The 'Shoots Barrage': An Indicative Energy Technology Assessment of a Tidal Power Scheme

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Cite as: Hammond, G. P., Jones, C. I., Spevack, R., "The Shoots Barrage": An Indicative Energy Technology Assessment of a Tidal Power Scheme, J. sustain. dev. energy water environ. syst., 2(4), pp 388-407, 2014, DOI: http://dx.doi.org/10.13044/j.sdewes.2014.02.0031

ABSTRACT

Several tidal power schemes have been proposed for the River Severn Estuary between the South West of England and Wales. An indicative technology assessment has been undertaken in order to evaluate the so-called 'Shoots Barrage' over its foreseen lifespan of 120 years in terms of its cradle-to-site, operation and maintenance requirements. It would be located just upriver of the Severn road crossings in the United Kingdom (UK), involve an estimated cost of £3.2 bn to construct, and could potentially generate around 2.7 TWh per year (or a little under 1% of UK electricity demand). This scheme is favoured by environmental groups, because to its more benign environmental impacts compared with the much larger, Cardiff-Weston scheme. The present analysis suggests that the proposed Shoots Barrage would yield relatively attractive 'figures of merit' in terms of its net energy and carbon emissions, although its financial performance is poorer than alternative power generators.

KEYWORDS

Shoots barrage, Tidal power scheme, Energy analysis, Carbon accounting, Financial investment appraisal, Sustainability.

INTRODUCTION

Background

Electricity generation presently contributes approximately 30% of United Kingdom (UK) carbon dioxide (CO_2) emissions [1, 2], the principal 'greenhouse gas' (GHG) having an atmospheric residence time of about 100 years [3]. This share mainly arises from the use of fossil fuelled (coal and natural gas) power stations. Changes in atmospheric concentrations of GHGs affect the energy balance of the global climate system. Human activities have led to quite dramatic increases since 1950 in the 'basket' of GHGs incorporated in the Kyoto Protocol; concentrations have risen from 330 ppm to about 430 ppm currently [4]. The cause of the observed rise in global average near-surface temperatures over the second half of the 20th Century has been a matter of dispute and controversy. But the most recent (2013) scientific assessment by the *Intergovernmental Panel on Climate Change* (IPCC) states that it is 'extremely likely' that humans are the dominant influence on the observed global warming since the mid-20th Century [4]. The British Government has therefore introduced a tough, legally binding target of reducing the nation's CO_2 emissions overall by 80% by 2050 in comparison to a 1990 baseline [5] in their 2008 *Climate Change Act* [6]. Achieving this

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carbon reduction target will require a challenging transition in Britain's systems for producing, delivering and using energy that is not only low carbon, but also secure and affordable; thus resolving the so-called energy policy '*trilemma*' [7].

The River Severn Estuary lies between the South West of England and Wales in the United Kingdom (UK). It experiences the second largest tidal range (~14 m) in the world and, over the years, a large number of private and UK Government studies have looked for ways to harness the tidal power for electricity generation [8]. But the concept of a Severn Barrage has remained at the feasibility stage since the 1920s, due mainly to concerns about economic viability and environmental impact [8, 9]. Nevertheless, with growing concern over anthropogenic climate change and a desire to ensure a secure energy supply as fossil fuels diminish, the UK Government have committed itself to both the carbon reduction target incorporated in its 2008 *Climate Change Act* [6], and to producing at least 15% of its energy from renewable sources by 2020 [10]. A large-scale Severn Barrage tidal power scheme that was operational by 2020 [11] would provide an estimated supply of 4.4% of the total energy demand of the UK [12]. This would be the so-called Cardiff-Weston barrage (Figure 1) that would be constructed between Lavernock Point near the town of Barry (on the south Wales coast) and Brean Down in Somerset (adjacent to Weston-super-Mare). Thus, by exploiting the tidal range in the Severn Estuary, the UK could improve the energy diversity of its supply mix via such a renewable and sustainable source. A tidal power project in the Severn Estuary could therefore make a significant contribution to reducing GHG emissions from the power sector, as well as helping to meet both international and domestic climate change targets [13].

