The estuary has a large tidal range of approximately 8m, exposing large areas of intertidal sediments at low tide. Important numbers of over wintering wildfowl and waders feed in these intertidal areas and on the saltmarshes. The sandflats support rich infaunal communities and one of the largest cockle (*Cerastoderma edule*) fisheries in Britain.

6.5.1 Summary of key environmental sensitivities/constraints

Table 6.5 – Summary of key environmental sensitivities/constraints

Feature	Summary	Potential adverse factors
Seabed sediments and transport processes	• Intertidal sediments are dominated by muddy sand on the mid-shore, with soft muds on the upper shore and sand and gravel on the lower shore. Permanently submerged channels and the estuary mouth are dominated by sands [6.4].	• Physical disruption to tidal flows may affect sediment transport

Feature	Summary	Potential adverse factors
Seabed sediments and transport processes (continued)	- Sediments are highly mobile below mid-tide level [6.4]. - Hard substrata are restricted to boulders and cobbles around Whiteford Point, occasional mussel scars and artificial structures (e.g. sea walls) on the north coast [6.4]. - The estuary mouth is a very high energy area, characterised by sandbanks and mobile fine to medium sands. - The estuary is currently infilling with sediment from seaward sources [6.5].	
Hydrology	- The majority of the inlet is intertidal, with only a few shallow channels remaining at low tide. - Mean spring tidal range is 8-10m, with tidal currents of up to 1.5m/s during peak spring tides in the deeper channels [6.6]. - The Loughor estuary drains a large area to the north and east, with numerous streams running into it from the foothills of the Black Mountains [6.7].	- Disruption of tidal flows, levels of vertical mixing and light penetration, salinity. - Alteration of tidal prism. - Change in wave exposure - Alteration to water table in adjacent land. - Alteration to groundwater flows.
Water and sediment quality	Water and sediment quality in the estuary is generally good.	- Contamination. - Disruption of tidal flows may allow accumulation of contaminants.
Landscape/ seascape	- The southern half of the Burry Inlet lies within the Gower Peninsula Area of Outstanding Natural Beauty, the Gower Heritage Coast and the Gower landscape of outstanding historic interest. - The Taf and Tywi Estuary landscape of outstanding historic interest lies to the north-west in Camarthen Bay.	- Visual intrusion. - Habitat loss. - Change in landscape character. - Increased coastal traffic. - Direct physical impact on landscapes of outstanding interest.

Feature	Summary	Potential adverse factors
Coastal habitats	- Saltmarsh fringes several areas of the upper shore, particularly in the south, while extensive sand dunes are present either side of the estuary mouth [6.4]. - Priority coastal habitats listed on relevant LBAPs include coastal and floodplain grazing marsh, coastal saltmarsh, reedbeds and coastal sand dunes [6.8].	- Physical disturbance. - Habitat loss. - Habitat change. - Loss of existing flood protection value of natural features such as saltmarshes.
Intertidal and subtidal habitats and communities	- Extensive areas of tidal and non-tidal reedswamps supporting diverse invertebrate communities, strongly related to salinities [6.9]. - Extensive areas of moderately stable, fine and very fine sands in the middle and lower estuary are characterised by bivalve molluscs and polychaete worms. These areas support large populations of cockles [6.10]. - The lower estuary contains rich infaunal communities including the presence of nationally rare worm <i>Ophelia bicornis</i>, a priority BAP species.	- Physical disturbance. - Habitat loss. - Habitat change.
Plankton	Plankton in the estuary waters provide food for many species, including commercially exploited fish and shellfish.	- Changes in the plankton community. - Harmful algal blooms.
Fish and shellfish	- The inlet provides nursery areas for whiting, plaice and sole [6.11]. - Anadromous fish migrate through the area, including allis and twaite shad and lamprey [6.12]. - Within the inlet, there are 3 designated production areas for cockles and 3 for mussels [6.13].	- Physical disturbance. - Habitat loss - Habitat change. - Collision risk - Noise
Birds	- Extensive sediment flats attract nationally and internationally important wintering populations of wildfowl and waders. - Mid-shore mussel beds are important bird feeding areas and major wildfowl roosts are present on the salt marshes at Whiteford and Penclawdd (south of inlet). Wader roosts tend to be concentrated along the north shore and at Llanrhidian marsh. - Llanrhidian Sands and Penclawdd are the main feeding grounds for most species, although oystercatcher and pintail are known to feed extensively in other areas. - The closest seabird colony of note lies some distance from the inlet, on the west-facing coast of the Gower Peninsula.	- Disturbance during installation and maintenance activities. - Change in feeding grounds.

Feature	Summary	Potential adverse factors
Marine mammals	• Sightings of marine mammals in the area are rare, but have included Risso's dolphin and harbour porpoise [6.14]. • Otter <i>Lutra lutra</i> are known to occur in the upper estuary and in the river Loughor.	• Noise • Collision risk • Displacement from foraging grounds and/or migration routes

6.6 Conservation sites and other key environmental sensitivities

The mouth of Loughor estuary overlaps part of the Carmarthen Bay and Dunes Special Area of Conservation (SAC) while the whole of the estuary is contained within the larger Carmarthen Bay and Estuaries SAC. These SACs are designated for habitat and species features under the EC Habitats Directive¹⁶ (Table 6.4). The estuary is also contained within the Burry Inlet Special Protection Area (SPA) for avian features under the EC Birds Directive¹⁷. Additionally, the Burry Inlet is identified as a Ramsar site for wetland features under the Ramsar Convention¹⁸, and an Important Bird Area (IBA) – a non-statutory site recognised as supporting internationally or nationally important numbers of birds (BirdLife International website) (Figure 6.3). In addition to the species of bird mentioned in Table 6.6, the Burry Inlet is of national importance for dark-bellied Brent goose *Branta bernicla bernicla*, shelduck *Tadorna tadorna*, shoveler *Anas clypeata*, knot *Calidris canutus* and dunlin *Calidris alpina alpina*.

Table 6.6 – International conservation sites

Map ref	Site	Area (ha)	Key Features
A	Carmarthen Bay Dunes SAC	1,206	Embryonic shifting dunes, shifting dunes along the shoreline with <i>Ammophila arenaria</i> ('white dunes'), fixed dunes with herbaceous vegetation ('grey dunes'), dunes with <i>Salix repens ssp. argentea</i> (<i>Salicion arenariae</i>), humid dune slacks and narrow-mouthed whorl snail <i>Vertigo angustior</i> , petalwort <i>Petalophyllum ralfsii</i> and fen orchid <i>Liparis loeselii</i>
B	Carmarthen Bay and Estuaries SAC	66,101	Sandbanks which are slightly covered by seawater all the time, estuaries, mudflats and sandflats not covered by seawater at low tide, large shallow inlets and bays, <i>Salicornia</i> and other annuals colonising mud and sand, Atlantic salt meadows (<i>Glauco-Puccinellietalia</i>) and twaite shad <i>Alosa fallax</i>
C	Carmarthen Bay SPA/IBA	33,411	<i>Over winter:</i> Common scoter <i>Melanitta nigra</i>
D	Burry Inlet SPA/Ramsar/IBA	6,628	<i>Over winter:</i> Oystercatcher <i>Haematopus ostralegus</i> , pintail <i>Anas acuta</i> <i>Assemblage:</i> Over winter, the area regularly supports 34,962 individual waterfowl.

Source: JNCC website.

There are several sites of national and local conservation importance in the area, including 3 Sites of Special Scientific Interest (SSSIs), 2 Geological Conservation Review sites (GCRs), 1 National Nature Reserves (NNRs), 2 Local Nature Reserve (LNR), 2 National Trust sites, 1

¹⁶ Council Directive 92/43/EEC on the conservation of natural habitats of wild flora and fauna

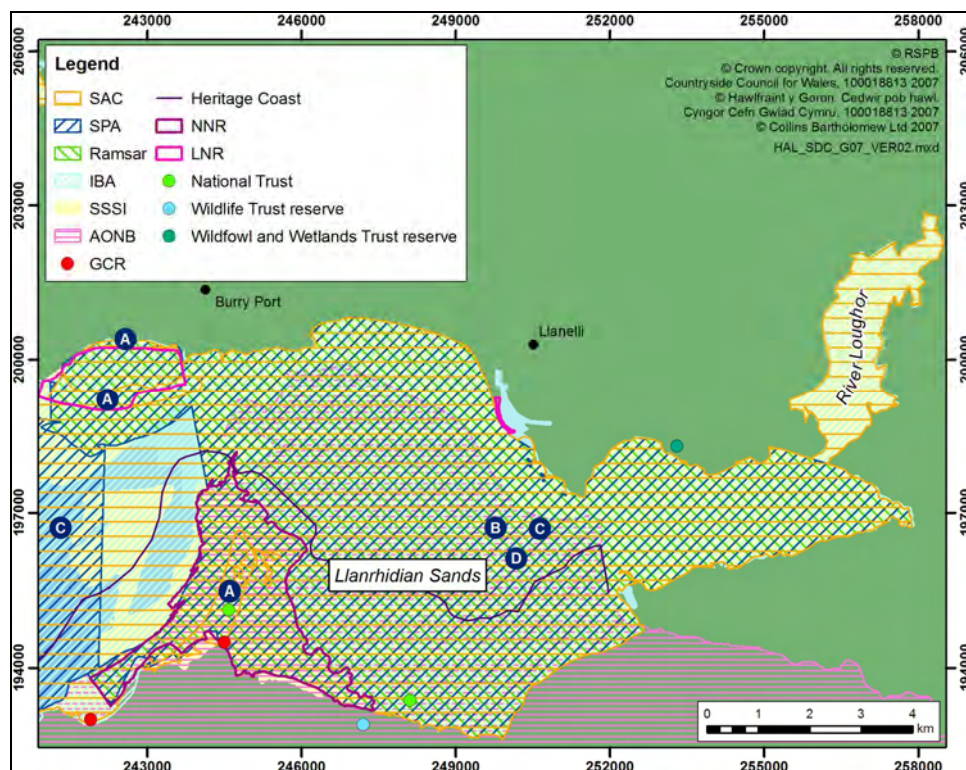
¹⁷ Council Directive 79/409/EEC on the conservation of wild birds

¹⁸ The Convention on Wetlands of International Importance, especially as Waterfowl Habitat

Wildlife Trust reserve and Wildfowl and Wetlands Trust reserve (Figure 6.3). These sites are designated for a variety of wildlife, coastal/estuarine habitat and geological features. Additionally, the southern section of the estuary falls within the Gower Area of Outstanding Natural Beauty (AONB), the Gower Peninsula Heritage Coast and the Gower Landscape of Outstanding Historic Interest. The Taf and Tywi Estuary landscape of outstanding historic interest lies to the north-west in Camarthen Bay.

The coastline of the Loughor estuary is covered by the Camarthenshire and Swansea Local Biodiversity Action Plans (LBAPs) which work towards delivering the national Biodiversity Action Plans¹⁹ (BAPs) for a variety of habitats and species of conservation interest. These include several coastal and intertidal habitats, along with species such as otter, allis and twaite shad, *Ophelia bicornis* and several species of water bird (UK BAP website).

Figure 6.3 – Conservation sites and other key features



6.6.1 Sedimentation

One of the major concerns for a barrage scheme across this estuary is the quantity of mobile sediment and its propensity to rapidly erode and accrete. The ability to predict sediment movement can be approximated using hydrodynamic models to simulate water movement, current strength and related sediment movement. Energy output from the scheme was calculated using a one-dimensional mathematical model of the estuary from its mouth at Burry Port to its tidal limit at Pontardulais. The model was also used to determine the post-barrage tidal regime and approximate rates of sediment transport and accumulation. The model developed for this estuary indicates that scouring and sediment removal is likely to occur immediately downstream of the barrage. Sediment transport and deposition would occur on the flood tide accumulating within the impounded basin. Initial estimates suggest that the basin capacity would be reduced by about half over a period of 45 years unless dredging was instigated. There are additional concerns that historic contaminants from

¹⁹ The UK Biodiversity Action Plan is the UK's response to the *Convention of Biological Diversity*

previous industrial activity could be remobilised by changes in the hydrodynamic regime induced by the barrage.

6.7 Other uses/users

In contrast to the rural southern shore, the northern side of the estuary is relatively developed. Llanelli is the largest town in the area with a population of 24,000. There is only limited industrial activity within the inlet. Saltmarsh grazing is locally important and produces a high value lamb crop. The harbours at Burry Port and Llanelli support a small fishing fleet and a few other commercial boats. To the north the hinterland is urban with some light industry in Llanelli. The Burry Inlet supports an important regulated cockle fishery. Harvesting is undertaken largely by the traditional methods of hand-raking and sieving, on Llanrhidian Sands and off Llanelli. There is a smaller mussel *Mytilus edulis* fishery based on Whiteford Point. Bait-digging is carried out primarily at Llanrhidian Sands and Whiteford Burrows. The wider area of Carmarthen Bay is both a fisheries resource and important nursery ground. Fishing for sole and plaice occurs in the region and important salmon fisheries are present.

