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Tidal Power in the UK and Worldwide to Reduce Greenhouse Gas Emissions

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Abstract This paper discusses the role of Tidal Power in the UK in fulfilling the UK's requirements for reducing greenhouse gas emissions. Generating electricity from tidal range of the Severn Estuary has the potential to generate some 5% of UK electricity from a renewable indigenous resource.

The paper focuses primarily on the proposed Severn Barrage considering potential benefits, conditions for sustainable development, energy policy context and compliance with environment legislation. UK tidal resource is reviewed: stream resource (that is KE contained in fast-flowing tidal currents), and tidal range resource (that refers to gravitation potential energy). The top tidal range and tidal stream sites in the UK with the resource (in TWh/year) are indicated.

A feasibility study for Tidal Range development in the Mersey Estuary is also summarised and other schemes including the Loughor Estuary (Wales), Duddon Estuary (located on the Cumbrian coast) and the Thames Estuary proposals are reported. Also given is a strategic overview of the Severn Estuary resource, electric output and characteristics, carbon emissions (carbon payback and carbon reduction potential) and physical implications of a barrage.

Keywords Energy sources and the environment, renewable energy, energy conversion systems, power generation (renewables), physics of tidal power, harnessing tidal power (tidal range, tidal stream), greenhouse gas emissions, Severn and Mersey barrage.

1. Introduction

This paper examines in a form not conveniently referenced in the literature heretofore the generation of electricity by tidal power in the UK with respect to complying with the Kyoto and the Bali Protocols. Approximately 40% of the UK's electricity will have to be generated from renewables (wind, tidal/wave, and plant energy) by 2020 as a result of a legally binding EU target under the Bali Protocol. It is likely to mean a six-fold increase in the amount of onshore wind turbines and a 50-fold increase in the number of offshore wind turbines. This is because the 20% target for all renewables by 2020 applies to energy across the board, including transport and heating, where the scope for renewables is less, implying the electric sector must do more. By 2050, the UK is planning to reduce its CO2 emissions by at least 60% compared with its emissions in 1990.

A study is ongoing to:

Assess in broad terms the costs, benefits and impact of a project to generate power from the tidal range of the Severn Estuary, including environmental, social, regional, economic, and energy market impacts;

Identify a single preferred tidal range project (which may be a single technology/location or a combination of these) from the number of options that have been proposed;

Consider what measures the Government could put in place to bring forward a project that fulfils regulatory requirements, and the steps that are necessary to achieve this; and decide, in the context of the Government's energy and climate change goals and the alternative options for achieving these, and after public consultation, whether the Government could support a tidal power project in the Severn Estuary and on what terms.

A decision to proceed is not expected until the economic situation improves. Under consideration is tidal range, including barrages, lagoons and other technologies, and includes a Strategic Environmental Assessment of plans for generating electricity from the Severn Estuary tidal range to ensure a detailed understanding of its environmental resource recognising the nature conservation significance of the Estuary. The scheme would use proven technology of a hydroelectric dam but filled by the incoming tide rather than by water flowing downstream. The Severn Estuary has some of the best tidal potential in the world and could more than double the current UK supply of renewable electricity and contribute significantly to targets for renewable energy and CO_2 emissions reduction. The scheme would have a capacity of 8640 MW and produce roughly 17 TWh/year with a load factor of 0.22.

First, the physics of tidal power is considered. Variations in output from tidal power due to spring neap cycle is assessed, and technically available tidal energy resource in Europe is estimated by parametric modelling. Existing tidal energy schemes and sites considered for development worldwide are reviewed. Then, harnessing tidal power (flow or basin, modes of operation and configuration, ebb generation, flood generation, two-way generation and pumping) is indicated. Tidal stream technology that is in the early stages of development but could harness half of the UK's tidal potential is reviewed. The proposed Severn barrage considering tidal resonance in the Severn Estuary, potential benefits, the conditions for sustainable development and energy policy context, compliance with environment legislation and UK tidal resource is reviewed.

The electricity transmission system in the UK in the Severn area is evaluated where system constraints and upgrades and implications of tidal power are considered. The awareness of energy sources (wind, solar, coal, nuclear, gas, tidal/wave and bio-energy) that can generate electricity in the UK is outlined.

Concerns on Environment Impact considering the protected status of the Severn Estuary (Habitats Directive and Nature 2000), the Birds Directive defining biodiversity objectives, habitats and ecology are considered. Potential carbon savings for the two Severn proposals are then reviewed.

A consensus view is given on tidal power in the UK (tidal stream long-term potential {policy improvements, strategic planning and consenting}, tidal lagoons, and tidal barrages). Conditions for a sustainable Severn barrage (energy policy context, ensuring public interest, apportionment of risks and benefits, avoiding short-termism, regional impacts and priorities) complying with environmental legislation (applying environmental limits and providing compensatory habitats) is given.

2. Tidal Power

2.1. Physics of Tidal Power

Tidal energy is derived from the gravitational forces of attraction that operate between a molecule on the earth and moon, and between a molecule on the earth and sun. The force is $f = K M m / d2$, where m is the mass of the molecule on the earth, M is the mass of the moon or sun, d is the distance between the bodies, and K is the universal constant of gravitation. The attractive force exerted by the sun is about 2.17 times less than that due to the moon due to the mass and much greater distance that separates the earth and sun. As the earth rotates, the distance between the molecule and the moon will vary. When the molecule is on the dayside of the earth relative to the moon or sun, the distance between the molecule and the attracting body is less than when the molecule is on the horizon, and the molecule will have a tendency to move away from the earth. Conversely, when the molecule is on the night side of the earth, the distance is greater and the molecule will again have a tendency to move away from the earth. The separating force thereby experiences two maxims each day due to the attracting body. It is also necessary to take into the account the beating effect caused firstly by difference in the fundamental periods of the moon- and sun-related gravitational effects, which creates the so-called spring and neap tides, and secondly the different types of oscillatory response affecting different seas. If the sea surface were in static equilibrium with no oscillatory effects, lunar forces, which are stronger than solar forces, would produce tidal range that would be approximately only 5.34 cm high.

2.1.1 Types of Tide

Tidal phenomena are periodic. The exact nature of periodic response varies according to the interaction between lunar and solar gravitation effects, respective movements of the moon and sun, and other geographical peculiarities. There are three main types of tide phenomena at different locations on the earth.