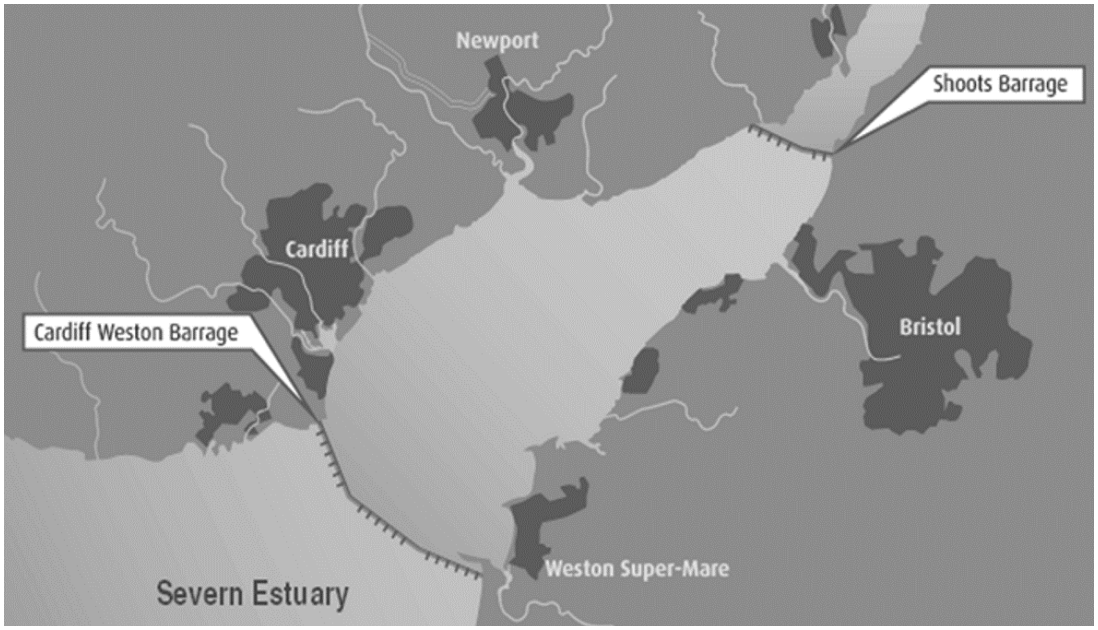

Figure 1. The locations of potential tidal power schemes in the Severn Estuary (Source: Adapted from the UK *Sustainable Development Commission* [12])

The UK Government's *Department of Energy and Climate Change* (DECC) shortlisted a number of tidal power schemes, including tidal barrages, as well as some alternative, embryonic schemes which would take advantage of the tidal stream. The so-called 'Shoots Barrage' scheme is one of several different tidal barrage possibilities for the Severn Estuary. It would be located upriver of the two present Severn road

crossings (see again Figure 1), involve an estimated cost of £3.2 bn (pounds sterling; ISO code: GBP) to construct, and could generate around 2.7 TWh/year (or a little under 1% of current UK electricity demand). The Shoots Barrage is favoured by a number of environmental groups, such as *Friends of the Earth*, due to its lower environmental impact compared, for example, to the much larger Cardiff-Weston scheme.

The issues considered

In October 2010 the new UK Coalition Government announced, following a 2-year cross-government feasibility study of different Severn Estuary tidal barrage and lagoon schemes [13] that it could not see a strategic case for public investment in a Severn tidal power scheme in the immediate term, though private sector groups would continue to investigate the potential. The costs and risks for the British taxpayer and energy consumer were regarded as being too high in the current financial situation, i.e., the post-2008 economic recession. However, it wished to keep the tidal barrage option open for future consideration. The decision not to rule out a scheme in the longer-term recognises its significance as a large-scale UK energy resource. There were half a dozen substantive responses to this announcement from organisations like the *Bristol Port Company*, the *Countryside Council for Wales*, the *Environment Agency*, WWF UK, and the consulting engineers *Parsons Brinckerhoff*. They argued that work should start now in order to:

- Address the significant uncertainties and data gaps;
- Monitor the detailed baseline of distribution of animal species and habitats;
- Study fish behavior and movement in the estuary;
- Assess measures to prevent or reduce possible environmental impacts. The present study of the Shoots Barrage scheme thereby represents a contribution to this ongoing research effort.