There is dredging of aggregates from Helwick Bank although this is subject to public enquiry. The Loughor estuary does not overlap with any military exercise areas. There are no submerged cables, pipelines, marine disposal sites or oil and gas infrastructure in the estuary and immediately surrounding area [6.15-6.17]. There are a number of major sites of sewage discharges along the coast of the estuary although the volume of the discharges is generally low. Large volumes of industrial waste water and sewage are discharged to the estuary from the Llanelli area in particular.

Most of the saltmarsh and Whiteford sand dunes are grazed and wildfowling clubs shoot over the estuary except in recognised refuge areas. Sailing and windsurfing are most intensive upstream of Loughor with mooring present at Loughor, Llanelli and Burry Port. Beach recreation is concentrated at Whiteford Burrows and the beach west of Llanelli. Some climbing takes place at Tor Gro cliffs on the southern side of the inlet. Bird-watching is also very popular. A number of sites of archaeological interest are located around the coast of the estuary, in addition to several sites in the intertidal zone [6.18].

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6.9 Loughor Barrage (Loughor Marine Lake Consortium)

Llanelli Borough Council
Lliw Valley Borough Council
Dyfed County Council
West Glamorgan County Council
Wales Tourist Board
Welsh Water Authority
Welsh Development Agency
Sports Council for Wales

7 Duddon tidal energy barrage

7.1 Background to the Duddon barrage

The Duddon Estuary forms a prominent embayment of 24km² between Haverigg and Sandscale Haws immediately north of Barrow-in-Furness on the Cumbrian coast. In common with many estuaries along the west coast of England and Wales, it has a comparatively high mean tidal range of 5.8m. Interest in its potential for tidal energy was first identified in 1988 in a report published by the regional utility company, Norweb, and the former Department of Energy [7.1]. The local authorities and the County Council were also interested in the potential of a new road crossing to improve the region's transport infrastructure.

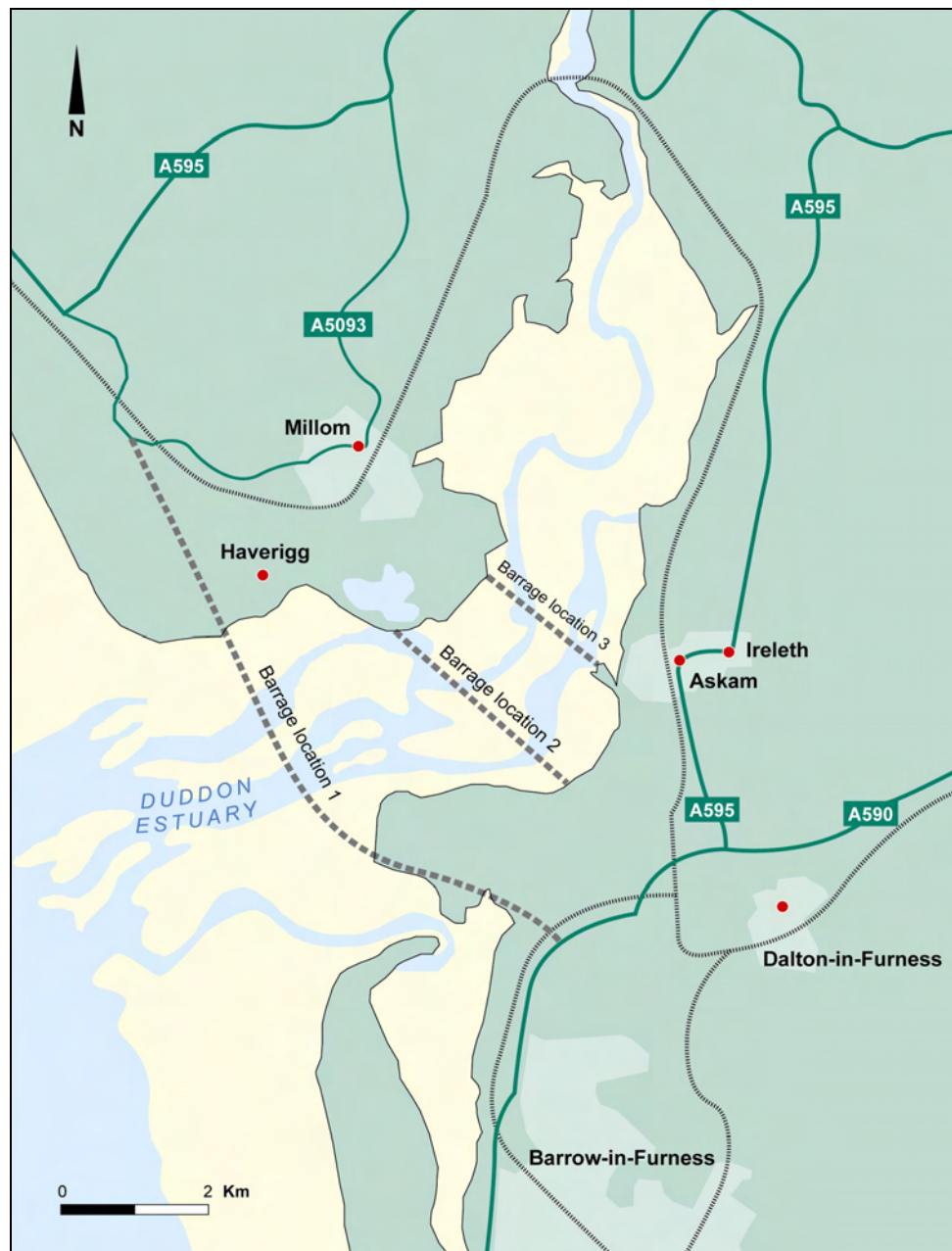
In 1992, a feasibility study was commissioned by the DTI in partnership with Sir Robert McAlpine Ltd and Balfour Beatty Projects Engineering Ltd, which provided the bulk of the technical expertise and 12% of the project costs. A minor technical contribution from Norweb contributed 14% of the costs [7.2]. The principal local authority involvement came from Cumbria County Council, but the Borough of Barrow-in-Furness, Copeland Borough Council and South Lakeland District Council, also contributed information on the local infrastructure.

The Duddon Estuary is notably shallow and is characterised by the extensive intertidal sand banks exposed at low water. The tidal range and prevailing wind have given rise to the formation of numerous dune systems along the north-west coast of England, locally represented at the mouth of the Duddon by Sandscale Haws. The combination of intertidal, saltmarsh and dune ecology is recognised as an area of national conservation value. Virtually the entire estuary is a designated Special Site of Scientific Interest (SSSI). Therefore, construction of a barrage across this estuary would need careful consideration to avoid potentially detrimental effects.

This case study briefly outlines the proposed barrage scheme taking account of its potential for both energy capture and as a road crossing. In parallel with the other case studies, the renewable energy potential, cost and carbon balance are reviewed. The regional and environmental implications are also briefly outlined.

7.2 Barrage location, design and cost

The 1992 feasibility study considered three different alignments across the Duddon Estuary [7.2]. Line 1 extended from the mouth of the estuary just west of Haverigg on the north shore to the southern side of the Sandscale Haws dune system. Line 3 would be much shorter crossing the estuary between Millom and Askam. Line 2 is about half way between these alignments. Line 3 would offer the shortest crossing (2.5km) and avoid the environmentally sensitive dune system at Sandscale Haws, but would generate only half the energy of the most seaward alignment, Line 1 (Figure 7.1). A barrage at this location would have an installed capacity of 100MW and offer good connection points into the existing road system. It would have the disadvantage of cutting through part of Sandscale Haws. The feasibility study concentrated on the Line 1 crossing because this location offered the greatest energy potential.

Figure 7.1 Proposed alignments for the Duddon barrage

The Line 1 alignment would be 4.5km long and would comprise mainly a sand-filled embankment protected by rock armour. The central power-house section that would contain the generator equipment, and sluices would be housed in prefabricated caissons built elsewhere and towed to the site. The design would also include a separate ship lock for vessels with a maximum beam of 11.5m. The barrage would be wide enough to support a 7.3m wide road. At the mid estuary point, the barrage would be 15m above Ordnance Datum (OD) and 10m OD closest to the shore, well above the highest flood defence requirement of 8.5m OD.

The proposed design for the Duddon barrage would include ten 10MW double-regulated 5.5m diameter turbines. There would be four 25m wide sluices with a total area of 1,600m². The number and size of turbines and sluices have been selected for the site-specific conditions, specifically the foundation constraints and the shallowness of the estuary.

The comparative shallowness of the estuary demanded that large volumes of sand would need to be dredged to enable emplacement of the caissons. The embankment would be built up by pumping sand partly from the dredged channel and dumping it within protected containment bunds. Once complete, the embankment would be covered with revetment along the basin side and secondary armour along the seaward side.

The caissons would be constructed from reinforced concrete. The volume of concrete, rock and sandfill were estimated as part of the 1993 feasibility assessment. These quantities have been used to estimate the 2006 construction costs and the embedded carbon required to manufacture the raw materials. The breakdown of component costs are the subdivisions used by the consultants in the 1993 feasibility study. The feasibility study also estimated the phases of construction and the time required to complete the project [7.2]. This information enables the cash flow to be estimated using 2006 construction prices and the unit cost of generation presented in Table 7.1.

Table 7.1 Capital and operating costs for the Duddon tidal energy barrage

Capital and operating costs	£million
Civil engineering	
Caisson construction	134.43
Rock blanket and scour protection	0.51
Grouting of rock blanket	2.33
Fish screens	0.00
Caisson tow	2.26
Caisson installation	7.49
Other works	0.61
Foundation prep	5.29
Dredging	14.19
Embankment (reclamation)	
Containment bunds	5.99
Sand fill	5.63
Slope protection	46.67
Lock	
Capital and operating costs	£million
Insitu construction	1.39
Gates, machinery, stop logs	0.77
Lead in jetties	2.07
Bascule bridge	2.58
Public highway	15.60
Access roads	5.05
Total for civils	166.24
M&E plant and equipment	
Turbines, gearboxes and generators	86.07
Sluice gates stop logs, fish pass	22.08
Mechanical and electrical services	23.69
Switch gear	6.22
Transformers	1.53
Cables on barrage	4.08
Power and control cables on barrage	10.50
Transmission	6.46
Total for M&E kit	160.63

Non construction costs including preconstruction design, consent and environmental studies	10.80
Total project cost	337.66
MW installed	100.00
£/kW installed	3,376.63
O&M	2.58

7.2.1 Electricity integration

The generator output would be split into two groups of five 10MW generators. Each group of five generators would have one 11kV/132kV step-up transformer. The 132kV system would transmit power via insulated cables within enclosed galleries to the south shore. This would avoid potential corrosion from salt-laden spray and visual intrusion from overhead cables. The 132kV cable would be connected to an existing 132kV line near Barrow via an overhead line.

The existing 132kV system would not be capable of transmitting the maximum output from the Duddon barrage. The feasibility study concluded that a new 132kV single circuit line would need to be constructed from the connection point near Barrow to Hutton, a distance of 45km. The capital cost of this line connection would be about 1.4% of the project total.

7.3 Energy output

The barrage would be designed for ebb generation only, although the turbines could be used in reverse as pumps at high water to increase the volume of retained water (flood pumping) (see Appendix 3 for a more detailed explanation of this operational mode). Depending on the state of the tide, this mode of operation could increase energy output by as much as 12%. The annual average energy output for the schemes was estimated to be 212GWh assuming flood pumping was included.

7.3.1 Unit cost of energy

The unit cost of energy was calculated assuming a 120-year technical life and major generation plant renewal at 40-year intervals. The unit costs of generation, presented in Table 6.2, assume an annual average energy output of 212GWh. If the basin capacity is reduced due to sediment accumulation, the energy output will progressively decline.

Table 7.2 Unit cost of generation for the Duddon tidal energy barrage

Discount rate (%)	3.5	8	10	15
Duddon (Line 1) unit cost p/kWh	7.5	15.42	19.31	29.9

7.3.2 Carbon balance

The quantity of embedded carbon in the Duddon barrage was based on the quantities of materials estimated in the 1993 feasibility study including the 45km overhead line link to the national grid. The amount of steel in the turbines was based on the quantities of the metal per MW installed for the Mersey barrage.