Semidiurnal Tides with Monthly Variation: This type of tide has a period that matches the fundamental period of the moon (12 hr 25 min) and is dominated by lunar behaviour. The amplitude of the tide varies through the lunar month, with tidal range being greatest at full moon or new moon (spring tides) when the moon, earth, and sun are aligned. At full moon, when moon and sun have diametrically opposite positions, the tides are highest, because the resultant centre of gravity of moon and earth results in the earth being closer to the sun, giving a higher gravity effect due to the sun. At new moon, maximum tidal range is less. Minimum tides (neap tides) occur between the two maxims and correspond to the half-

moon when the pull of the moon and sun is in quadrature, i.e., the resultant pull is the vector sum of the pull due to moon and sun, respectively. In this case, the resultant gravitation force is a minimum. A resonance phenomenon in relation to the 12 hr-25-min periods characterizes tidal range.
Diurnal Tides with Monthly Variation. This type of tide is found in the China Sea and at Tahiti. The tidal period corresponds to a full revolution of the moon relative to the earth (24 hr- 50-min). The tides are subject to variations arising from the axis of rotation of the earth being inclined to the planes of orbit of the moon around the earth and the earth around the sun.
Mixed Tides. Mixed tides combine the characteristics of semidiurnal and diurnal tides. They may also display monthly and bimonthly variation. Examples are of mixed tides are those observed in the Mediterranean and at Saigon.

2.1.2 Major Periodic Components

The following periodic components in tidal behaviour can be identified: (i) a 14-day cycle, resulting from the gravitational field of the moon combining with that of the sun to give maxims and minima in the tides (called spring and neap tides, respectively); (ii) a ½ year cycle, due to the inclination of the moon's orbit to that of the earth, giving rise to a period of about 178 days between the highest spring tides, which occur in March and September, (iii) the Saros, a period of 18 2/3 years required for the earth, sun, and moon to return to the same relative positions, and (iv) other cycles, such as those over 1600 years which arise from further complex interactions between the gravitational fields.
Maximum height reached by high water varies in 14-day cycles with seven days between springs (large tide range) and neaps (small tide range). The spring range may be twice that of the neaps. Half-yearly variations are +/-11%, and over 18 2/3 years +/- 4%. In the open ocean, the maximum amplitude of the tides is less than 1 m. Tidal amplitudes are increased substantially particularly in estuaries by local effects such as shelving, funnelling, reflection, and resonance. The driving tide at the mouth of the estuary can resonate with the natural frequency of tidal propagation up the estuary to give a mean tidal range of over 11 m in the Severn Estuary, UK and can vary substantially between different points on the coastline 1 The physics of tidal range is examined by Baker in more depth in (Baker, A., 1991).

[1] Tidal range is the tidal height between high-tide and low tide. Typical tidal ranges are Bay of Fundy (Canada) 19.6 m; Granville (France) 16.8 m; La Rance (France) 13.5 m.

2.2 European Energy Potential

The amount of energy available from a tide varies approximately with the square of tidal range. The energy available from a tidal power plant would therefore vary by a factor of four (eight for tidal stream) over a spring-neap tide cycle. Typical variation in output from tidal range and tidal stream power in the Severn Estuary due to the spring-neap cycle is indicated in Fig. 1(a) and 1(b), respectively. Approximately 20 suitable regions for development of tidal power worldwide have been identified.
A parametric approach (Baker, A., 1986) has been used to estimate tidal energy potential for appropriate EU countries (Belgium, Denmark, France, Germany, Greece, Ireland, Portugal, Spain, The Netherlands, and UK). An assessment of all reasonably exploitable sites within the EU with a mean range exceeding three meters yielded a total energy potential of about 105 TWh/year. This potential is mainly in the UK (50 TWh/year) and France (44 TWh/year), with smaller contributions in Ireland, The Netherlands, Germany and Spain. Technically available resource for tidal energy estimated using parametric modelling is given in Table 1.

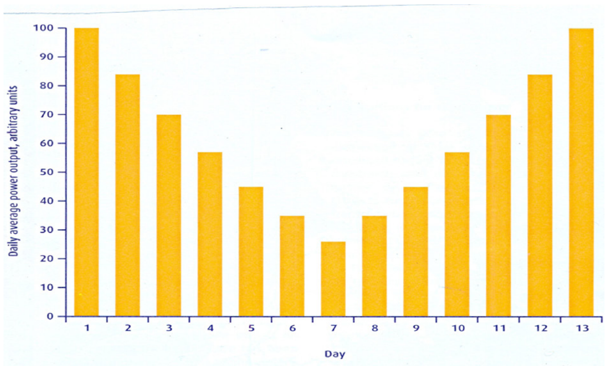


Figure 1(a). Typical variation in output from tidal range power due to spring-neap cycle

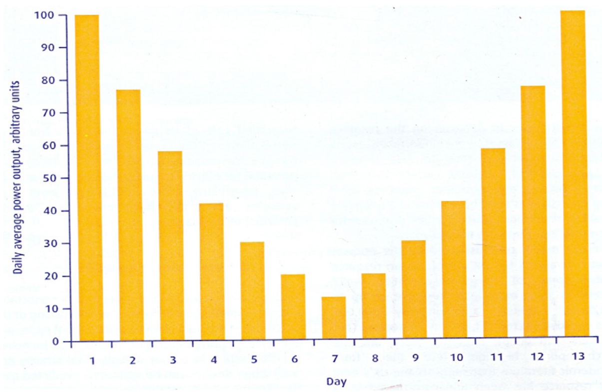


Figure 1(b). Typical variation in output from tidal stream power due to spring-neap cycle.

Country	Technically available tidal energy resource		Percentage of European tidal resource
	GW	TWh/year	
United Kingdom	25.2	50.2	47.7
France	22.8	44.4	42.1
Ireland	4.3	8.0	7.6
Netherlands	1.0	1.8	1.8
Germany	0.4	0.8	0.7
Spain	0.07	0.13	0.1
Other W European	0	0	0
Total W European	63.8	105.4	100.0

Table 1. Technically Available Tidal Energy Resource in Europe Estimated by Parametric Modelling

2.3 Existing Tidal Energy Schemes

Relatively few tidal power plants have been constructed to date. The first and largest is the 240 MW barrage at La Ranch (France) (Banai, M. & Bichon, A., 1982), which was built for commercial production in the 1960s. Other tidal power plants include the 17.8 MW plant at Annapolis (Canada), the 400-kW experimental plant at Kislaya Guba (former Soviet Union), and the 3.2 MW Jiangxia station (China).

2.4 Sites Considered for Development Worldwide

Economic feasibility of tidal barrage schemes is dependent on the world market price of fossil fuels, interest rates over scheme expected life, and on level of fossil fuel levies based on the carbon content of fuel and electricity not produced by renewable energy sources, etc. Tidal power sites of capacity above 1GW considered for development with installed capacity and approximate annual output include: (i) Argentina San Jose, 6.8GW, 20.0 TWh; (ii) Canada Cobequid, 5.34 GW, 14.0 TWh; (iii) Canada Cumberland 1.4 GW, 3.4 TWh; (iv) Canada Shepody, 1.8GW, 4.8 TWh; (v) India Gulf of Cambay, 7.0 GW, 15 TWh; (vi) UK Severn, 8.6 GW, 17 TWh; (vii) USA Knit Arm, 2.9 GW, 7.4 TWh; (viii) USA Turnagain Arm, 6.5 GW, 16.6 TWh; (ix) Former Soviet Union Mezen, 15 GW, 50 TWh; (x) Former Soviet Union Tugur, 10 GW, 27 TWh; and (xi) Former Soviet Union Penzhinskaya, 50 GW, 200 TWh.