An indicative technology assessment has been conducted comprising a detailed investigation into the cradle-to-site, operation and maintenance energy consumption for the Shoots Barrage tidal power scheme (Figure 1). An 'integrated approach' was used (similar to that of, for example, Allen *et al.* [14]) to assess the impact of this scheme, employing both energy analysis and carbon accounting applied on a 'whole systems' basis from 'cradle-to-grave', alongside related financial investment appraisal. Energy analysis (EA) required estimates of the energy outputs of the power generators during use, and the energy requirements for their construction and operation. The total energy output of the scheme over its foreseen lifespan of 120 years was estimated in order to determine the associated energy gain ratios (EGR) and energy payback periods (EPP). But carbon footprints have become the 'currency' of debate in a climate-constrained world. They represent the amount of carbon (or carbon dioxide equivalent [CO_{2e}]) emissions associated with a given activity or community, and are generally presented in terms of units of mass or weight (kilograms per functional unit [e.g., kg CO_{2e}/kWh]). Embodied energy and carbon appropriate to the various power generators specified in the current work were determined using the '*Inventory of Carbon and Energy*' (ICE) [developed at the University of Bath (Hammond and Jones [15, 16])]. 'Embodied energy' is here defined as the total primary energy consumed from direct and indirect processes associated with power production and within the boundary of 'cradle-to-gate' [16]. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the power plant is constructed for operational use. Similarly, 'embodied carbon' is the sum of fuel-related carbon emissions (i.e., embodied energy which is combusted, but not the feedstock energy which is retained within materials) and process-related carbon emissions [16].

The present contribution is part of an ongoing research effort aimed at evaluating and optimising the performance of alternative sustainable, centralised and distributed energy systems for the UK [14, 17-19] in the context of transition pathways to a low carbon future for the UK [7, 20]. Here the 'Shoots Barrage' tidal power scheme has been evaluated using various appraisal techniques to determine its net energy output, carbon footprint, and financial investment issues. This study is 'indicative' in the sense of being a simplified evaluation and illustration of the performance of this tidal power scheme in the light of imperfect information. Thus, the uncertainties involved are quite large, because of the rough estimates available at the concept design stage of the proposal.

THE SHOOTS BARRAGE

Overview of the scheme

The Shoots scheme is a proposed 1.05 GW barrage located upriver of the Second Severn Crossing (Figure 1); its position would coincide with the highest tidal range in the Severn. The site was first investigated by the first Severn Barrage Committee (1925-33) under Lord Brabazon at which time it was referred to as 'The English Stones Scheme'. The *Severn Tidal Power Group* (STPG) in 1986 [21] studied this barrage in detail alongside the Cardiff-Weston barrage. They raised concerns regarding the rate at which sediment could build up in the basin. The latest proposed Shoots Barrage scheme is outlined in Table 1 as more recently examined by the UK Government's independent *Sustainable Development Commission* (SDC) [12]; established by the then Labour Government in 2000 (although the subsequent Coalition Government withdrew funding after coming to power in 2010, and the SDC had to close in March 2011). This barrage scheme is potentially able to generate some 2.75 TWh per year using 'Straflo', or rim generator, turbines [8] operating via solely ebb generation (see the schematic representation in Figure 2). Thus, the incoming flow is allowed to pass through the barrage sluice gates, where the water is trapped behind the barrage at high-tide by closing the sluice gates [8]. The head of water then drives water back through the turbines on the outgoing or 'ebb' tide in order to generate power. A single navigation lock was included in the proposed SDC scheme [12] which is able to handle ships up to 25,000 deadweight tonnes (dwt), allowing the English port upstream of this proposal at Sharpness in Gloucestershire to remain fully functional. Sharpness handles approximately 400 vessels per year. The Shoots Barrage scheme, which was analysed by the consulting engineers Parsons Brinckerhoff, abates the concerns of the STPG report [21] relating to the rate of silting in the basin through the use of high-level sluice gates [12]. These gates would close the turbine during the flooding of the basin and exclude the lower part of the flow, which is more sediment rich. It should be noted, however, that Parsons Brinckerhoff recommended that further analysis should take place at the next design phase to corroborate their findings**.**

Table 1. Outline of the proposed shoots tidal barrage scheme
(Source: The UK *Sustainable Development Commission* [12])

Length of embankments	4.1 km
Generating capacity	1.05 GW (1,050 MW)
Annual average electricity output	2.75 TWh
Number of turbines	30
Number of sluice openings	42
Ship lock size	225 m × 37.5 m