Table 7.3 Life cycle carbon savings for the Duddon barrage

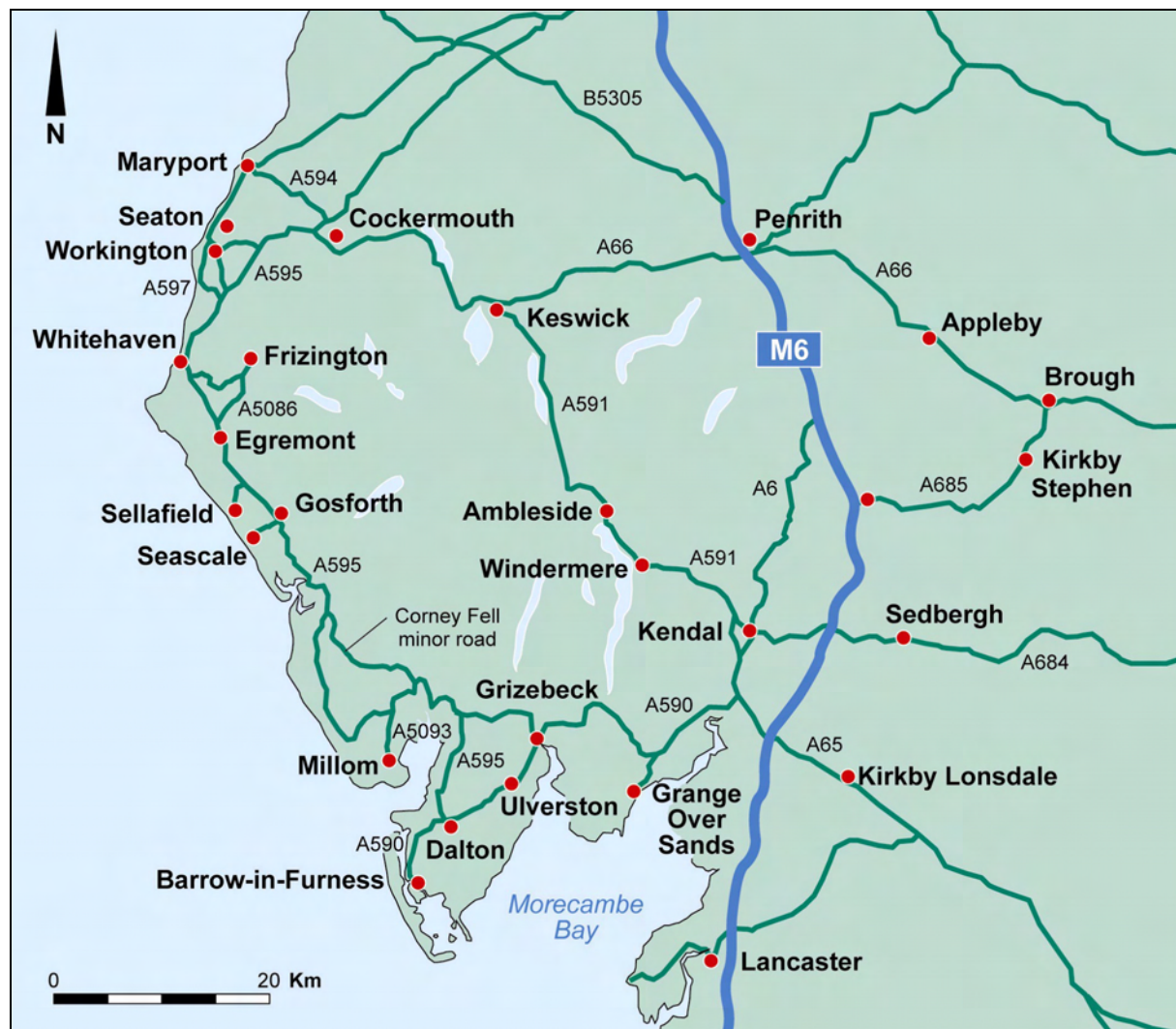
	Duddon barrage
Total volume of concrete (m ³)	93,667
Total mass of steel (t)	51,692
Total mass of copper (t)	49
Estimated embedded CO₂ (t)	
Minimum	103,073
Maximum	125,574
GWh/year	212
CO ₂ /year displaced (t/GWh)	91,160
CO ₂ saved technical life	10,939,200
Carbon payback minimum (months)	14
Carbon payback maximum (months)	17

7.4 Regional impacts and benefits

7.4.1 Infrastructure improvements

The main route connecting Barrow and south Cumbria with the west coast centres of population is A595/A5092. This route skirts around the northern flanks of the Duddon Estuary passing through villages of Hallthwaites, Broughton, Foxfield and Grizebeck. There are a number of small settlements around the Duddon that also generate substantial amounts of local traffic. Millom and Haverigg are disadvantaged by the current road network because of their relative isolation. Improvements to the A595 around the head of the estuary have been proposed as part of a wider upgrading programme for this route.

A new route across the Duddon could offer several advantages to the existing infrastructure. Single journey times between Barrow and west Cumbria could be reduced by about 20km or 40 minutes. Upgrading the 28km stretch of the A595/A5092 between Whicham and Greenodd would not need to be as extensive as originally proposed. The short cut over Corney Fell would also lose its time-saving appeal with an improved coastal link across the barrage (Figure 7.2). The communities of Millom, Haverigg and the Hill would be much better served and allow quick access to Barrow. These undoubted improvements would need to be balanced against potentially detrimental environmental effects described in Section 7.5.

Figure 7.2 Major road network in west Cumbria

7.4.2 Economy and employment

The major industrial towns of Barrow and Sellafield have suffered as the core manufacturing economy of the region has declined. This trend has been countered to a certain extent by the growth in tourism, principally dominated by the attraction of the Lake District. Therefore, the construction of a relatively large infrastructure could offer immediate employment and longer term opportunities.

The feasibility study estimated that a labour force of 1,200 would be required during the height of construction lasting about two years. A further 300 jobs would be supported by indirect requirements such as accommodation. These estimates do not include caisson construction which would benefit fabrication yards located elsewhere. About 30 people would be required to operate the barrage when fully commissioned. A further 15 individuals could be employed in tourist and exhibition facilities near the barrage.

Improved road links could boost the local economy by attracting investment and business activity. The net gain in employment has been estimated to be 5% of existing employment in manufacturing equivalent to 700 jobs in the Barrow area. The stimulus induced by the barrage after a period of five years has been estimated to increase local employment by about 5,000 [7.2].

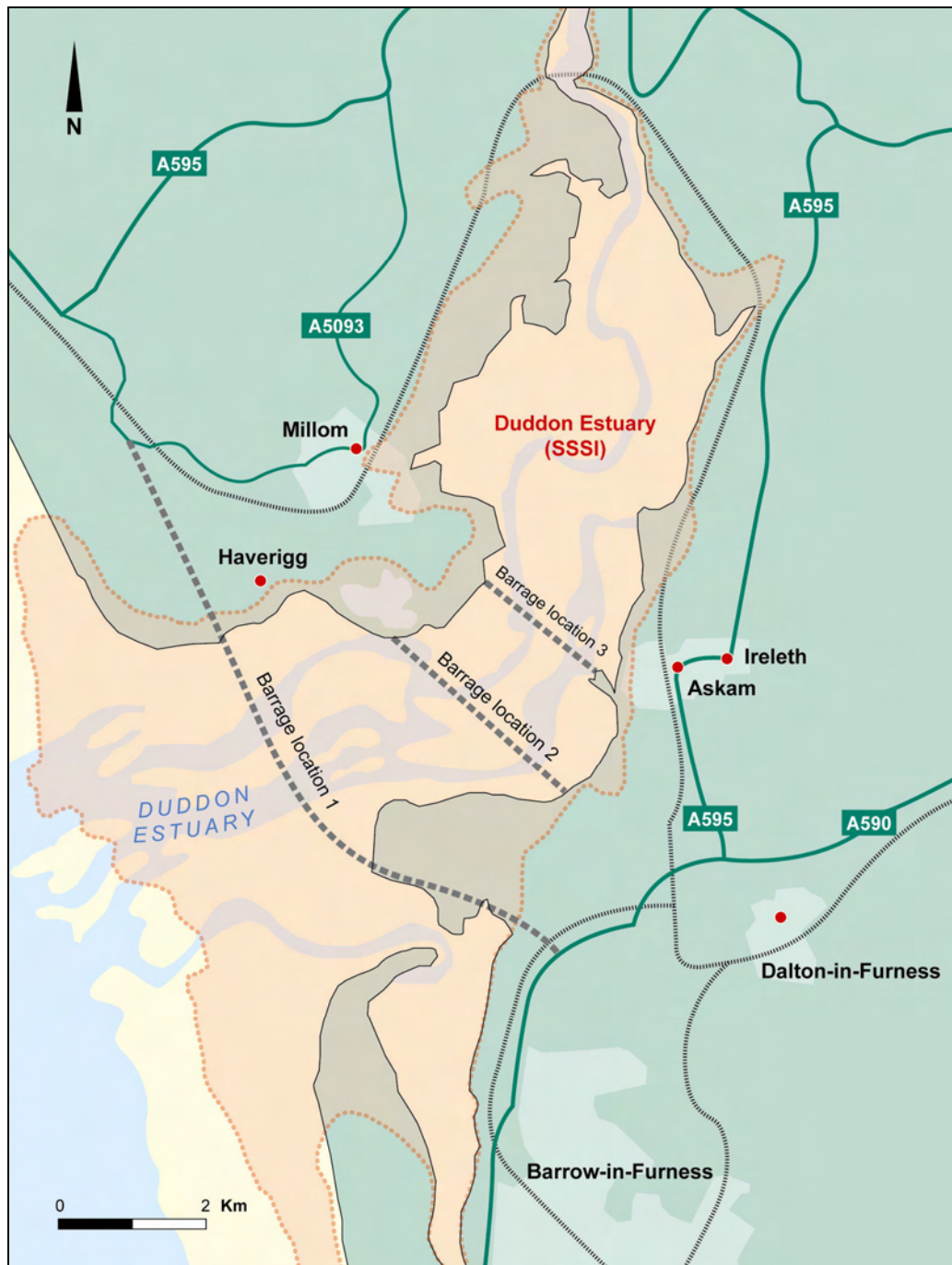
7.5 Environmental issues

7.5.1 Landscape considerations and nature conservation status

The Duddon Estuary lies within an area designated as a County Landscape. This landscape category applies to areas that are judged to be of particular visual, cultural or historic importance. The barrage would have a low profile by virtue of its structure. Therefore, the visual impact would be minimal, although the barrage would be more noticeable at low tide particularly as much of the estuary would be exposed until the return of the flood tide.

If a barrage were built along Line 1, the land fall would encroach on part of Sandscale Haws Nature Reserve. The reserve is owned by the National Trust and has statutory inalienability status. This designation means that the Trust cannot voluntarily relinquish the freehold of the land. Other land owners could also be affected by changes to water levels. Virtually the entire estuary is a SSSI and it meets the criteria for designation as a Wetland of International Importance under the Ramsar Convention (Figure 7.3, 7.4). Clearly these are significant constraints that would need to be addressed before consent for a barrage could proceed.

Figure 7.3 Boundary of the Duddon Estuary SSSI



7.5.2 Environmental effects induced by the barrage

Highlights

- The estuary provides an extensive area of intertidal muddy sandflats bordered by a diverse array of coastal habitats, including extensive saltmarsh and sand dune systems.
- The coastal and intertidal habitats support a variety of waterfowl, including important populations of breeding tern and waders over-winter and on passage.
- Benthic communities are generally species-poor, but support large numbers of a few polychaete, bivalve and small crustacean species – providing an important food source for water birds.
- The area is of limited importance for marine mammals and fish.
- The majority of the coastline is rural, with several adjacent villages and small towns.
- Some limited fishing and tourist activity takes place, while the adjacent Walney Island has a number of sites of archaeological importance.

The Duddon estuary is a fairly small, sandy inlet on the northwest coast of England covering an area of approximately 6,000ha. Over 80% of its area is intertidal, dominated by mud- and sand-flats, and fringed by extensive areas of saltmarsh and sand dune habitat. These intertidal and coastal habitats provide habitat and food resources for large populations of migrating and over-wintering water birds, in addition to an important breeding population of tern. The area is largely rural, and supports a population of approximately 56,000 amongst various villages and small towns lying adjacent to the estuary (excluding Barrow-in-Furness).