2.5 *Harnessing Tidal Power (flow or basin, existing tidal energy schemes, modes of operation and configuration, adaptation of tide-generated to grid network requirements)*

Devises include waterwheels, lift platforms, air compressors, water pressurization, etc. Energy can be extracted either directly by harnessing the kinetic energy of a tide flow, or by using a basin to capture potential energy of a rising and falling mass of water.

2.5.1 Tidal Flow: Tide flows have a poor energy density

Theoretical available power P is given by $P=D\ A\ V3$, where D is the fluid density, A is the area swept out by the turbine rotor, and V is the undisturbed stream velocity (Grant, A., 1981). The energy can be harnessed only with poor maximum efficiency, similar to a windmill, where an efficiency of 59.3% is possible. Directly harnessing power in this way, however, does not require expensive additional structures.

2.5.2 Basin

This method involves constructing a barrage and forming a basin from a natural bay or estuary. Considerable extra cost is incurred, but this is more than outweighed by the extra energy that is extractable. The energy available from a turbine in an effective barrage is one or two orders of magnitude greater than that from a similar size of turbine in a tide stream of, for example, 2 m/s. The extra cost of constructing the barrage may be only a third of scheme overall cost.

2.6 Modes of Operation and Configuration

The tide is the only factor that affects the generating activity of a tidal power plant that is programmed to produce maximum output. The output at any given time can be accurately calculated as far in advance as is necessary.

2.6.1 Single-Action Outflow (Ebb) Generation

Barrages can use either one basin or a combination of basins, and can operate by ebb, flood, or two-way generation, with or without pumping. The simplest method is ebb generation using a single basin. The basin is permitted to fill through sluices (gated openings). Generation takes place as the basin is emptied via turbines once the tide level has dropped sufficiently. There are two bursts of generation each day.

Typical day-to-day fluctuations are: (i) there are two bursts of generation activity each day, beginning approximately three hours after high tide and lasting 4-6 hours; (ii) for each cycle production levels rapidly increase with tidal range, the output characteristic therefore displaying a 14-day cycle; (iii) high-water times shift by about 1 hr per day; (iv) in each 14-day period, the generation will not be evenly distributed throughout the 24-hr of the day; (v) output levels will only show slight variation from one fortnightly period to the next; and (vi) annual production levels will show fluctuations of around +/-5% and will follow a cycle of 18 2/3 years.

2.6.2 Flood Generation

Here, power is provided as the basin fills. The basin empties through sluices as the tide falls. This method is not as efficient as ebb generation since it involves using the basin between existing low tide level and slightly above normal mid-tide level, thus producing less energy. An advantage of this mode is that it facilitates the production of energy out of phase with a neighbouring ebb generation scheme, complementing its output and perhaps providing some firm capacity.

2.6.3 Two-way Generation

This is a combination of ebb and flood generation, generating as the basin both fills and empties, but with a smaller power output for simple ebb generation (except at the highest tide ranges) due to reduced range within the basin. There is a resultant reduction in efficiency with two-way generation since turbines and water flow cannot be optimized. Two-way generation produces electricity in approximately 6-hr cycles, with smaller power output and a greater plant utilisation factor.

2.7 Tidal Stream

Tidal current turbines are basically underwater windmills where tidal currents are used to rotate an underwater turbine. First proposed during the 1970s' oil crisis, the technology has only recently become a reality. Horizontal axis turbines are more commonly employed. Marine Current Turbines (MCT) {http//www.marineturbines.com/home.htm} installed the first full-scale prototype turbine (300kW) off Lynmouth in Devon, UK in 2003. Their second project, a 1 MW prototype, is expected soon. It will be followed by an array of similar systems (farm) to be installed in an open sea, where three turbines will be added to provide a total capacity of 5 MW. A similar project is the Hydro Helix project in France.
The Norwegian company Hammerfest Strom AS installed their first grid-connected 300kW devise that was tested and the concept proven {http//www.e-tidevannsenergi.com/} A tidal stream turbine has been designed for the Pentland Firth between the North of Scotland and the Orkney Islands (Bryden, I., et. al., 2003) where the first design was for twin turbines with 20 m rotors and was rated at 1-2 MW depending on current speed. In today's design, the 60 m deep four 20 m rotors cover water flow rather than a pair to keep blade loads within practical limits and the whole power output is 4 MW. The SMD Hydrovision TidEL Project (UK) {http//www.smdhydrovision.com} consists of a pair of contra-rotating 500 kW turbines mounted together on a single crossbeam. The 1 MW units are designed to be mounted in an offshore tidal environment with a peak tidal velocity of 5 knots (2.5 m/s) or more and a water depth of greater than 30 m. The Lunar Energy Project (UK) and the HyroHelix Energies Project (France) {http//www.lunarenergy.co.uk http//www.hyrdohelix.fr/} feature a ducted turbine fixed to the seabed via gravity foundation. A 1/20th model was tested in 2004 and a 1 MW prototype is expected soon. The ideal sites are generally within several kilometres of the shore in water depths of 20-30 m.
There are also vertical axis turbines that are cross flow machines whose axis of rotation meets the flow of the working fluid at right angles. Cross flow turbines allow the use of a vertically oriented rotor that can transmit the torque directly to the water surface without need of complex transmission systems or an underwater nacelle. The vertical axis design permits the harnessing of tidal flow from any direction, facilitating the extraction of energy not only in two directions, the incoming and outgoing tide, but making use of the full tidal eclipse of the flow (Kiho, S., et. al., 1996). In these types of turbines, the rotational speed is very low, of the order of 15 rpm.

2.7.1 The Enermax Project (Italy) {http//www.pontediarchimede.com}

This uses the Kobold turbine. Its main characteristic is its high starting torque that permits it to start even in loaded conditions. A pilot plant is located in the Straight of Messina, close to the Sicilian shore in Italy, in an average sea tidal current of 2m/sec.