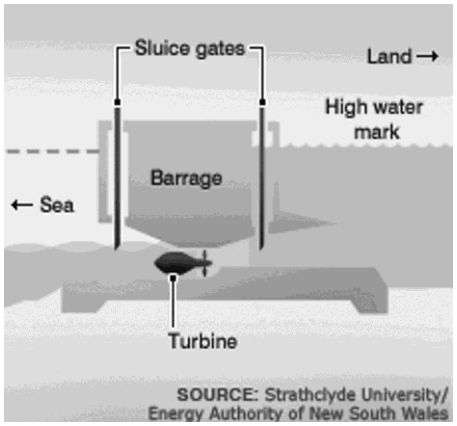

Figure 2. The 'Shoots Barrage': based on ebb generation using 'straflo' turbines

Construction methods and costs

The construction method for the Shoots Barrage scheme involved the towing of caissons out to site and then they were sunk into place. Similarly, the navigation lock would consist of a single steel caisson, which would be fully fitted out before being placed onsite [12]. This site was assumed able to provide better foundations for the barrage than the Cardiff-Weston site, due to inter-tidal rock outcrops. These enable rather simpler construction arrangements. Parsons Brinckerhoff/Black & Veatch [11] estimated the need for a 4 year design and planning phase, followed by a construction period of 5 years (2014-2019). The operation and maintenance phase of the barrage would then last over the period 2019-2140, when decommissioning would commence. The Parsons Brinckerhoff/Black & Veatch options analysis report for DECC [11] assumed a constant annual expenditure for the pre-construction period, as well as a constant expenditure during the construction period. A more realistic breakdown of the latter expenditure was adopted for the present study based on the profile given in the 1986 STPG report [21]. No inclusion of the cost for public road construction or of a rail link was included in either the DECC-sponsored report [11] or in this present study.

Maintenance, operation, and decommissioning

The methods used to calculate the maintenance and operational costs vary within earlier studies. That by Parsons Brinckerhoff/Black & Veatch for DECC [11] presents a 'worst case' having 70% of the present value for the supply, installation and commissioning costs of mechanical and electrical equipment being incurred every 40 years. The cost of the turbine generators was estimated at £5,841 mln [11]; equivalent to £817 mln per annum over the 5 year maintenance period. In order to estimate the corresponding energy requirements and carbon emissions during the maintenance period; 70% of the total emissions for the mechanical and electrical (M&E) equipment was, therefore, adopted. DECC took a value of 1.75% of the total construction cost as the annual maintenance cost of the project (equal to £314 mln). This figure was assumed to remain constant even when the barrage is running at only 25% total output during the maintenance years. The costs associated with the decommissioning of the barrage have been excluded from this study – a practice that is in-line with all earlier studies [11-13, 21]. The decision to disregard this, potentially significant, item is due to the long design life of the barrage of 120 years. Over the past 120 years attitudes to decommissioning and recycling have changed significantly, as have decommissioning/recycling methods, and it is therefore not possible to predict how future generations would dispose of a tidal barrage.

ENERGY ANALYSIS

Methodology

In order to determine the primary energy inputs needed to produce a given artefact or service, it is necessary to trace the flow of energy through the relevant industrial sector [14, 15, 17, 19, 20, 22]. This is based on the *First Law of Thermodynamics* (the principle of conservation of energy) or the notion of an energy balance applied to the system. The system boundary should strictly encompass the energy resource in the ground [23-25] (known as the 'cradle' - for example, oil in the well or coal at the mine). In the present analysis the downstream boundary is known as the 'site' (hence, 'cradle-to-site' [16, 20]), or national electricity network (operated by the 'transmission network operators' [TNOs] and 'distribution network operators' [DNOs]). Consequently, it effectively accounts for all UK power sector primary energy use (and associated emissions). Energy analysis yields the whole-life or '*Gross Energy Requirement*' (GER) of the product or service system [15, 23-25]. Thus, the sum of all the outputs from this system multiplied by their individual energy requirements must be equal to the sum of inputs multiplied by their individual requirements. The process consequently implies the identification of feedback loops, such as the indirect or 'embodied' energy requirements for materials and capital inputs. Several differing methods of EA have been developed (see Figure 3), the most significant being statistical analysis, Input-Output (I-O) analysis, process analysis (or energy 'flow charting'), and hybrid analysis [15, 23-25].