7.6 Summary of key environmental sensitivities/constraints

Table 7.4 – Summary of key environmental sensitivities/constraints

Feature	Summary	Potential adverse factors
Seabed sediment and transport processes	• Mostly littoral muddy sand, with littoral sand and gravel at the mouth of the estuary, and littoral sandy mud in upper reaches of estuary [7.3]. • Some small areas of rocky shore are also present, particularly around the mouth of the estuary on open shore [7.3].	• Physical disruption to tidal flows may affect sediment transport.
Hydrology	• Predominantly intertidal, only narrow channels of water remain at low tide. • The estuary receives a mean spring tidal range of approximately 8m, with peak spring tidal currents of approximately 1m/s [7.4]. • Water is well mixed and ranges from upper estuarine to low salinity marine [7.5, 7.6].	• Disruption of tidal flows, levels of vertical mixing and light penetration, salinity. • Alteration of tidal prism. • Change in wave exposure
Water and sediment quality	• Water and sediment quality is generally good, with limited urban/industrial development in the surrounding area and basin [7.5].	• Contamination. • Re-suspension of

		- contaminated sediments. - Disruption of tidal flows may allow accumulation of contaminants.
Landscape/seascape	- The coastline is mainly rural, particularly the inner estuary, while the mouth/outer estuary is more developed with several towns present. - A flooded iron-ore working (Hodbarrow Lagoon) forms the largest coastal lagoon in north-west England [7.7]. - A small onshore windfarm is located near Haverigg. - Designated landscapes in the region include the Lake District National Park.	- Visual intrusion. - Habitat loss. - Change in landscape character. - Increased coastal traffic.
Coastal habitats	A range of grazed and un-grazed saltmarsh habitats fringe the estuary, particularly in sheltered inner areas, while important sand-dune habitat is also present [7.7].	- Habitat loss. - Habitat change.
Intertidal and subtidal habitats and communities	- Mostly mobile muddy sand flats of low species richness, with large numbers of a few polychaete, decapod and bivalve species dominating [7.3]. - Most widespread communities are those typically associated with fine muddy sands. Ragworms and mud shrimps on upper shore, grading to bivalves and lugworms on lower shore [7.3]. - Small areas of rocky shore support typical rocky shore species including the reef building worm <i>Sabellaria alveolata</i> (a priority BAP habitat) [7.3]. - There are dense mussel beds in the Walney Channel.	- Physical disturbance. - Habitat loss. - Habitat change. - Loss of existing flood protection value of natural features such as saltmarshes.
Plankton	- Plankton communities form the base of the food chain and provide a key food source to higher trophic levels such as commercially exploited fish and shellfish. - Plankton communities and productivity are related to the level of mixing and availability of nutrients in the water column.	- Changes in the plankton community. - Harmful algal blooms.
Fish and shellfish	- The area supports spawning grounds for sprat, and provides a nursery area for herring, whiting, plaice and sole [7.8]. - Cod, bass and rays are commercially exploited in the area [7.9]. - The estuary is a designated production area for cockles [7.10]	- Physical disturbance. - Habitat loss. - Collision risk. - Noise.
Birds	Important for large numbers of water birds over-winter and on passage, and supports an important breeding population of sandwich tern [7.7].	- Physical disturbance. - Habitat loss.

	Overall vulnerability of surrounding area is moderate – low, but high during autumn/winter, and very high in August & March along the Cumbria coast to the north [7.11].	Noise.
Marine mammals	- Harbour porpoise are regularly sighted in the area [7.12]. - There are no known important haul-out or breeding sites for seals in the estuary or adjacent coastline [7.7].	- Physical disturbance. - Habitat loss. - Noise.

7.7 Conservation sites and other key environmental sensitivities

The Duddon estuary is designated a Special Protection Area (SPA) for avian features under the EC Birds Directive²⁰ and forms part of a larger Special Area of Conservation (SAC) for habitat and species features under the EC Habitats Directive²¹ (Table 7.5). The estuary is also identified as a Ramsar site for wetland features under the Ramsar Convention²², and an Important Bird Area (IBA) – a non-statutory site recognised as supporting internationally or nationally important numbers of birds (BirdLife International website) (Figure 7.4).

Table 7.5 – Nature conservation sites of international importance

Map ref	Site	Area (ha)	Key features
A	Duddon Estuary SPA/Ramsar/IBA	6,806	<i>Breeding:</i> Sandwich tern <i>Sterna sandvicensis</i> <i>On passage:</i> Ringed plover <i>Charadrius hiaticula</i>, sanderling <i>Calidris alba</i> <i>Over winter:</i> Knot <i>Calidris canutus</i>, pintail <i>Anas acuta</i>, redshank <i>Tringa totanus</i> <i>Assemblage qualification:</i> Regularly supports 78,000 waterfowl over winter <i>Non-bird Ramsar features:</i> Natterjack toad <i>Bufo calamita</i>, supports a rich assemblage of wetland plants and invertebrates - at least one nationally scarce plant and at least two British Red Data Book* invertebrates.
B	Duddon Mosses SAC	313	Active raised bogs, degraded raised bogs still capable of natural regeneration
C	Morecombe Bay SAC	61,506**	Estuaries, mudflats and sandflats not covered by seawater at low tide, large shallow inlets and bays,

²⁰ Council Directive 79/409/EEC on the conservation of wild birds

²¹ Council Directive 92/43/EEC on the conservation of natural habitats of wild flora and fauna

²² The Convention on Wetlands of International Importance, especially as Waterfowl Habitat

perennial vegetation of stony banks, *Salicornia* and other annuals colonising mud and sand, Atlantic salt meadows (*Glaucopuccinellietalia maritima*), shifting dunes along the shoreline with *Ammophila arenaria* (white dunes), fixed dunes with herbaceous vegetation (grey dunes), humid dune slacks, sandbanks which are slightly covered by seawater all the time, coastal lagoons, reefs, embryonic shifting dunes, Atlantic decalcified fixed dunes (*Calluno-Ulicetea*), dunes with *Salix repens* spp. *argentea* (*Salicion arenariae*), great crested newt

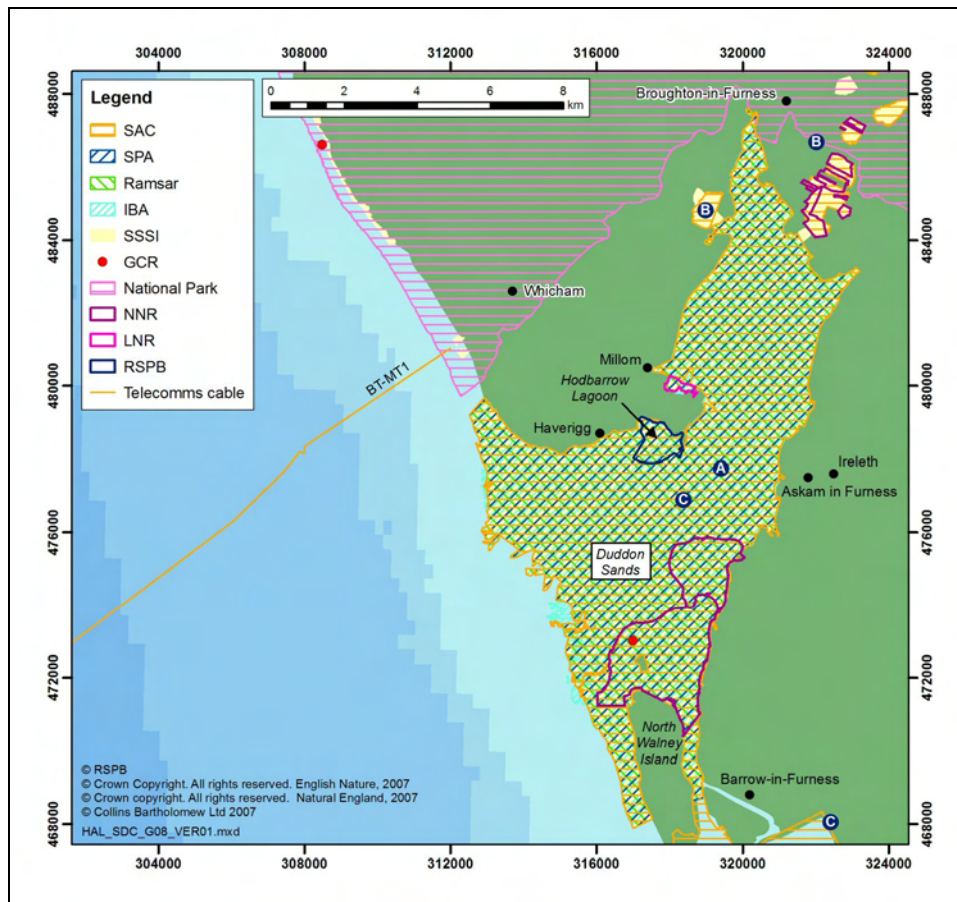
Source: JNCC website.

Note: *Red Data Books provide lists of species whose continued existence is threatened. **Duddon estuary overlaps with a small part of the large Morecambe Bay SAC, and does not contain all habitat types listed here.

There are several sites of national and local conservation importance in the area, including 5 Sites of Special Scientific Interest (SSSIs), 2 Geological Conservation Review sites (GCRs), 3 National Nature Reserves (NNRs), 1 Local Nature Reserve (LNR), 1 RSPB reserve and 1 Wildlife Trust reserve (Figure 7.4). These sites are designated for a variety of wildlife, coastal/estuarine habitat and geological features. Additionally, the Lake District National Park lies to the north.

The coastline of the Duddon estuary is covered by the Cumbria Local Biodiversity Action Plans (LBAPs) which work towards delivering the national Biodiversity Action Plans²³ (BAPs) for a variety of habitats and species of conservation interest. In the Duddon estuary area these include *Sabellaria alveolata* reefs, reedbeds, rivers and streams, along with several amphibians occupying wetlands adjacent to the coast [7.13].

²³ The UK Biodiversity Action Plan is the UK's response to the *Convention of Biological Diversity*

Figure 7.4 – Conservation sites and other key features

7.7.1 Environmental studies conducted as part of the Duddon Barrage feasibility study

The Duddon Estuary is dominated by coarse sandy sediments most of which are exposed at low tide. The abundance of this deposit and the tidal range define the varied ecosystems that occur in and around the periphery of the estuary. The mineralogy of the sand shows that it originates from the Irish Sea [7.14]. The combination of an extensive intertidal area and exposure to prevailing westerly winds also induces the formation of dunes adjacent to the shore line. In more sheltered locations along the upper intertidal zone, the formation of saltmarshes has also occurred. Most of the original saltmarsh has now been reclaimed for agricultural purposes and only 2km² remains.

The variety of habitats around the estuary supports a wide range of fauna and flora. Of notable importance is the Sandscale Haws nature reserve dominated by a dune system fringed by saltmarsh. Within the dune system there are hollows or slacks that become periodically flooded. The slacks form one of the most important habitats for rare species such as seaside centaury and the coral root orchid. This habitat is also one of the UK's most important locations for natterjack toads that breed in the slacks and adjacent marshes. It has been estimated that the Duddon environs support between 18-24% of the total UK population [7.15]. The ability of natterjack toads to breed in these slacks is partly attributed to the periodic inundation by saline water that inhibits colonisation by predatory amphibians and invertebrates [7.16]. Natterjacks toads are also able to survive in conditions that rival species cannot tolerate.

The intertidal habitat, including saltmarsh, supports nationally important populations of wader including curlew, dunlin, knot, oystercatcher, grey plover, ringed plover, redshank and sanderling. Three species of wildfowl are also present in nationally important numbers namely pintail, red-breasted merganser and shelduck [7.17]. The Line 1 alignment borders areas where there are significant concentrations of wildfowl. Therefore, bird populations may be adversely affected by disturbance during construction and later by traffic on a new road.

Construction of a tidal energy barrage will cause two important changes to any estuary: change in the intertidal area and related current strength on both the ebb and flood tides; and the amount of sediment that is transported into and retained within the impounded basin. In this instance, the high water levels would be largely unchanged. Low water levels would be unchanged over most of the area except in close proximity to the central part of the barrage (see Figure 7.1). Water levels within the immediate vicinity of the barrage will occur for about double the time they occur at present. The only change seaward of the barrage would be in the deep channel leading away the central section of the barrage.

The change in the strength of the flood and ebb currents once the barrage became operational is likely to change the volume of sediments within the estuary. The reduction in ebb flows is likely to cause some sediment accretion. It is also possible that there would be a greater accumulation of fine-grained sediment within the estuary. Changes to the sediment regime, particularly the increase in fine grained, muddy sediments may induce greater colonisation of invertebrates which in turn would attract waders and wildfowl. The presence of the barrage would also reduce wave action and may have some affect on the supply of material for the dune system if a barrage were built along the outermost alignment. The extent of changes to wind-derived sand clearly needs to be studied in much greater detail before definitive conclusions can be drawn. Predicting changes in sediment movement induced by water currents would require a detailed transport model linked to hydrodynamic modelling of the barrage. Sediment modelling was not included as part of the 1992 feasibility study.

The potential affects to the dune system and its ecosystem would need careful appraisal particularly given the importance of the estuary's conservation status. The potential for habitat change or loss would need to be fully assessed. This would require detailed monitoring including field measurements and modelling. It is also possible that mitigation measures could be implemented. One possibility is to artificially induce periodic inundations ensuring that brackish conditions are maintained, thereby sustaining viable survival conditions for this unusual ecosystem including the natterjack toad population. The barrage could raise impounded water levels on spring tides by pumping water into the impounded basin.

7.8 Other uses/users

The coastline is mostly rural, with several adjacent villages and small towns, the largest of which is Barrow-in-Furness (population of ~70,000) [7.18]. A flooded iron-ore working forms Hodbarrow lagoon - the largest coastal lagoon in northwest England, while slag banks form other artificial habitat [7.7].