2.7.2 The Blue Energy Project (Canada) {http//www.bluenergy.com}

Four fixed hydrofoil blades of the Blue Energy tidal turbine are connected to a rotor that drives an integrated gearbox and electrical generator assembly. The turbine is mounted in a durable concrete marine caisson that anchors the unit to the ocean floor, directs flow through the turbine further concentrating the resource supporting the coupler, gearbox, and generator above it. The hydrofoil blades employ a hydrodynamic lift principle that causes the turbine foils to move proportionately faster than the speed of the surrounding water. The rotation of the turbine is unidirectional on both the ebb and flow of the tide. A unit turbine is of the order of 200 kW output power. For large-scale power production, multiple turbines are linked in series to create a tidal fence across an ocean passage or inlet

2.7.3 The Gorlov Helical Turbine (GHT) (USA) {http//www.gcktechnology.com/GCK/}

The turbine consists of one or more long helical blades that run along a cylindrical surface similar to a screw thread, having a airfoil or airplane wing profile. GHT blades provide a reaction thrust that can rotate the turbine faster than the water flow itself. The GHT is self-starting and can produce power from water current flow as low as 1.5 m/sec with power increasing in proportion to the water velocity cubed. Due to axial symmetry, the GHT always rotates in the same direction, even when tidal currents are reversed. The standard model (1 m in diameter, 2.5 m in length) can be installed either vertically or horizontally to the water current (Gorlov, A., 1996). A single GHT has a rated power of 1.5 kW for 1.5 m/s water speed and 180 kW for 7.72 m/sec. A similar concept to the GHT is the Achard known as the Harvest project (France) {http//www.legi.hmg.inpg.fr/cavit/Deta/Harvest.html}.

2.8 Adaptation to Grid Network Requirements

The output from a tidal plant displays characteristics that are not compatible with those of conventional generation, transmission, and system load. A pumping system increases average output levels and enhances flexibility of the scheme. This in turn leads to improved economic efficiency as supply times can be varied to match energy cost levels.

Single-action outflow (ebb) generation barrages can use one basin or a combination of basins, and can operate by ebb, flood, or two-way generation, with or without pumping.

3. Proposed Severn Barrage

The Severn is probably the most well known of all potential tidal energy locations, and projects for damming the Severn estuary date back for over a century. The tide range is up to 11 m near the head, being amplified and funnelled by the Bristol Channel. The channel and estuary form a resonator having an effective length equivalent to ¼ of that of the tidal wave. Most attention is focussed on schemes further down the estuary where tide range is reduced and a longer barrage is needed, but where the energy extractable is many times greater. Tidal resonance in the Severn Estuary is illustrated in Fig. 2.

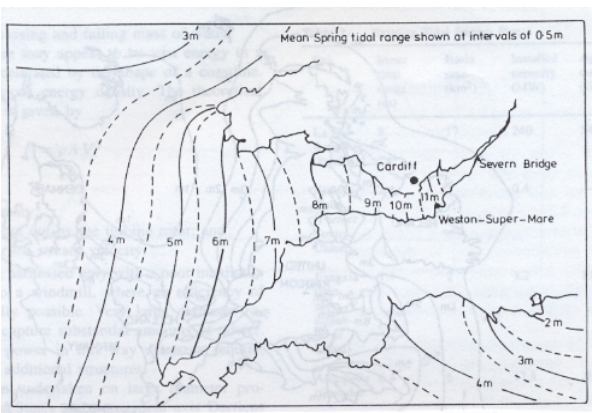


Figure 2. Tidal resonance in the Severn Estuary.

A number of different barrage options have been proposed. The Cardiff-Weston scheme is one of the largest and would have a generating capacity of around 8.64GW. The Shoots scheme (which would run near to the two Severn road crossings is 1.05GW with an annual output of around 2.75 TWh. Power output and cost summary for the two options are given in Table 2.

3.1 Potential Benefits

The assumption is that both barrages would be operated on the ebb tide, with the addition of flood pumping to increase total energy output. This means that they would be generating electricity for around 7~8 hours on each tide, and output would vary within this period. The annual output of each barrage is less than that implied by their size, around 4.4 % of UK electricity supply, about the same as would be produced by a 2 GW conventional fossil-fuel or nuclear power station.

The high capital cost of a barrage project leads to a very high sensitivity to the discount rate used (Table 2). At a discount rat of 2 % that could be justified for a climate change mitigation project, cost of electricity from both barrage proposals is highly competitive with other forms of generation. At a commercial discount rate of >8 %, these costs escalate significantly, making private investment unlikely without significant Government market intervention.

There would be substantial flood risk benefits. The timing of output is not optimal, but output is not a major problem for the electricity grid that can be managed at very low cost. The output would displace output from fossil-fuelled plants and would make a genuine and sizable contribution to meeting the UK's targets on renewable energy and on reducing carbon dioxide emissions.

3.2 Conditions for Sustainable Development

The issue has been approached from a general position that favours renewable energy under which its development might be sustainable. It has been done within a framework that places a high value on long-term public interest and on maintaining the overall integrity of internationally recognised habitats and species.

Tidal Range Sites		Tidal Stream Sites		
Site Name	Resource (TWh/yr)	Site name	Area	Resource (TWh/yr)
Severn	17	Pentland Skerries	Pentland Firth	3.9
Mersey	1.4	Stroma	Pentland Firth	2.8
Duddon	0.212	Duncans-by Head	Pentland Firth	2.0
Wyre	0.131	Casquets	Alderney	1.7
Conwy	0.06	South Ronaldsay	Pentland Firth	1.5
		Hoy	Pentland Firth	1.4
		Race of Alderney	Alderney	1.4
		South Ronaldsay	Pentland Firth	1.1
		Rathlin island	North Channel	0.9
		Mull of Galloway	North Channel	0.8

Table 2. Power Output and Cost Summary for the two main Severn Barrage Options

3.3 Energy Policy Contexts and Compliance with Environment Legislation

There is risk that development of a barrage might divert Government's attention away from other necessary solutions to the challenge of climate change, including development of a more decentralised energy system and the reduction of energy demand. A Severn barrage has a number of disadvantages that are similar to those of nuclear power, and developing such a large amount of electricity generating capacity in a single location would not itself move the UK any closer to a more decentralised energy system. The Government does not have policies in place at this time to deliver the carbon savings that will be required by 2050, and in particular the delivery of emissions reductions over the next 15 years. A Severn barrage could be pursued (the economy permitting) as part of a major drive to reduce emissions substantially over both the short- and long-term.

3.4 UK Tidal Resource

Available estimates of the UK's tidal range and tidal stream resource for potential electricity generation are given in Table 3. Estimating potential electricity output requires a number of assumptions on technical constraints of the devises installed, their efficiency, and effect of resource extraction on the remaining resource. This implies that there is a large degree of uncertainty in all resource estimates given in Table 3.