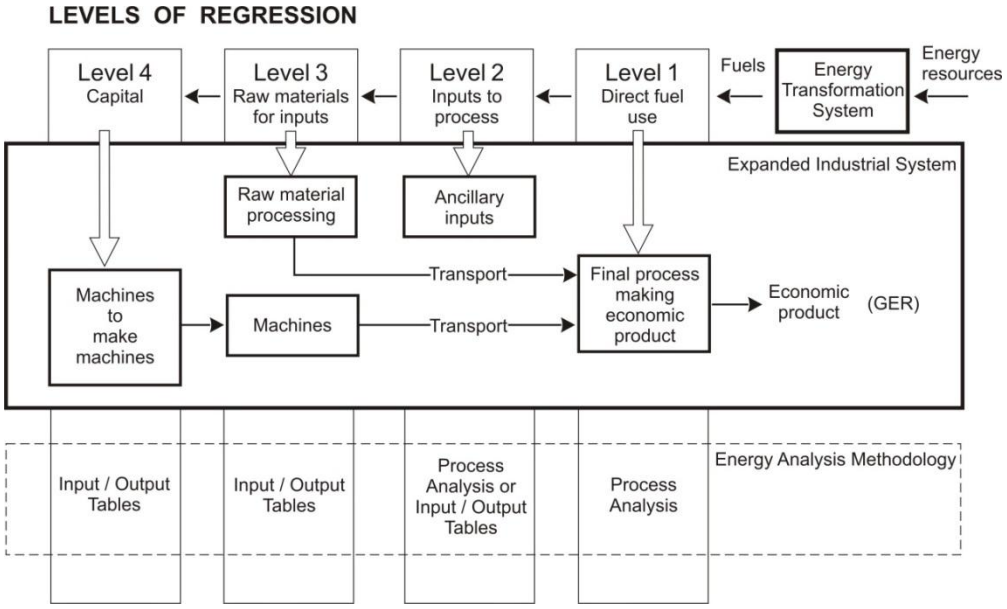

Figure 3. Schematic representation of the energy analysis process
(Source: Allen *et al.* [14]; adapted from Slesser [25])

Application of energy analysis to the shoots barrage

Energy analysis, as indicated above, is an established method of tracing the flow of energy through a system [14, 15, 17, 19, 20, 22-25], and can be readily applied to large-scale civil engineering projects. The present analysis has been conducted in order to assess and compare the envisaged energy benefits of the proposed Shoots Barrage scheme as a more benign option for the generation of electricity than those from fossil fuels. The methods used to carry out an EA mainly stem from studies completed in the 1970s (e.g., [23-25]). They can account for, and hence suggest ways to reduce, the energy

consumed and expended over the lifetime of the system under consideration. This includes the embodied energy of the raw materials, transportation, construction, maintenance, operation, and decommission. The stages investigated in process energy analysis employed here are illustrated in Figure 4. It can be seen that there was limited data available some processes, and where simplifying assumptions needed to be made. Other processes had to be excluded from the study because of the unavailability of suitable data. These generally had an insignificant impact on the life-cycle energy requirements of the barrage.

Component fabrication, which has been excluded from the present study, refers specifically to the fabrication of items such as the turbine generators and the caissons. No accurate data was available to account for the direct energy required to manufacture the turbines. However, the raw materials required in the manufacture of the turbine (which accounts for the bulk of the energy requirements), and the transportation from the manufacturer to the barrage site were estimated. Likewise, no data exists for the energy required to fabricate items such as the ship locks and caissons, and this was again excluded from the energy analysis.