Fishing activity in the estuary consists of up to 20 boats and 5 tractors, mainly exploiting shrimps during spring-autumn. During winter, set nets and lines are used to catch cod. Gill and tangle nets are also used to exploit cod, in addition to bass and rays. Some fishing for cockles and mussels takes place, in addition to non-commercial bait-digging. Access to local mussel beds is difficult on foot due to liquefied sands [7.9].

Shipping density is low at <1,000 vessels annually in the surrounding area. When considering the level of shipping activity and sensitivity of the environment, DfT [7.19] identified the outer Duddon estuary as a very low risk area.

Several pipelines extend west-southwest from South Walney Island. Two plugged and abandoned exploration wells lie ~10km southwest of the mouth of the estuary. The 30-turbine Barrow offshore windfarm (OWF) lies ~7km southwest of South Walney Island. Proposals for a further 2 OWFs several kilometres off the west Cumbria coast have been submitted (West Duddon, Walney) [7.20]. A telecommunications cable extends southwest from the coast north of the estuary [7.21]. No military control areas overlap with the Duddon estuary [7.18].

A series of settlements dating back to the Neolithic have been discovered on Walney Island [7.22], and there are several scheduled ancient monuments around the Duddon estuary area [7.23].

Tourism is a growing industry in the area, with recreational activities including walking, water sports, beach activities and wildlife watching [7.24].

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8 Wyre tidal energy barrage

8.1 Background to the Wyre tidal energy barrage

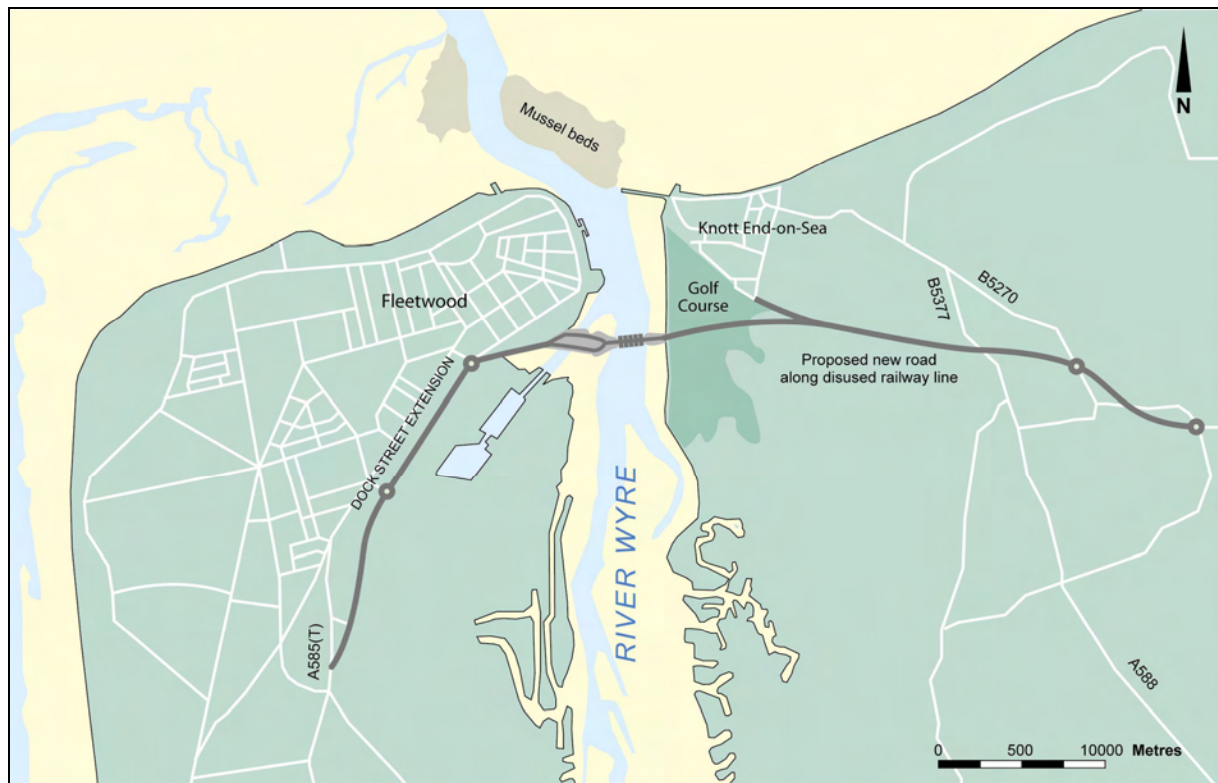
The River Wyre flows into the Irish Sea mid way between Blackpool and Morecambe Bay. The estuary is tidal from its mouth between the Lancashire port of Fleetwood and the village of Knot End and St Michael's on Wyre, a distance of 4km. The Wyre, like many estuaries along the coast of North Wales and North West England, has a comparatively high tidal range (6.6m mean). A previous study indicated the potential for tidal energy at this location [8.1]. The estuary divides this area of west Lancashire into two broad districts: the urban developments of Fleetwood, Cleveleys and Thornton to the west and the rural district of Overwyre to the east. The only road crossing is the Shard Bridge 8km from the mouth of the estuary. The old toll bridge at this location was replaced over ten years ago by a new toll-free alternative.

Fleetwood has a roll-on/roll-off (Ro-Ro) ferry facility and two small enclosed basins. Although the town's fishing industry has been in sharp decline, the docks have the potential to be redeveloped as a marina with adjacent residential properties. In the late 1980s, Lancashire County Council (LCC) saw the potential for a new road crossing and regeneration of Fleetwood. In 1990, the Council commissioned a feasibility study in collaboration with the DTI and the former National Rivers Authority (now part of the Environment Agency). The objectives of this feasibility study, completed in December 1991, were to assess the tidal energy potential with the added objective of incorporating a road crossing [8.2]. The instigation for the project, completed at a cost of £212,000, came from the LCC, which funded 21% in partnership with the DTI (66%) and Norweb plc (7.5%), Lancashire County Enterprises Ltd (2.5%) and National Rivers Authority (2.5%).

This case study summarises the results of that feasibility study including the renewable energy potential and cost at 2006 values. The case study also quantifies the embedded carbon that would be necessary to build a barrage and summaries the benefits and impacts of the road crossing near the mouth of the Wyre Estuary. The environmental effects are also briefly assessed.

8.2 Barrage alignment, design and cost

Three sites were initially considered for the proposed barrage. The most southerly of these, adjacent to the demolished Fleetwood Power Station, was discounted at an early stage with attention focused on two locations: a central alignment 100m upstream of the entrance to Fleetwood Docks (Figure 8.1) and a more northerly position 400m further downstream (Figure 8.2).

Figure 8.1 Proposed central alignment for the Wyre barrage**Figure 8.2 Proposed northern alignment for the Wyre barrage**

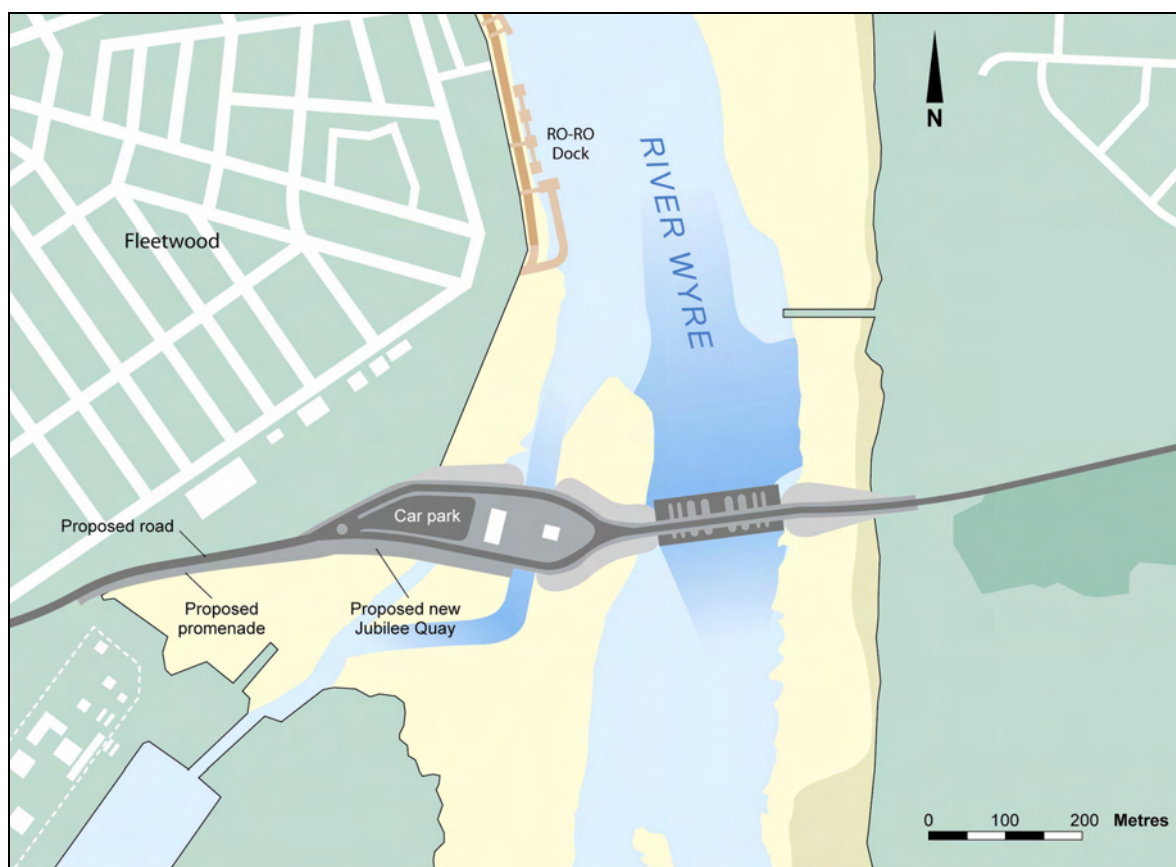
The feasibility study established that the most northerly site would offer the greatest number of advantages. These include the shortest barrage length (about 500m), the maximum area of enclosed basin, the greatest energy output and the minimum dredging requirement.

Unlike the central alignment, the more northerly location would not require any alteration to the marina village development planned at the time by Associated British Ports Ltd (ABP). Furthermore, a barrage at this point would allow access to Fleetwood Docks at all states of the tide, together with direct access from the marina to the enclosed basin. If associated with a road crossing, the northerly barrage location could also offer the most direct links with the existing road network (see Figure 8.2).

The eastern part of the barrage would comprise two adjacent caissons, each housing two pit turbines with a rated output of 15.9MW and 6.2m diameter runners, five sluice gates and a fish pass equipped with fish ladders. A short length of embankment would link the eastern caisson to the shore. To the west of the caissons, a reclamation area would be constructed of material dredged from the caisson foundations, and from the turbine and lock approaches. A navigation lock, with steel radial gates and bascule bridges, would be constructed within the reclamation area, together with roads, a control building, a transformer and a visitor centre with car parks. A new Jubilee Quay would be constructed on the south side of the reclaimed area (see Figure 8.3). The lock would be 74m long by 10m wide for the north barrage site, but only 60m by 10m for the south site.

If the barrage were to be used to form a road crossing, traffic flow could be almost continuous by utilising both bascule bridges, located at each end of the navigation lock. A link road to the east would be necessary that might have to be routed across Knott End golf course to connect with the existing road network east of Preesall. A new road link was not regarded as paramount to the scheme, but included as an opportunity to improve local infrastructure.

Figure 8.3 Proposed plan of the northern alignment. The central section houses a combination of turbines and sluices



As with other barrage schemes caisson construction, including the installation of hydroelectric plant and mechanical equipment, would take place at a fabrication facility

remote from the estuary. These reinforced concrete structures would then be towed during a period of spring tides, initially to temporary moorings downstream of the barrage site, and then, on a neap tide, to their final position where they would be winched and then sunk onto prepared foundations. The gap between the caissons and the eastern embankment would then be closed using temporary stop logs, which would be subsequently replaced by concrete. This construction technique has been advocated for a number of barrage schemes including the Severn and Mersey. However, small-scale schemes, such as the Wyre would require substantial dredging to widen and deepen the channel that links the mouth of the estuary with the open sea at low tide. Most of the dredged material would need to be dumped in the open sea, although some would be used to form a reclamation area adjacent to the barrage and lock.

Barrage construction would take an estimated two years from the initiation of coffer-dam construction to the start of electricity generation. The overall project programme, including further studies, planning approval, detailed design, construction, installation and commissioning prior to commercial generation, would take up to six years.

The cost of the barrage has been determined from the quantities of materials estimated in the 1991 study, but using 2006 prices for construction materials and generator equipment using the COPI index. Therefore, the unit cost of energy can be calculated using a discounted cash flow analysis.