		Cardiff-Weston	Shoots
Length of Embankments		16.1 km	4.1 km
Generating Capacity		8.64 GW	1.05 GW
Annual Average Electricity Output		17 TWh	2.75 TWh
Contribution to UK Electricity Supply (2006 Data)		4.4 %	0.7 %
Estimated Cost of Construction		£15 bn	1.5 bn
Estimated cost of output at various discount rates (high case scenario)	2 %	2.31p/kWh	2.58 p/kWh
	3.5 %	3.68 p/kWh	3.62 p/kWh
	8 %	9.24 p/kWh	7.52 p/kWh
	10 %	12.37 p/kWh	9.54 p/kWh
	15 %	22.31 p/kWh	15.38 p/kWh

Table 3. Top Tidal Energy Sites in the UK with the Resource

4. Electricity Transmission System

The Electricity Transmission Network in Great Britain is illustrated in Reference (NGET, 2007). Most generating

system, with some 12 GW of generating capacity connected to the distribution networks. The capacity of the transmission system to connect generation and manage the flows of electricity depends on the capacity of the network. The process of connecting to the network is based around the principle of matching the Connection Entry Capacity (CEC) (the generating capacity of the power station) with the Transmission Entry Capacity (TEC) (the capacity of the network to accept a new generator). Connection offers are made on the basis of an invest and connect approach whereby CEC can never exceed TEC, so new lines must be built to connect new generation. At present, there are significant TEC constraints in the north of England and in Scotland, which are preventing the connection of new generation projects. Areas of the transmission network will need to be upgraded to higher voltage levels to increase the TEC.

These issues pose significant challenges for the connection of tidal stream projects. Existing capacity constraints and delays to network upgrades will further delay the date by which tidal stream projects might be connected. If the current approach to transmission connection is not modified, it is unlikely that the UK will see any significant level of tidal stream connection before 2020.

For tidal range, the situation is less significant. Firstly, tidal range resources are generally located in areas where grid constraints capacity transmission lines are less pronounced, and are closer to high capacity transmission lines and to centres of demand. Secondly, tidal barrages are likely to be larger one-off projects when compared to a tidal stream array, making the incorporation of grid connection costs a smaller part of the overall project cost and therefore more manageable.

The Severn Estuary area has significant network capacity for new generation, with negative transmission network use of system (TNUoS) charges currently in force. This applies for generators in the southwest of England due to a shortage of generation to meet local requirements.

The transmission network around the Severn Estuary is shown in Fig. 3. It is quite well developed, with possible connections at both 400kV and 275kV on both sides of the estuary not far from the landing points for a barrage. For the larger Cardiff-Weston scheme, two connections into the 400kV network would be required at both north sides of the barrage (i.e. four connections in total) as the 275kV network on the north side is near to capacity and there is very limited capacity on the 132kV network on the south side.

For the much smaller-rated capacity of the Shoots scheme, all of the connection options seem to have sufficient capacity to accommodate this through just one connection. A connection to the Hinkley Point-Melksham 400kV double-circuit line would be appropriate due to high demand for new capacity. This could further increase with decommissioning of the nuclear power station at Hinkley Point (if it is not replaced by new nuclear generation). Both schemes would require some new transmission infrastructure to connect into the existing network. This requirement is far higher for the Cardiff-Weston scheme due to its higher rated capacity.

5. Feasibility Studies

Mersey Estuary, Loughor Estuary (Wales), Duddon Estuary (Cumbrian Coast), Wyre Barrage (Lancashire), and Thames Barrier.

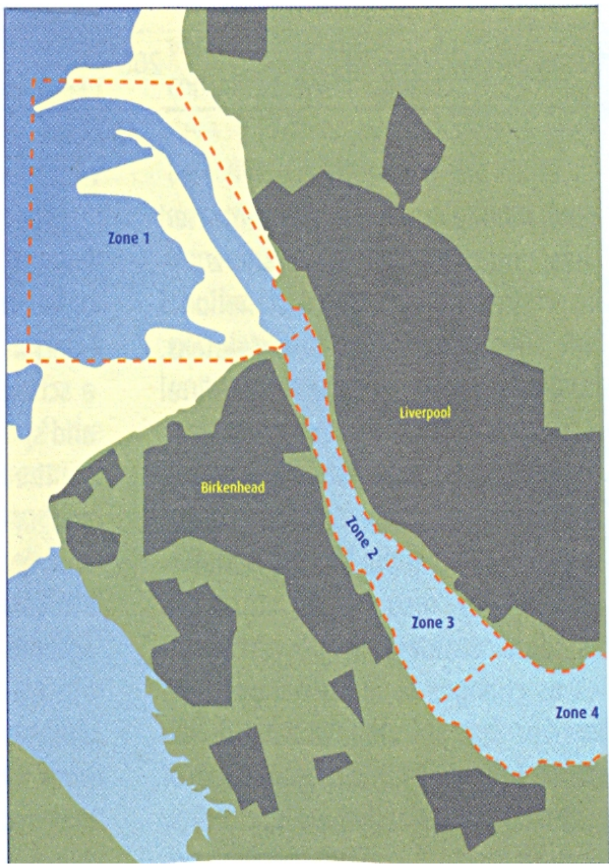
Fig. 3. Electricity transmission network (400 and 275kV) around the Severn Estuary

5.1 Mersey Barrage

The first stage of the feasibility study was completed in 1988 (Tidal Power from the River Mersey, 1988), which included hydraulic and energy modelling together with a preliminary examination of the geo-technical conditions, socio-industrial benefits and likely effects on shipping and the ecology of the estuary. No overriding impediments to the construction of a barrage were identified at that time. The Mersey Estuary has a mean spring tidal range of 8 m and a potential annual resource of about 1.4 TWh. The barrage would have 28 turbine-generators with 8-m turbines rated at 25 MW, giving an installed capacity of 700 MW (Hammond, N. & Wood, P., 1989). The proposed barrage would be approximately 2 km long, with a design life of at least 120 years for the main structure, with two periods of turbine renewal at 40-year intervals.

There is renewed interest as a result of a recent study commissioned by Peel Environmental Ltd in association with the North West Regional Development Agency (NWDA) and the Mersey Basin Campaign (Peel Environmental Ltd, 2007). There are a number of potential options for harnessing energy from the Mersey. To assess the options, the estuary was divided into study zones. These are indicated in Fig. 4. The only viable option for zone 1 was considered to be a tidal lagoon. This could be operated independently from the other options. For the remaining zones, the two most productive options were two tidal barrage options (one termed as a tidal gate), although several tidal stream options were also studied.

The capacity and estimated electricity output from each option is indicated in Table 4. The construction cost of a Mersey Barrage was estimated in 2006 to be at £1.5bn (2006 prices). This results in a unit cost of output ranging from 12.27p/kWh to 15.79p/kWh when a commercial discount rate of 8-10% is assumed. This would reduce to about one third if a 2% discount rate were used. The costs using the higher discount rates would result in electricity that is not commercially competitive under current conditions.



Source: Peel Environmental Ltd.

Figure 4. Mersey showing study zones

Technology Option	Rated Capacity (MW)	Annual Electricity Output (GWh}
Tidal lagoon (Zone 1)	350	650
Tidal Barrage (Zone 2)	700	1200
Central reservation (Zone 2)	20	40
Constrained channel (Zone 2)	50	100
Tidal fence (Zone 2)	35	80
Tidal gate (Zone 3)	380	700
Water wheel (Zone 3)	200	500

Source: Peel Environmental Ltd

Table 4. Comparison of Main Tidal Power Options for the Mersey Estuary.