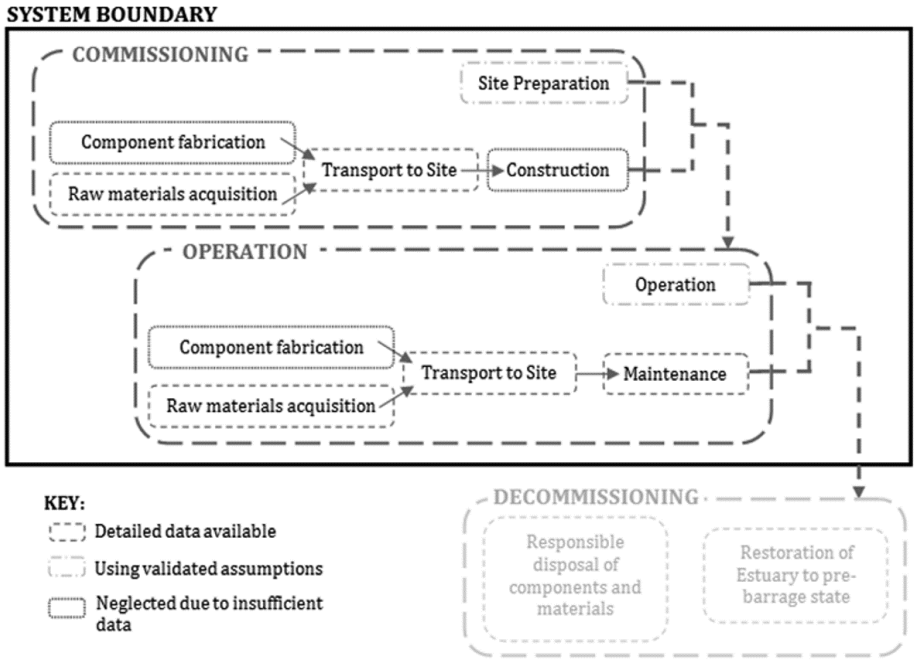

Figure 4. System boundary for tidal power energy analysis and carbon accounting

Calculation of the Energy Gain Ratio (EGR)

The energy gain ratio (EGR) divides the useful energy produced by the barrage over its lifespan by the total energy consumed from cradle-to-grave [25]. The net energy produced is the total net electricity generation - converted from Watt-hours to Joules for consistency [26]:

$$\text{Energy Gain Ratio} = \frac{E_{\text{n,L}}}{E_{\text{mat,L}} + E_{\text{con,L}} + E_{\text{op,L}} + E_{\text{dec,L}}} \quad (1)$$

where $E_{\text{n,L}}$ is the net energy produced over the lifetime (L) of the barrage; $E_{\text{mat,L}}$ is the total energy invested in materials; $E_{\text{con,L}}$ is the total energy invested in construction; $E_{\text{op,L}}$ is the energy required to operate the plant over its lifetime, and $E_{\text{dec,L}}$ is the energy required to

decommission the barrage at the end of its life. The energy required to decommission the barrage (the 'grave') is outside of the system boundary for this energy analysis (see again Figure 4 above). This is in-line with all earlier studies of the Severn Barrage schemes [11-13, 27]. It has only been possible to partially examine the energy required to construct the Shoots Barrage, because of the rough estimates available at the pre-detailed design stage of the proposal.

Calculation of the Energy Payback Period (EPP)

The energy payback period (EPP) represents the period (the number of years) that a renewable energy (RE) device must operate before it has captured and delivered as much primary energy as has been used to construct the RE technology [24, 25]. The values calculated here were obtained on the basis of a 'static' energy analysis approach [25]. The number of years at which the electricity generated by the barrage equals the primary energy invested in the barrage is the EPP.

The opportunity cost convention

In the discipline of economics the notion of 'opportunity cost' relates the financial opportunity or return that is foregone when an investment is made in one project (the opportunity) in contrast to an alternative [24]. Thus, the equivalent convention in EA concerns the energy foregone in order to provide energy via another conversion process. In the power sector, fossil fuels (thermal or primary energy) are typically invested in constructing conventional plants rather than in low carbon alternatives, such as nuclear power or various renewable energy technologies. In the tidal power case, the opportunity cost (or 'opportunity energy requirement') will therefore represent the primary energy foregone during the construction of a barrage that is required to generate electricity over its lifetime [24, 25]. In order to calculate the opportunity cost (OC) in the present study, the weighted average efficiency of the electricity sector (η) was taken as 38.5% (see, for example, Hammond [3]). The OC equivalent of the standard EGR and EPP above is then obtained by:

- Dividing the former by η;
- By multiplying the latter by η and adding the initial construction period (in years).

Assumptions and approximations

Construction materials: Gate-to-site. The cradle-to-site energy requirements include the raw material extraction, processing and transportation to the construction site [15]. These reflect the 'embodied energy' associated with these activities, i.e., the total primary energy consumed from direct and indirect processes associated with power production and within the defined cradle-to-site boundary as indicated in Figure 4 above [16]. In the present analysis, the transportation was examined separately on such a basis. Thus, information relating to the quantity of each raw material required in construction was taken from a 2007 report compiled by Black & Veatch (a global engineering, consulting, and construction company) for the SDC [12]. The University of Bath's ICE database (v2.0) [15, 16] was then used to determine the embodied energy relating to the raw materials. This database provides a range of embodied energy figures associated with material component, along with an indicated of the prevailing scatter in the data. Woollcombe-Adams *et al.* [26] estimated the carbon emissions for the Cardiff-Weston Severn Barrage tidal barrage scheme. They assumed distances that raw materials would have to be transported and, combined with the mass of the material, determined the total