Table 8.1 Capital and operating costs for the north and central Wyre barrage alignments

Capital, operating costs and energy output	£million	£million
	Wyre North Site	Wyre Central Site
Civil engineering		
Caisson construction	21.50	19.70
Rock blanket and scour protection	2.30	2.23
Grouting of rock blanket	1.04	0.98
Fish screens	0.63	0.63
Caisson tow	0.77	0.77
Caisson installation	0.77	0.77
Other works	1.37	1.35
Dredging	12.28	15.50
Reclamation and embankment		
Sheet pile cofferdams	3.13	3.07
Embankment (reclamation)	7.67	7.80
Lock		
In-situ construction	5.92	5.22
Gates, machinery, stop logs	2.35	2.35
Lead-in jetties	0.40	0.40
Bascule Bridge	0.55	1.30
Civil works for bridge	0.18	0.49
Public highway		
Access roads	1.46	1.66
Landscaping	0.54	0.54
Total for Civils	62.86	64.75
M&E plant and equipment		
Turbines, gearboxes and generators	34.53	32.73
Sluice gates stop logs, fish pass	7.80	7.50
Mechanical and electrical services	7.67	7.67
Transmission	3.45	3.45

Total for M&E kit	53.45	51.36
Land drainage	3.07	3.07
Buildings	1.84	1.84
Non construction costs including preconstruction design, consent and environmental studies	16.80	16.80
Total project cost	138.03	137.83
MW installed	63.60	60.00
£/kW installed 2006	2,170.23	2,297.12
O&M	1.11	1.11

8.2.1 Electricity integration

Output from the scheme would be just over 63MW at peak output, transmitted via buried 11kV crosslink, polythene-insulated cables to a transformer compound at the western end of the barrage. The supply would then be transmitted at 33kV via an underground cable to the existing substation on the site of the disused Fleetwood Power Station a distance of about 1km. The same system would be used in reverse to supply electricity for the turbines during pumping.

8.3 Energy output barrage

The tidal energy potential of the estuary depends on the position of the barrage alignment, the tidal range and basin area, and the distance to the open sea. The two alignments assessed in the feasibility study showed that the northern-most location offered greater energy capture (~7.4%) compared with the alternative central position. The northerly location is also shorter and would require less dredging, thus lowering the overall cost. The northern site would also offer a more favourable location for a road crossing, although it would be closer to the Ro-Ro terminal. The inclusion of a lock would allow access to the marina for most vessels at all states of the tide. At present vessels can only move in or out of the marina two hours either side of high water.

The Wyre barrage would be operated only on the ebb tides, although the turbines would be used in reverse at high water to increase the volume of water in the impounded basin (flood pumping). Tidal energy schemes evaluated for the Severn and Mersey have concluded that this mode of operation is the most economical for tidal-energy barrages. Barrages must be design to optimise the flow of water during the flood tide and during ebb-flow generation. Care must be taken to ensure that the turbine size is appropriate for the site and avoids cavitation. This is a phenomenon that occurs if there is insufficient vertical head between the turbine and the impounded reservoir. Air bubbles form if the pressure becomes too low leading to energy loss and damage to the turbine.

To determine the energy output from each barrage location different configurations of turbine and sluices are tested against a hydraulic model. The model simulates the flow of water from the intertidal channel that extends to the open sea as far as the Wyre Lighthouse to the furthest extent of the tidal range at St Michael's on Wyre. The model can be used to estimate the energy output for any given tide that can be accumulated over a year to determine the annual energy. The hydraulic model can also be used to predict water levels upstream and downstream of the proposed barrage, river flooding and the effect of tidal surges, changes in sedimentation and water quality. The northern alignment was estimated

to generate 133GWh/year compared with 123GWh/year for the central alignment. The difference can be attributed to the greater basin area of the northern alignment and its closer proximity to the sea.

8.3.1 Unit cost of generation

The unit cost of energy was calculated assuming 120-year technical life and major generation plant renewal at 40-year intervals. The unit costs of generation, presented in Table 8.2, assume an average energy output of 133GWh/year for the northern alignment and 123GWh/year for the central alignment. If the basin capacity is reduced due to sediment accumulation, the energy output will progressively decline.

Table 8.2 Unit costs of generation for the North and Central Wyre barrage alignments

Discount rate:	3.5	8	10	15
Wyre north site unit cost p/kWh	5.05	9.8	12.08	18.12
Wyre Central site unit cost p/kWh	5.37	10.42	12.85	19.27

8.4 Carbon balance

The embedded carbon used in the manufacture of the materials (principally steel and concrete) has been estimated based on the quantities estimated in the feasibility study. The results are presented in Table 8.3. The range in values for embedded carbon represents the maximum and minimum estimates of embedded carbon for steel and concrete. The quantity of saved carbon emissions assumes an average energy output over the life of the scheme. In reality, this may not necessarily be the case if the capacity of the basin is reduced by sediment deposition.

Table 8.3 Life cycle carbon savings for the north Wyre barrage alignment.

	Wyre barrage
Total volume of concrete (m ³)	30,495
Total mass of steel (t)	9,557
Total mass of copper (t)	22
Estimated embedded CO₂ (t)	
Minimum	21,713
Maximum	28,166
GWh/year	133
CO ₂ /year displaced (t/GWh)	57190
CO ₂ saved technical life	6,862,800
Carbon payback minimum (years)	0.38
Carbon payback maximum (years)	0.49
Carbon payback minimum (months)	5
Carbon payback maximum (months)	6

8.5 Regional impacts and benefits

8.5.1 Infrastructure improvements

One of the primary benefits of a barrage would be a secondary use as road crossing. The feasibility study evaluated the potential benefit of a road crossing within the context of other improvements to the road system, principally the replacement of the Shard Bridge. A road across the northern alignment would be linked to the existing A585 trunk road to the west via a new promenade. This would require the construction of a new quay for inshore fisherman who would need to be relocated. The eastern link road would cut across part of the Knot End Golf Club course on the opposite shore, and follow a disused railway line before connecting with the A588 at a new roundabout east of the village of Preesall. Two bascule bridges would be required, one at either end of the lock. This configuration allows near continuous traffic movement because one bridge can always remain operational if a vessel is entering or leaving the lock. If a southern alignment were selected, the link road to the west would need to cross part of the marina development.

The construction of a road across the barrage would attract about 5,500 vehicle trips per day. It would cut the travel time by road between Knott End and Fleetwood from half an hour to a few minutes. This would divert about 25% of the existing traffic from the A588 Shard Bridge and from the A586 Great Eccleston route. The feasibility study also evaluated the potential growth in traffic that a new link could generate. It concluded that a projected growth in traffic could possibly reach 10,300 vehicles/day. However, the study has concluded that the greatest benefit to the region would be derived from a combination of a new Shard Bridge and a barrage crossing.

A new road crossing could change the nature of the Knott End and Preesall communities that are relatively isolated because there is no direct road link between these communities and Fleetwood. A new road would invariably attract commuters and new development to an area currently dominated by a retirement community and holidaymakers. The construction of the link road across an existing golf course is also likely to generate some hostility.

The only housing development that would be directly affected by the barrage is the Marina Village around the Fleetwood Dock. During the Wyre barrage feasibility assessment, the developers were consulted to ascertain their views on the impact of a barrage development. The developers expressed the view that the barrage would have no significant impact on property values, largely because the majority of the proposed dwellings will face the dock rather than the estuary. The authors of the feasibility study expressed a tentative view that those properties facing an impounded estuary would increase in value. In 1991, the overall increase in property value was estimated to be worth around £0.9 million. Translating this value to 2006 prices is highly speculative because property prices are driven by a series of factors. Without detailed local knowledge, it is not possible to quantify accurately the additional value of a property facing an impounded estuary. Plans to redevelop the marina site are still under consideration. In March 2004, Wyre Borough Council received an outline application for 380 residential properties at the marina site [8.3].

One key benefit of a barrage built across the northern most alignment would be unrestricted access to the impound estuary for small boats. If a barrage were built adjacent to the marina, boats would be restricted by the tide. The feasibility study concluded that the value of berths in the marine would double in value if the northern alignment was developed, but only by 25% if the southern alignment became the preferred option.

8.5.2 Employment benefits

The feasibility study did not estimate the number of man years of effort that would be required to build a barrage at this location. The construction period would last about two years. The feasibility study did not estimate the number of construction jobs that would be required, but it is likely to be relatively minor in comparison with the larger tidal-energy schemes. By comparison, the work force estimated for the much larger Mersey barrage would peak at 2,000 at the height of construction. Unlike the Mersey scheme, the caissons for the Wyre would be prefabricated at construction yards elsewhere before being towed to the estuary.

The feasibility study estimated that when fully operational, the barrage and associated locks would require a permanent work force of 17. A further 86 people would be employed to run the visitor centre and other related activities. In addition, it is estimated that 22 jobs would be created to run water recreational activities as a result of the opportunities from an impounded estuary.

The construction of a barrage and the creation of an impounded basin could offer considerable tourist potential. The 1991 feasibility study estimated that with successful marketing, the Wyre barrage could attract an estimated 200,000 visitors/year, while the impounded estuary would offer opportunities for recreational pursuits. The study concluded that the net benefits from increased visitor spending could reach £324,000 (1991 prices), with a further £81,000 from water sports and £230,000 from improved mobility due to improved road links. Given the preliminary nature of this study, these estimates should be treated with caution.

8.6 Environmental effects

Highlights

- Wyre Estuary supports the largest areas of ungrazed saltmarsh and associated plant communities in north-west England.
- The whole estuarine complex is of international significance for wintering wading birds.
- Of national importance for wintering and passage are black-tailed godwit, wintering turnstone and teals.
- The area is of limited importance for fish and marine mammals.
- To the west of the Wyre Estuary, around Fleetwood and Blackpool, the area is relatively densely populated and there are numerous other users/uses of the coastline, including tourism, fishing and oil & gas developments.

The Wyre Estuary is located in Lancashire, England and its catchment covers an area of 548km². The river itself flows into the Irish Sea at Fleetwood, and is approximately 800m wide, with a 200m channel at low tide and 600m of mudflats and sandbars. The area to the west of the Wyre is saltmarsh, subject to regular flooding from the River Wyre [8.4]. The Wyre Estuary is an integral part of Morecombe Bay, one of the largest areas of intertidal estuarine flats in Britain.

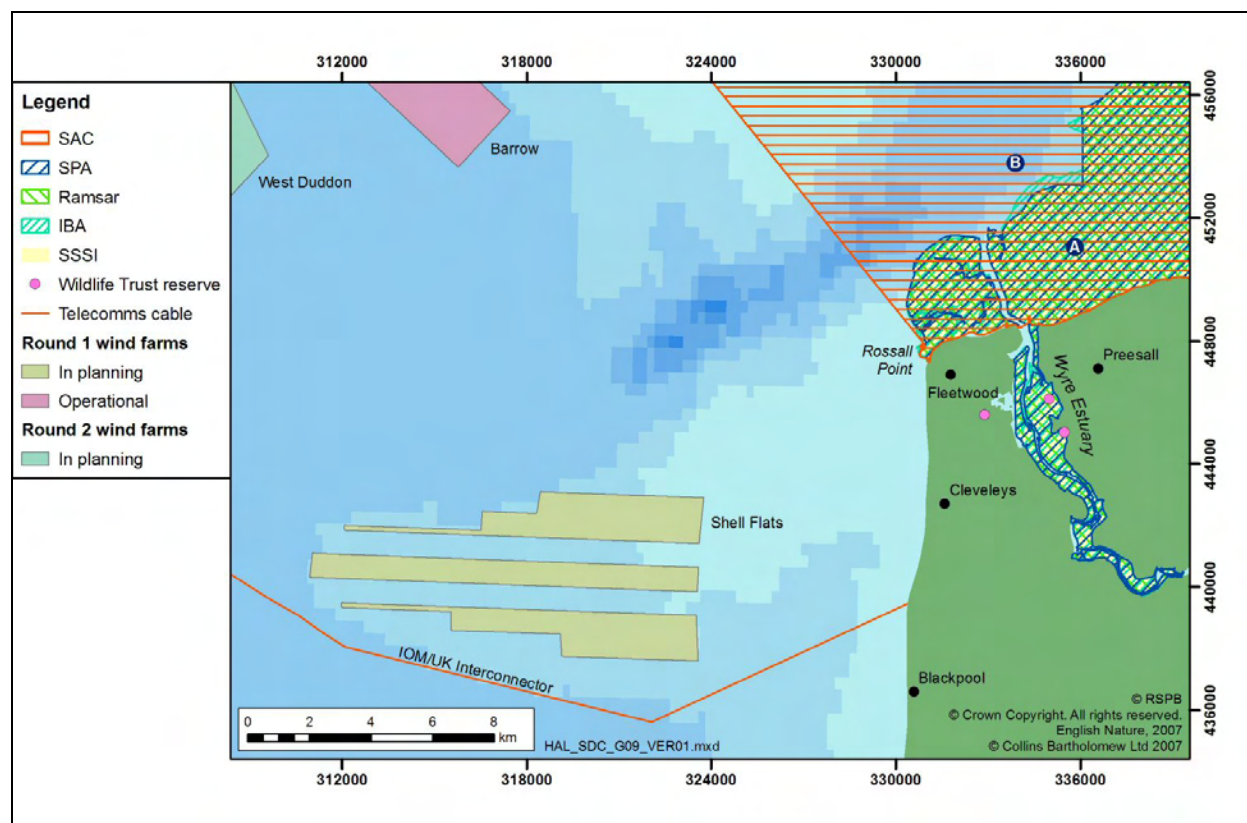
In general, the upper Wyre is largely undeveloped and rural in character. Other than the town of Garstang, urban areas are mostly concentrated in the western part of the catchment around the seaside towns of Blackpool and Fleetwood.