5.2 Other UK Barrages

These include the Loughou Estuary in Wales which has an annual spring tide of 3.9 m and could generate 5 MW, the Duddon Estuary located on the Cumbrian coast that has a mean tidal range of 5.8 m and could generate 0.212 TWh/year from ten 10 MW turbines, the Wyre Barrage (Lancashire) with a mean tidal range of 6.6 m and installed capacity of around 60 MW that would generate about 0.131 TWh/year, the Thames Barrier that would form a new flood protection barrier that could generate possibly up to 800 MW, and the Conwy Barrage (North Wales) that would have six 5.5-MW generators giving an installed capacity of 33 MW. Here, the mean tidal range varies from 7.1 m (spring) to 3.5 m (neap) and average energy is 0.0568 TWh/year (0.0602 TWh/year with pumping)

6. Environment Impact

The Severn Estuary is a unique and dynamic environment. It has the second largest tidal range in the world, combined with a high-suspended sediment load, and has a number of special features, including extensive areas of salt marsh, and mobile sandbanks. It is an important site for migratory birds, and for fish movements in and out of the estuary's tributaries, such as the Wye and Usk. For these reasons the Severn Estuary has been designated a protected site under national and international legislation.
The most important pieces of conservation legislation for a prospective Severn barrage are the EU Directives on Birds and Habitats that protect sites designated as Special Protection Areas (SPAs) and Special Areas of Conservation (SACs). Identification of sites is a science-led process that is based on protecting important ecosystem types and threatened bird species. The Severn Estuary is a SPA and a candidate SAC. The aim of designation is to protect against biodiversity loss by conserving a series of important or at-risk habitats and species that make up the Europe-wide Natura 2000 network. The Natura 2000 network is based on the need to conserve biodiversity across Europe, and internationally.
A Severn barrage could lead to a loss of biodiversity, resulting in the need for a compensatory habitats package to maintain overall integrity of the Natura 2000 network. The EU Directives provide a clear and robust legal framework for achieving sustainable development and therefore compliance with the Directive is a central condition for a sustainable Severn barrage. Providing compensatory habitat would be a very significant undertaking on a scale hitherto unprecedented in the UK. It would have to be an integral part of any barrage proposal.
In summary, there is a strong case to be made for a sustainable Severn barrage. Much wider and stronger action on climate change is a pre-requisite for UK Sustainable Development Commission's (SDC) support. There may be an environmental opportunity available by linking a compensatory habitats package to climate change adaptation. A Severn barrage must be publicly led as a project and publicly owned as an asset to ensure long-term sustainability. The New UK Government should consider a range of innovative financing mechanisms that would maintain overall public control and ownership of the project.

7. Carbon Emissions

One of the main arguments for building a Severn barrage is its potential contribution to reducing carbon dioxide emissions and therefore its ability to help the UK meet its national and international obligations on renewables and emissions of greenhouse gases2.
The reduction in carbon dioxide emissions from a Severn barrage depends heavily on assumptions made on the carbon intensity of the displaced electricity. The output from a tidal barrage is intermittent, is highly predictable, and has very low operational cost. It would be treated as base-load generation, similar to that for nuclear power plants. Therefore, tidal power output is most likely to displace the output from large, centralized, fossil fuel plants.
The long lifecycle of a Severn barrage has a positive impact on the carbon emissions factor as the embedded emissions from construction are counter-balanced by 120 years of zero emissions electricity generation. The emissions factor

[2] Under the recently-agreed EU target for 20% of all energy requirements to come from renewables by 2020 www.defra.gov.uk/news/latest/2007/climate-0309.htm , the UK will need to commit to developing at least this amount. On greenhouse gases, it is assumed that the UK will need to make substantial progress in its goal for a 60% reduction in carbon dioxide emissions by 2050, and that the UK 's commitment will most likely need to rise to a 80-90% cut in line with scientific evidence.

for the Severn Cardiff-Weston barrage is estimated to be 2.42gC02/kWh and 1.58gC02/kWh for the Shoots scheme, which translates into a carbon payback of around 5-8 months for the two schemes. It is in the very lowest category for power generation and compares well against other low carbon technologies such as nuclear power (16gC02/kWh) (Sustainable Development Commission).

The Severn barrage would displace the need for some other form of new capacity, such as CCGT, as this is currently the preferred choice for new-build base-load generation. New-build gas-fired plant has a carbon intensity of around 90tC/GWh.

Table 5 presents the likely annual carbon savings (as both carbon and carbon dioxide) from the two Severn barrage proposals. Although it is possible to calculate the lifetime carbon savings (over the 120 years expected life of a barrage), the figures are unlikely to be realistic because over this period the generating capacity being displaced will be progressively less carbon intensive.

8. Physical Implications of a Barrage

The construction, presence and operation of a Severn Barrage would involve major physical changes to water levels, geomorphology, and sedimentary processes. These physical changes underlie and have significant implications for (i) the environment—the estuarine ecosystem, inter-tidal and wetland habitats, birds, fish; and (ii) the economy and society at a local and regional scale—ports and navigation, land drainage and flooding, water quality, infrastructure and transport, employment, industry and recreation.

The changes that a barrage would cause extend well beyond the direct physical footprint of the structure, and involve physical changes to the estuary as a result of reducing the tidal range and changing the water levels within the barrage basin (upstream) and outside the barrage (downstream). The physical barrier across the estuary (Cardiff-Weston barrage is about 16km long), together with the changes to water levels, the tidal currents and the wave regime of the estuary, also mean that the sedimentary and morphological characteristics and processes of the estuary would be significantly changed.

The hyper-tidal nature of the estuary is responsible for creating a series of unique conditions and habitats such as extensive mud flats and mobile sand banks and extracting energy from this dynamic regime in the form of a tidal barrage would fundamentally change the nature of the Severn Estuary. On the whole, a barrage would raise the average water level inside the basin by raising the low tide levels to around present mean sea level and by reducing high tide levels by up to 1m (up to about 0.5m for the Shoots scheme) The mean sea level in the estuary would be raised by some 2.5m to3m for the Cardiff-Weston scheme. The overall effect is to reduce the tidal range by about 50%. For the Cardiff-Weston scheme, the range would decline from 11.5m 20 4.5m on spring tides, and 5.5m to 2.5m on neaps. For the Shoots scheme, the result would be a similar reduction in tidal range, from 12.5m to 4.5m on spring tides, and 6.5m 20 3.5m on neaps. Down stream of a barrage, model predictions for the Cardiff-Weston alignment are that low water level would be raised somewhat and high water levels would be reduced, the effects declining with distance up to 75km seawards.

Morphology refers to the form and development of the landscape. Morphology and the sediment regime have implications for the environment, the engineering of a barrage, and in relation to ports and navigation.