carbon emissions. However, the basis for these assumptions is unclear. Therefore, in order to determine transport distances for the present study, suitable quarries or manufacturers in closest proximity to the barrage site were identified. Having located these sources and the quantities of raw materials required, the primary energy consumption was calculated using data taken from a 2008 report by the *Institut fur Energie und Umweltforschung* (IFEU) [28]. The IFEU report provides coefficients relating the primary energy consumption of various modes of transport to the weight of the material transported and the distance travelled.

Construction. Little information is available relating to the exact work requirements to construct the barrage. A decision was therefore made to neglect the construction of components, such as the turbine generator and caissons, in this study. This amounts to an EA terminated at Level 3 Regression as indicated in Figure 3. However, data for other items (such as dredging and the towing energy) was accounted for here. Roberts [29] provides information on caisson building for various large tidal barrages. It has been assumed for the current purposes that each casting yard consumed 1.75×10^6 GJ during construction.

Dredging. In order to calculate the energy consumed by dredging, the estimates used by Roberts [29] were again adopted to determine the energy required to extract this material from a quarry. This value has been verified by comparison with the data in the ICE database (v2.0) [16]. In the case of the Shoots barrage, the embodied energy is significantly lower using the dredging figure given by Roberts [29] than that in the ICE database [15]. It is believed that this is due to the difference in the geology type at the two sites considered by Roberts and the Shoots site. Owing to the far smaller initial investment energy of the Shoots scheme, and the lower energy delivered following commissioning, the value used had a significant impact on the final energy gain ratio and energy payback periods. It was therefore decided that the value derived using the ICE data (v2.0) [16] related to a rock-based foundations was most appropriate to the Shoots scheme.

Towing energy. Roberts [29] assumes what he termed ‘towing out’ energy gave rise to energy consumption of 54×10^6 MJ/caisson. This figure has been compared to the energy consumed to transport each caisson a distance of 100 km; to represent an approximate distance between a barrage and fabrication yard. Here the *EcoTransIt* database [28] was used to estimate towing for the purposes of energy analysis. In the case of the Shoots Barrage, it is presently uncertain as to where the caissons would actually be constructed. Only the float-out weights of the Cardiff-Weston caissons are presently known, each at 126,000 tonnes [12] for the heaviest of the caissons. All caissons have been assumed to be of the same mass for the Cardiff-Weston and Shoots barrages; thereby representing a worst case. This suggests that the towing energy had a value of 9.1×10^6 MJ/caisson. Thus, the data provided by Roberts [29] above appears to be pessimistic. To account for the towing energy required to install the ship locks, the segments of the locks were approximated to the same float out weight as the caissons. The Shoots scheme is presumed to be composed of just one segment for its ship lock.

Operation and maintenance allowances. Roberts [29] adopted a value for the energy intensity equivalent to 5.28 MJ/£ (2010) to account for the annual operational cost of the barrage. This represents about 1.75% of the total capital cost, in accordance with data more recently provided by the DECC [11] for options analysis of the development of

tidal power in the Severn Estuary. A similar share of the total embodied energy from construction per year of operation was adopted for the present energy analysis. Maintenance was assumed to be required every 40 years, and hence there would be two 2-year maintenance periods for the Shoots scheme over its total envisaged lifespan of 120 years. An assumption was made that 70% of embodied energy related to the manufacture of turbines, their transport and installation (in line with the financial analyses published by the DECC [11], where they made an allowance of 70% for the mechanical and electrical [M&E] equipment costs). This resulted in 2×10^6 GJ over a 120 year lifespan for the Shoots barrage.