8.7 Summary of key environmental sensitivities/constraints

Table 8.4 – Summary of key environmental sensitivities/constraints

Feature	Summary	Potential adverse factors
Seabed sediments and transport processes	• Mostly littoral muddy sand with some rocky shores at the mouth of the estuary and soft mud shores further inland [8.5]. • Within the estuary, sediment transport is expected to be concentrated in the low water channel, with comparatively little transport along the estuary margins. • Sediment transport dominated by tidal currents, although waves may have some influence at the estuary margins, especially at the mouth of the estuary [8.6].	• Physical disruption to tidal flow may affect sediment transport
Hydrology	• Mean spring tidal range is 7-8m [8.7]. • Peak flow for a mean spring tide is about 2m/s in this part of Morecambe Bay [8.7]. • Wind speeds and directions affect the movement of water along the sea shore, but in general have a limited effect inside the estuary. • Annual mean significant wave height is 0.6-1.0m [8.7]. • The orientation of the estuary mouth is such that significant wave energy does not enter the estuary [8.8].	• Disruption of tidal flows, levels of vertical mixing and light penetration, salinity. • Alteration of tidal prism. • Alteration to water table in adjacent land. • Alteration to groundwater flows.
Water and sediment quality	• Given rural nature of much of the catchment, significant contamination of water and sediments in the estuary is unlikely. • Water quality in Morecambe Bay generally good [8.5] although several contaminants have been found in the sediments [8.9].	• Contamination. • Re-suspension of contaminated sediments. • Disruption of tidal flows may allow accumulation of contaminants.
Landscape/seascape	• The Wyre Estuary comprises a series of low lying mud flats and salt marshes. • The landscape is largely rural in character, with scattered settlements and little industrial development.	• Visual intrusion • Habitat loss • Change in landscape character. • Increased coastal traffic
Coastal habitats	• Good examples of botanically rich, ungrazed saltmarsh at Barnaby Sands and Burrow's Marsh. It also has good examples of transition zones in the upper tidal reaches. • The endemic rock sea-lavender (<i>Limonium britannicum</i>), a priority species, has a population on the Wyre [8.10].	• 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	- Wyre estuary contains nationally significant mudflat habitat. - Intertidal communities characterised by the polychaete <i>Hediste diversicolor</i> and the bivalve <i>Macoma balthica</i> (or <i>Scrobicularia plana</i> in areas of finer sediment). In low salinity areas where mud accumulates, the shrimp <i>Corophium volutator</i> dominates [8.5]. - Epifaunal organisms such as crabs <i>Liocarcinus depurator</i>, <i>Carcinus maenas</i> and <i>Pagurus bernhardus</i> and the common starfish <i>Asterias rubens</i> characterise current swept sands outside the estuary [8.5].	- Physical disturbance - Habitat loss - Changes in species composition - Habitat change due to changes in wave exposure.
Plankton	High levels of phytoplankton production in the estuary due to nutrient recharge from river discharges. Diatoms abundant throughout growth season (6-7 months). Dinoflagellates peak during late summer [8.11].	- Changes in the plankton community. - Harmful algal blooms.
Fish and shellfish	- Sprat spawn in the area from May to August [8.12]. - The area is a nursery ground for herring, whiting, plaice, sole [8.13]. - Virtually all rivers draining into Morecambe Bay are important for salmon and sea trout. River and sea lamprey are also present [8.5]. - The mouth of the Wyre Estuary is a designated shellfish area with commercial fisheries for brown shrimp, edible cockle, and mussel [8.4].	- Physical disturbance, particularly to migration routes. - Electromagnetic field (EMF) disturbance. - Habitat loss - Collision risk. - Noise.
Birds	- The estuary is important for wintering wading birds and wildfowl, especially black-tailed godwit and turnstone - Other species of interest are sandwich terns, oystercatcher, golden plover and lapwing (BAP priority species) [8.6]. - Bird vulnerability in the area is moderate – low during spring, winter and autumn. Highest bird vulnerability during June to August [8.14, 8.15].	- Physical disturbance - Habitat loss - Noise
Marine mammals	- Morecambe Bay is not particularly important for marine mammals. - Harbour porpoise are regular visitors in the area (Reid <i>et al.</i> 2003) - Few seals are recorded from the area.	- Noise - Disturbance to feeding, migration & breeding behaviour - Collision risk

Figure 8.4 – Conservation sites and other key features

Note: Letters refer to Map ref in Table 8.5

8.8 Conservation sites and other key environmental sensitivities

There are several conservation sites of international and national importance around the Wyre Estuary and proposed tidal barrage site. Table 2 provides an overview of the two international sites, the Morecambe Bay Special Protection Area (SPA), and Morecambe Bay Special Area of Conservation (SAC)

Table 8.5 – Nature conservation sites of international importance

Map ref	Site	Area (ha)	Key features
A	Morecambe Bay SPA/Ramsar/IBA	37404.6	<i>During breeding season:</i> Sandwich tern <i>Sterna sandvicensis</i> <i>Over winter:</i> Pintail <i>Anas acuta</i>, pink-footed goose <i>Anser brachyrhynchus</i>, ruddy turnstone <i>Arenaria interpres</i>, dunlin <i>Calidris alpina alpina</i>, oystercatcher <i>Haematopus ostralegus</i>, red knot <i>Calidris canutus</i>, bar-tailed godwit <i>Limosa lapponica</i>, curlew <i>Numenius arquata</i>, black-bellied plover <i>Pluvialis squatarola</i>, shelduck <i>Tadorna tadorna</i>, redshank <i>Tringa totanus</i> <i>On passage:</i> Ringed plover <i>Charadrius hiaticula</i>

B	Morecambe Bay SAC	61506.22	Estuaries, mudflats and sandflats not covered by seawater at low tide, large shallow inlets and bays, perennial vegetation of stony banks, <i>Salicornia</i> and other annuals colonising mud and sand, Atlantic salt meadows (<i>Glaucopuccinellietalia maritimae</i>), Shifting dunes along the shoreline with <i>Ammophila arenaria</i> ('white dunes'), great crested newt <i>Triturus cristatus</i> .
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Source: JNCC website, BirdLife International website

In addition, there are a number of relevant statutory and non-statutory designated sites of national conservation importance. The Wyre Estuary Site of Special Scientific Interest (SSSI) is of national significance for its mudflats and saltmarsh habitats and for the wild bird species it supports. Another SSSI in the area is Lune Estuary. There is one Local Nature Reserve near Blackpool, two nature reserves, Barnaby's Sands & Burrow Marsh and Fleetwood Marsh, both managed by the Wildlife Trust, and one biological heritage site (River Wyre). There is one Regionally Important Geological and Geomorphological Site (RIGS) located on the Wyre Estuary to the north of Cote Walls Farm – Knott End. In addition, there are a number of local biodiversity action plans (LBAPs) which work towards delivering the national biodiversity action plans (BAPs) for a variety of habitats and species of conservation interest. These include the saltmarsh and mudflats of the Wyre Estuary as well as a number of birds and other animals these support

8.8.1 Environmental studies conducted as part of the Wyre Barrage feasibility study

The feasibility study concluded that construction of a barrage across the mouth of the estuary would have a significant effect on water levels upstream. The change in the timing of the main estuary discharge downstream would probably increase the seaward movement of bed material, possibly eliminating the current need for dredging in the vicinity of the Ro-Ro ferry terminal. Water levels would not be affected significantly.

Upstream, there would be an increase in low-water levels, to about the present mid-tide levels, and an increase in the duration of the high-water stand, from perhaps half an hour to between three and five hours. Lower water velocities and circulation rates would also reduce sediment movement. There is a tendency for fine sediment that passes through the barrage on the flood tide to be trapped within the basin together with some material brought downstream by the river and material derived from shoreline erosion. However, conservative estimates suggest that at least 150 years would elapse before the capacity of the basin was halved.

Although some areas upstream of the barrage would experience material deposition, others might be subject to greater erosion as a result of locally generated wave action during the prolonged periods of high water. The edge of the existing saltmarsh is likely to come under localised wave attack once the impounded basin's water levels become established. Ameliorative protective measures might be necessary to control localised erosion particularly along those lengths adjacent to the Burrows Marsh and Barnaby Sands Marsh on the east bank of the estuary.

Test results from hydraulic modelling have shown that flood water levels within the estuary could be controlled by appropriate barrage operation, by early closure of the sluices and the temporary use of the structure as a flood defence system, particularly during high spring

tides and storm surges. This would limit the risk of flooding to low-lying land in the middle and lower estuary.

However, the overall increase in water levels landward of the barrage would raise water-table levels in low-lying adjacent land. This would reduce the effectiveness of land-drainage systems, necessitating their improvement with use of controlled pumping. The likely effect of water table changes on an existing landfill site near Fleetwood, and a proposed new sewage treatment plant, have also been identified, and would be key areas for further investigation.

A very small increase in salinity (less than five parts per thousand) would probably be experienced upstream of the barrage, mainly in the middle part of the estuary. However, this is unlikely to have any detectable effect on the estuarine ecosystem. There would be a reduction in both ammonia and phosphorus concentrations in mid-estuary, and a reduction in the ratio of nitrogen to phosphorus that could result in less algal material. A very small fall in dissolved oxygen is also likely, but longer retention times behind the barrage should reduce biological oxygen demand. Effluent dispersal might take place at a lower rate. However, measures already being implemented to improve the quality of estuary water and future proposed improvements will lead to more efficient effluent treatment and should ensure that barrage construction would not adversely affect water quality.

The Wyre Estuary lies at the southern end of Morecambe Bay, an extremely important site for waterfowl and winter migrants. The estuary is specifically considered to be nationally important for the black-tailed godwit and, on a more occasional basis, for teal, redshank, turnstone, golden plover, sanderling and pink-footed geese. Although the numbers of migrant waders and wildfowl is comparatively small by comparison with the much larger open expanses of Morecambe Bay to the north and the Ribble estuary to the south, the Wyre is known to act as a refuge for migrants during adverse weather conditions.

In January 1995, most of the Wyre Estuary including the intertidal area off the coast was designated as a Site of Special Scientific Interest (SSSI). The designation was extended from two smaller areas of saltmarsh Burrows Marsh and Barnaby Sands Marsh. The expansion of the SSSI was partly in recognition of the Wyre's role as an integral part of the Morecambe Bay complex of estuaries that collectively meet the criteria for an area of international importance under the Ramsar Convention. The Wyre SSSI is also classified as a Special Protection Area under Article 4 of the European Community Directive 79/409/EEC on the Conservation of Wild Birds [8.17].

Specific detail on the bird population in the estuary is not available, but this could be affected to some extent by the construction of a barrage, notably by changes in the saltmarsh vegetation and associated food sources, and by the partial reduction in area of the lower inter-tidal mudflats. Increased human activity within the estuary, particularly for recreational purposes, might cause disturbance to birds. The manner in which winter migrants use the estuary, and the possible effects of the barrage and human recreational pursuits, would be a major element of further research.

8.9 Other uses/users

Fleetwood is the largest fishing port in the eastern Irish Sea and the region has one of the largest commercial fisheries. Morecambe Bay is a focus for brown shrimp, edible cockle and mussel fisheries. Salmon and sea trout are also abundant. The coastal waters support designated shellfish fisheries between Rossall Point and the mouth of the Fylde Coast [8.4]. The ports of Barrow, Heysham and Fleetwood are important economic interests.

Maintenance dredging is undertaken at the port of Fleetwood with substantial quantities of material deposited in Morecambe Bay close to Lune Deep in recent years [8.4].

Land use is predominantly urban to the west of the Wyre Estuary and around Fleetwood, while to the east of the Wyre, the land is mostly agricultural. The coastline around the Wyre Estuary shows signs of coastal development and is predominately associated with tourism, with the foreshore extensively used for recreation, including walking, cycling, bird watching, bathing, bait digging, mussel gathering, inshore fishing, boat and shore angling, and shrimp push netting [8.4].