	Cardiff-Weston		Shoots	
	MtC	MtC02	MtC	MtC02
Annual carbon savings (based on 90tC/GWh)	1.53	5.60	0.25	0.91
Percentage reduction in UK carbon emissions (1990 baseline)	0.92%		0.15%	
For Comparison				
Annual carbon savings based on average gas displacement (100tC/GWh)	1.7	6.22	2.75	1.00
Annual carbon savings based on grid mix displacement (131tC.GWh)	2.23	8.15	0.36	1.32

Table 5. Potential Carbon Savings from a Severn Barrage

9. Other Carbon-Free Developments

The UK government announced in November 2009 a draft National Policy Statement (NPS) to guide decisions on energy infrastructure to reduce GHG emissions. The threat of climate change means we need to make a transition from a system that relies heavily on high carbon fossil fuels to a radically different system that includes nuclear, renewable and clean coal power. The UK is undertaking fundamental reform of the planning system which will result in a more effective, transparent and accessible process.

In excess of six NPSs have been published—one overarching and one for each of the following areas: fossil fuels, nuclear, renewables, transmission networks and oil and gas pipelines—alongside the Government's

Framework for the Development for Clean Coal. Decisions on proposals bigger than 50 MW (or 100 MW for offshore wind) was reduced from two years to one year or less.

The Nuclear NPS sets out why new nuclear power is needed and that the UK Government is satisfied that the effective arrangements will exist to manage and dispose of the waste that will be produced by new nuclear power stations that will supply up to a quarter of the country's electricity demand. The go-ahead for a new generation of nuclear power stations to be built in the UK was recently given by the UK government, but none will be in Scotland.

It is the only site-specific energy NPS. A rigorous Strategic Siting Assessment has been carried out by the Government focussed on sites that are deployable by the end of 2025 to meet the UK's pressing climate change and energy security goals. The assessment looked at exclusionary and discretionary criteria, a Habitats Directive assessment and an Appraisal of Sustainability, and took on board advise from the Regulators and inputs from a Public Comments Window.

Ten of the eleven sites nominated in March 2009 have been assessed as potentially suitable for new nuclear deployment by the end of 2025; Bradwell, Braystones, Hartlepool, Heysham, Hinkley Point, Kirksanton, Oldbury, Sellafield, Sizewell and Wylfa. Subsequently, eight are currently being considered.

Dungeness is not listed on account of the Government does not consider that potential environmental impacts at this site can be mitigated. There are also concerns about coastal erosion and associated flood risk at this site.

No sites are being assessed in Scotland on account of the Scottish Government's objections to Nuclear power

Following a rigorous independent study in line with the Habitats Directive, three alternative sites were identified as worthy of consideration; Druridge Bay in Northumberland, Kingsnorth in Kent and Owston Ferry in South Yorkshire. It was concluded that all three of them have serious impediments, none of them is credible for deployment by the end of 2025, nor are they necessary to the Government's plans, and they have not been listed in the draft Nuclear NPS. Proposed sites for new Nuclear power stations are indicated in Fig. 5.

Wind farms that comprise the largest proportion of the UK's renewable energy have typical load factors of around 33% and generation is intermittent. Tidal stream power that has a 12 hr. 25 min. period that is proposed for development in the UK (principally in Scotland) when technology permits is periodic with typical load factors of 25 % and peak output due to the spring-neap cycle that varies by a factor of ten (see Fig. 1 (b)).

There are significant challenges for the connection of tidal stream, wave and wind power projects in Scotland and to accommodate wind power the transmission system is currently being upgraded. To fill in the gaps in wind power and prospective tidal stream and wave generation in Scotland, Scottish and Southern Energy renewed contacts with Iceland in November 2009 to review the high level economics on a possible cable link to Scotland (Harmmons, T., et. al., 2010).

Figure 5. Proposed Sites for New Nuclear Power Stations—Eight are under consideration in 2011

Much has progressed in the GB market with new carbon targets and recognition of the need for transmission investment to facilitate development of renewable energy. The 275 kV transmission line from Dounreay in North Scotland to the central belt is currently being up rated from single- to double-circuit. The fast breeder reactor nuclear power plant at Dounreay has recently been decommissioned. The proposed power link from Iceland could be to Peterhead (preferred) or to Dounreay of capacity with one or two cables of 600~1000 MW at 0.7 load factor to supply energy and compensate for the intermittent nature of both wind- and tidal stream power in Scotland. Studies on a possible cable connection from Iceland to Scotland were first undertaken 10~20 years ago (Harmmons, T., et. al., 1989, 1991, 1993). There are no technical reasons why the connection should not go ahead. The economics are now significantly improved. When the earlier investigations were undertaken there was a surplus of generation in Scotland and the connection to England was weak. There will be deficit of generation in Scotland within a decade on account of decommissioning of nuclear and other plant unless alternative generation that includes wind- and tidal-stream power comes on line.

10. Consensus View on Tidal Power in the UK

10.1 Tidal Power

The UK has considerable tidal power resource that could be exploited to produce renewable electricity. Current estimates suggest that the UK total resource is divided roughly equally between tidal range and tidal stream potential, with a combined output equal to around 10% of UK electricity supply. All options for exploiting this resource should be considered by the UK government as a narrow focus on just one project (a Severn barrage) could be detrimental to the development of a whole class of emerging tidal stream technologies, some of which could be sizeable generators of renewable electricity. There is no conflict between the tidal range and tidal stream technologies that could be deployed in the Severn. Tidal stream devises are unlikely to be viable in the Severn Estuary, but there are more appropriate conditions further out in the Bristol Channel where this might be viable. Small-scale tidal lagoon development could take place alongside a tidal barrage. Large-scale tidal lagoon development in the Severn Estuary would not offer any economic or environmental advantage over a barrage.

10.2 Tidal Stream

The long-term potential of tidal stream technologies (Harmmons, T., 2008, 2009), subject to constraints that might be imposed due to location-specific impacts upon the environment, natural marine processes, and long-term costs being acceptable, should be exploited. The UK is in a unique position with superior tidal stream resource combined with devices being developed or tested. Tidal stream technologies could make a substantial contribution to the sustainable energies of the UK. Considering the progress that has been made on tidal stream, the objective now should be to stay the course. In many ways, the tidal stream industry is the same as wind power was 20 years ago, and the timescale for bringing prototype technologies to large-scale deployment needs to be as fast-tracked as possible.

The Scottish Government approved ScottishPower Renewables' (SPR) plans to develop a 10 MW tidal power array in The Sound of Islay on Scotland's west coast in March 2011.

The project envisages generating enough renewable electricity to power the equivalent of the whole island.

It is the first array project to be approved by Marine Scotland, the directorate of Scottish Government responsible for the management of Scotland's seas.