There are a number of subsea communication cables and pipelines [8.18] within Morecambe Bay; however none are located in the vicinity of the Wyre Estuary. A number of gas fields (Morecambe Bay Fields) are situated about 32km off the Lancashire coast

There are no offshore windfarms around the mouth of the Wyre Estuary. The closest offshore windfarms would be the proposed Shell Flats (7km off the coast of Cleveleys) and the active Barrow site (7km southwest of Walney Island). However, the Morecambe Bay area and its estuaries is an attractive location to harness tidal power due to its high tidal range [8.19].

8.10 References

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9 Glossary of Technical Terms

k	kilo (10^3).
M	Mega (10^6) or million(s)
G	Giga (10^9)
T	Tera 10^{12})
kWh	kilowatt-hour(s).
m	metre(s).
m/s	metre(s) per second.
m ³ /s	cubic metre(s) per second.
MHWS	mean high water level of spring tides
MLWS	mean low water level of spring tides.
MW _e	megawatts electrical output.
MWh	megawatt-hour(s).
t	tonne(s); 1t = 1,000kg.
kt	kilotonnes, 1,000 tonnes
1V:2H	A slope of 1 vertical to 2 horizontal.
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.
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 that 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 about to the level of a lowest astronomical tide (LAT).
Coefficient of performance, C_p	Power out/ $(1/2\rho AV^3)$ where A = swept area 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. (For a more detailed explanation see Appendix 1).
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.
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 vertical difference in levels between the basin and the sea which drives a tidal power turbine.
Intertidal 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 a 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.
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.
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.
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, gearbox and generator combination which converts energy in a fluid flow into electrical energy.
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 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 rotary 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 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 1/3 rd 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

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:

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

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 2

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 A2.1 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.

TableA2.1 carbon emissions associated with primary construction, component and electrical materials

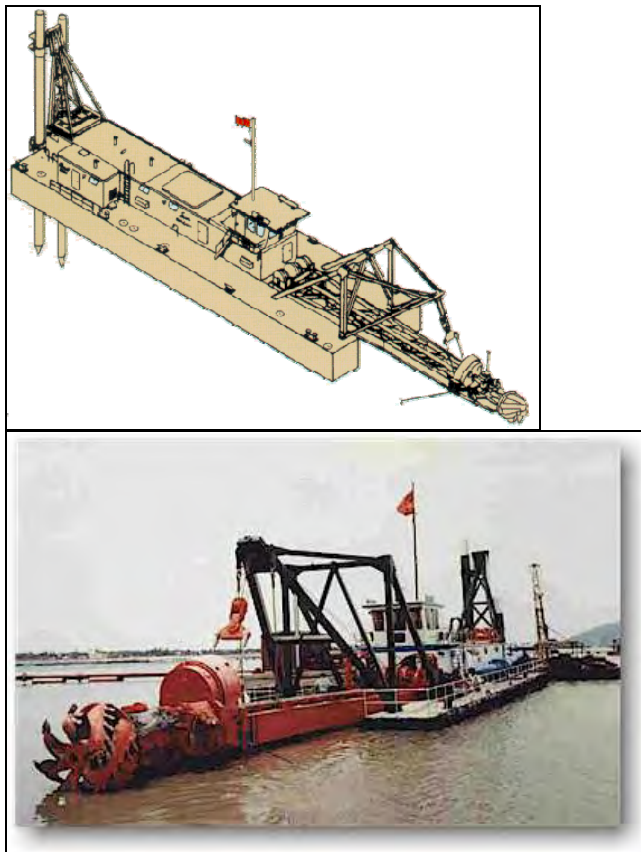
	min	max	
Concrete	0.2	0.374	t CO ₂ /m ³
Steel	1.63	1.75	t CO ₂ /tonne
Copper	1.652	1.652	t CO ₂ /tonne

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.

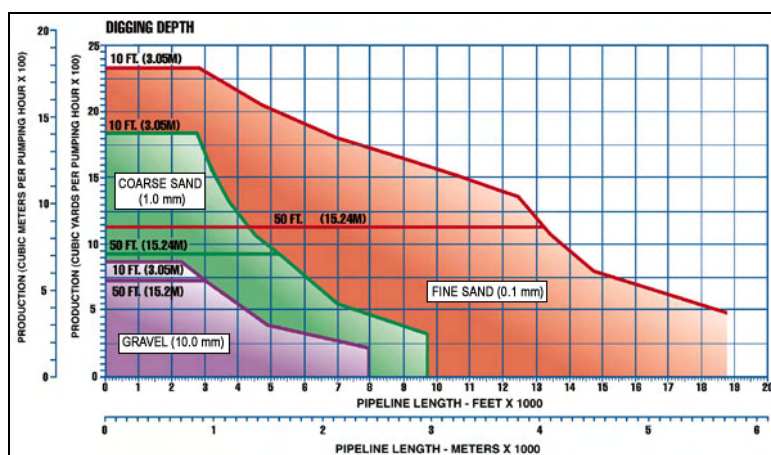
This company manufactures a wide range of dredgers. The model 4170 Series "Super-Dragon" was selected as being the most appropriate for this application. This is a portable heavy-duty dredger that discharges the dredged material via a 24" or 27" (609-686 mm) discharge pipeline. It has a centrifugal pump 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 A2.1 shows the configuration and layout of this dredger.

Figure A2.1 - 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 A2.2

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 A2.2.
- 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 A2.2 these conditions would imply that a pumping rate of approximately 1000m³/hour would be achieved.

It has been assumed that diesel fuel has a carbon emission factor of 0.068 kg(C)/kWh or 0.249 kg(CO₂)/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(CO₂)/hour.

Division by the pumping rate gives the emission per m³ of material dredged. This is 0.00034 te(C)/m³ or 0.00125 te(CO₂)/m³ of material dredged.

Appendix 3

Energy Generation Modes for Tidal Energy Barrages and Lagoons

Tidal barrages or lagoons can be designed to operate in various modes (Figure A3.1). 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 A3.2).
- *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.

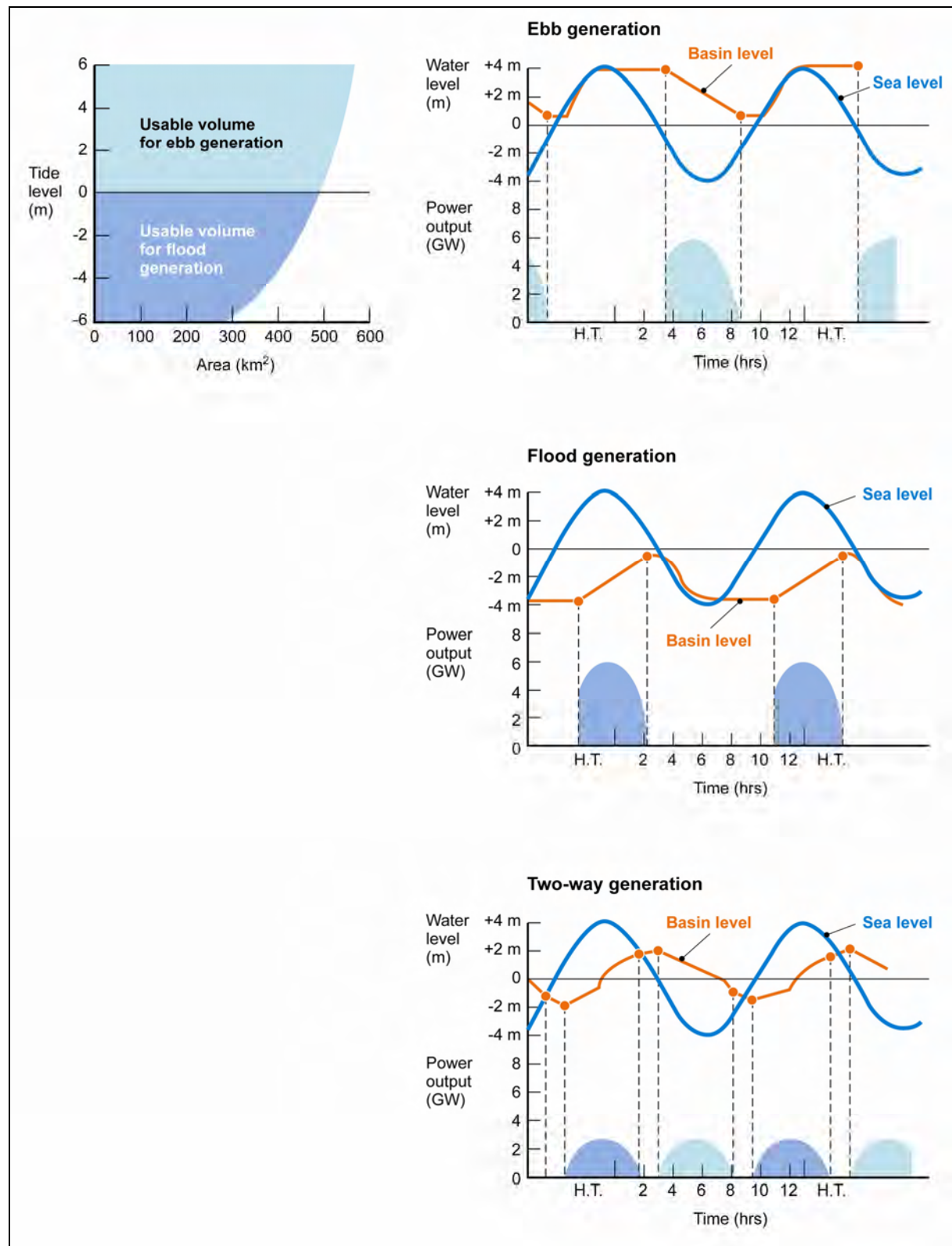


Figure A3.1 Energy generation modes for tidal energy barrages and lagoons.

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.

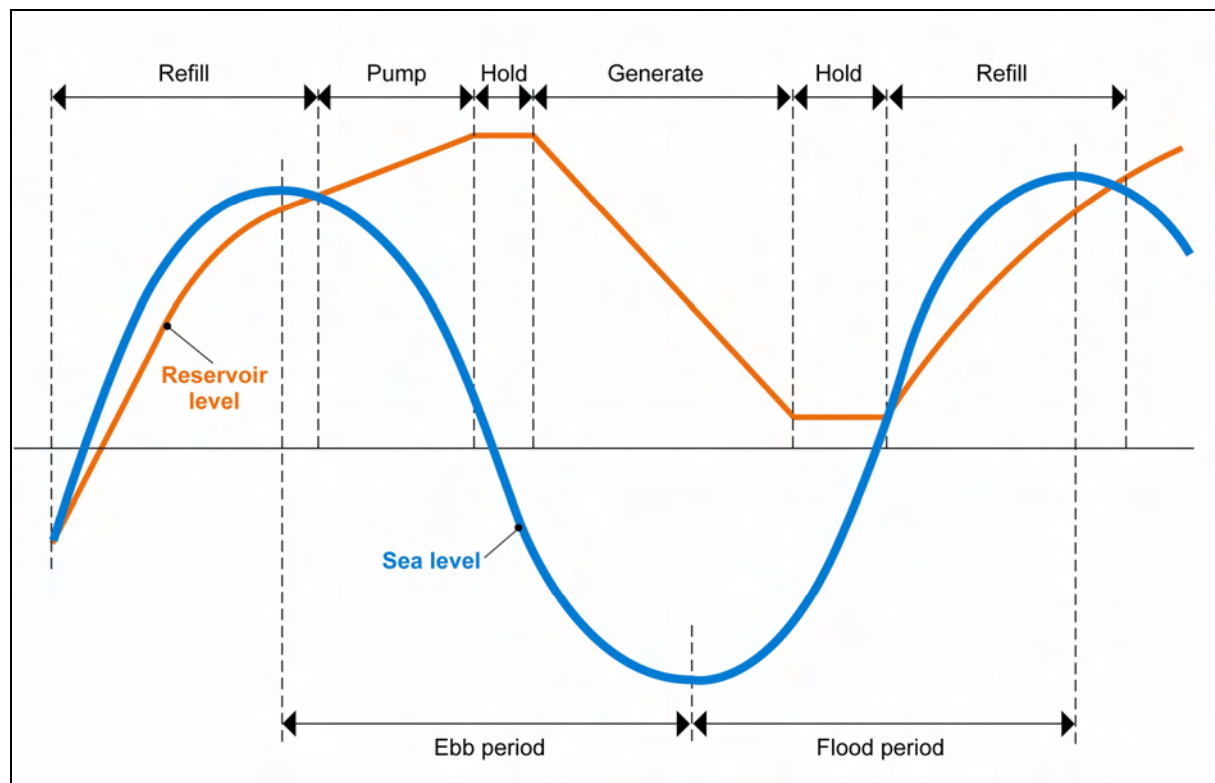


Figure A3.2 Energy generation for tidal energy barrages or lagoons using ebb generation in combination with flood pumping.

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 through 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% [A3.1, A3.2]. This method of operation also offers additional control of the basin water level, which has benefits for the estuarine environment and shipping. Figure A3.2 illustrates this mode of operation and the effect on water levels and energy output.

A3.1 References

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