Ten tidal turbines, each capable of producing 1 MW of electricity, are planned. The project will use HS 1000 tidal turbines developed by Hammerfest Strom AS, a company partly owned by Iberdrola (SPR's parent company). The company is currently construction the first HS 1000 devise that will go into waters off Orkney, Scotland, late in 2011.

10.3 Policy Improvements

There are a number of areas where Government policy could be improved. The support and funding structures need to be reviewed and improved in line with circumstances as they develop and change. A flexible approach could be taken on the future of the Department for Business, Enterprise and Regulatory Reform's (BERR) Marine Renewables Deployment Fund (MRDF), which has so far not had any applicants due to delays in getting demonstration projects off the ground. Lessons could be learnt from the success of the Scottish Government's £8 m support package for marine energy technologies, which has had strong interest from both tidal and wave developers. Increased support for marine renewables under a branded Renewables Obligation is also very welcome. This may provide an opportunity to revise the support available under the MRDF so that it focuses on providing grant funding for project development and testing, with the aim of stimulating progress towards initial tidal arrays and pre-commercial schemes.

The European Marine Energy Centre in the Orkney Island is an excellent example of public sector funding being used to stimulate public sector investment and innovation in a strategic and efficient manner. Looking to the future, it is thought that there is potential to exploit the activity entered around the European Marine Energy Centre (EMEC) to develop a regional hub around the Orkney Island and parts of the Caithness coastline, away from the Pentland Firth for commercial testing of devices beyond the prototype stage. In the long-term, lack of transmission capacity would appear to be a serious constraint on development of the UK's tidal stream resource in the north of Scotland. This also impacts on the offshore and onshore wind industry and on wave power devises. There are a number of problems with the current regime for connecting renewable generation and a real absence of long-term thinking on solutions to overcome them. This has serious consequences for the UK's ability to meet its targets for renewable electricity and the more ambitious EU targets that will eventually be implemented.

10.4 Strategic Planning and Consenting

Lack of good baseline information on the marine environment and on effects of large-scale deployment of different devices is a real issue. The gaps have to be filled over time through research of a strategic and generic nature as well as by developers. The Scottish Government is in the process of completing a strategic environmental assessment for marine renewables around the west and north coasts of Scotland, and the Welsh Assembly Government is developing a marine renewable strategy.

10.5 Tidal Lagoons

It is difficult to come to a clear view on the long-term potential of tidal lagoons due mainly to the lack of authoritative evidence and that the concept remains unproven. Government should investigate options to encourage one or more tidal lagoon demonstration projects.

10.6 Tidal Barrages

Extensive information is already available on the Severn Barrage that contains the majority of the UK's tidal range resource, and also for the Mersey. There does not seem to be an extensive overlap between tidal barrages and tidal stream devices, leading to the conclusion that they can, on the whole, be considered separately. The UK's potential for developing different tidal barrage options other than the Severn is extensive, but the reason why this potential has not been developed in the past is that they have not appeared to be economically viable. Further investigation into UK tidal barrage options outside the Severn Estuary should be considered on a case-by-case basis, as potential benefits will differ considerably.

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12. References

Baker, A. C., (1986), The development of functions relating cost and performance of tidal power schemes and their application to small-scale sites. Tidal Power. London: Thomas Telford, 1986.

Baker, A. C., (1991) Tidal Power. United Kingdom: Peter Peregrinus Ltd. 1991.

Banai, M. & Bichon, A. (1982). *Tidal Power in France: The Ranch tidal power station: Some results after 15 years of operation, Energy Digest*, pp. 39-45, October.

Bryden, I. G. et.al. (2003). Assessing the Potential of a Simple Tidal Channel to Deliver Useful Energy, *Applied Ocean Research*, Vol. 26, pp. 198-204.

Grant, A. D. (1981). Power Generation from tidal flows for navigation buoys, 2nd Int. *Symp, Wave and Tidal Energy*. BHRA, Cambridge, September, pp. 117-128.

Gorlov, A. M. (2003). The Helical Turbine and its Application for Tidal and Wave Power. Proceedings IEEE OCEANCS'03, Vol. 4, San Diego (USA), September, pp. 1996.

Hammond, N. W. & Wood, P., (1989), Tidal Power from the Mersey: History and Prospects, in *Developments in Tidal Energy*, Proc. 3rd Conf. Tidal Power, London, UK, November 1989.

Hammons, T. J., (2008). Energy Potential of the Oceans in Europe and North America: Tidal, Wave, Currents, OTEC, and Offshore Wind. *International Journal of Power and Energy Systems*, Paper 203-4142, Vol.28, (4), 2008, pp. 416-428.

Hammons, T. J., (2009), (Ed.). *Book, Renewable Energy, InTech*, ISBN: 978-953-7619-52-7, 580 p.,. Available on Line.

Hammons, T. J., Hreinnsson, E. B. & Kacejko. P., (2010), Proposed Iceland/UK (Peterhead) 1.2 GW HVDC Cable. 45th International Universities Power Engineering Conference Proceedings (UPEC), Paper 386, University of Cardiff, September 2010, pp. 1-9.(available on line at IEEE Xplore)

.Hammons, T. J., Lee, K. O., Chew, K. H. & Chua., T. C., (1998), Competitiveness of Renewable Energy from Iceland via the Proposed Iceland/UK HVDC Submarine Cable Link. *Electric Machines and Power Systems*, Vol. 26, pp. 917-933.

Hammons, T. J., Olsen, A. & Gudnundsson, T.(1989), Feasibility of Iceland/United Kingdom HVDC Submarine Cable Link, *IEEE Transactions on Energy Conversion*, Vol. 4, (3), 1989, pp. 414-424.

Hammons, T. J., Olsen, A., Kacejko, P. & Leung, C. L., (1993), Proposed Iceland/United Kingdom Power Link—An Indepth Analysis of Issues and Returns, *IEEE Transactions on Energy Conversion*, Vol. 8, (3), pp. 566-574

Hammons, T. J., Palmason, G. & Thorhallsson, S.. (1991). Geothermal Electric Power Generation in Iceland for the Proposed Iceland/United Kingdom HVDC Power Link, *IEEE Transactions on Energy Conversion*, Vol. 6, (2), pp. 289-296.

Kiho, S. et. al. (1996). The Power Generation from Tidal Currents by Darrieus Turbine, *Renewable Energy*, Vol. 9, (1-4), pp. 1242-1245.

NGET (2007). GB 7 year Statement. www.nationalgrid.com/uk/electricity/sys/current/

Peel Environmental Ltd (2007). Mersey Tidal Power Study. www.merseytidalpower.co.uk

Sustainable Development Commission (SDC). Paper 2, Reducing CO2 Emissions--Nuclear and the Alternatives. From the SDC Project 'The Role of Nuclear Power in a Low Carbon Economy' {www.sd-commission.org.uk/pages/060306.html}.

Tidal Power from the River Mersey: A feasibility Study—Stage 1 Report. Mersey Barrage Co., 1988