CARBON ACCOUNTING

Methodology

It is widely recognised that in order to evaluate the environmental consequences of a product or activity the impact resulting from each stage of its life-cycle must be considered [22]. This has led to the development of a range of analytical techniques that now come under the 'umbrella' of environmental life-cycle assessment (LCA). One of the antecedents of this approach was energy analysis of the type described above. In a full LCA study, the energy and materials used, and pollutants or wastes released into the environment as a consequence of a product or activity are quantified over the whole life-cycle; 'from cradle-to-grave' [30, 31]. The methodology of LCA follows closely that developed for energy analysis [14, 20, 22, 25], but evaluates all the environmental burdens associated with a product or process over its whole life-cycle. This requires the determination of a balance or budget for the raw materials and pollutant emissions (outputs) emanating from the system. Energy is treated concurrently, thereby obviating the need for a separate EA [22]. LCA is often geographically diverse; that is, the material inputs to a product may be drawn from any continent or geo-political region of the world [15]. But, as previously argued, carbon footprints have become the 'currency' of debate in a climate-constrained world. Consequently, the emphasis in the present study was on CO_2 emissions, rather than the wider set of environmental burdens [14, 17, 19, 20, 27]. An emissions coefficient (in gCO_2/kWh_e) for the Shoots barrage scheme was calculated using as expression derived by White and Kulcinski [26]:

$$\frac{\mathrm{kg} \times \mathrm{CO_2}}{\mathrm{kWh}} = \frac{\sum_{\mathrm{i}} \left(\frac{\mathrm{kg} \times \mathrm{CO_2}}{\mathrm{kg} \times M_{\mathrm{i}}} \right) \times \mathrm{kg}M_i}{E_{\mathrm{n,L}}} \tag{2}$$

where $E_{\mathrm{n,L}}$ is the net electrical energy produced over the lifetime of the barrage, L; $kgCO_2$. M_{i} is the kg of CO_2 emitted per kg of material i produce; kgM_{i} is the quantity of material i needed to constructed and/or operate the barrage. The same methods used to calculate the embodied energy [15] and other primary energy requirements have been applied to the carbon analysis.

Assumptions and approximations

In order to calculate the cradle-to-site CO_2 emissions a similar approach was taken to that employed for the energy analysis described above (see Figure 4). The University of Bath's ICE database (v2.0) [16]; was again used to determine the cradle-to-gate CO_2 emissions associated with raw materials employed found for the EA. The gate-to-site emissions were then calculated per tonne of material per km travelled. However, the energy consumed to construct the Shoots Barrage has been neglected due to a lack of

available data. No specific data exists relating to the carbon emissions generated during dredging. The emissions released to quarry the materials were therefore extracted again from the ICE database [15]. This approach provided comparable results to that employed in the EA. Carbon emissions during towing out have been ignored due again to insufficient data being available. The method used for the energy analysis (employing the EcoTransIt database [28]) did not adequately represent the 'towing out' energy for the caissons, and hence cannot reliably be used to estimate carbon emissions. The carbon emissions generated during the annual operation of the Shoots Barrage, as well as the maintenance periods every 40 years, were estimated by adopting the same approximations as described for the EA above. Maintenance has been equated to 70% of the total M&E equipment carbon emissions, producing 0.13×106 tonnes CO_2 for the barrage. Annual operational carbon emissions have been taken as 1.75% of the total emissions released during construction; this converts to 1.77×106 tonnes CO_2 for the Shoots scheme based on a 120 year lifespan. But CO_2 emissions released during the projected decommissioning phase were again not been accounted for.

FINANCIAL INVESTMENT APPRAISAL

Methodology

Background. Economic appraisal evaluates the costs and benefits of any project, programme, or technology in terms of outlays and receipts accrued by a private entity (household, firm, etc.) as measured through market prices [32]. Financial appraisal is used by the private sector and omits so-called environmental 'externalities'. In contrast, *economic cost-benefit analysis* (CBA) is applied to take a society-wide perspective, with a whole systems view of the costs and benefits [14, 22]. It accounts for private and social, direct and indirect, tangible and intangible elements; regardless as to which they accrue and whether or not they are accounted for in purely financial terms [32]. Allen *et al*. [14] applied both financial appraisal and CBA to evaluate a number of micro-generators, whereas Hammond *et al*. [19] more recently used them to evaluate a building-integrated solar photovoltaic (PV) array. A further distinction between *financial appraisal* and *CBA* is in the use of the discount rate to value benefits and costs occurring in the future [14, 19, 22]. Financial appraisal uses the market rate of interest (net of inflation) as a lower bound, and therefore indicates the real return that would be earned on a private sector investment.

Capital expenditure and the breakdown of annual costs. The capital expenditure associated with a Severn Estuary tidal barrage project was taken from a 2008 study sponsored by DECC [11]. The report on this study provides detailed cost estimates for the Cardiff-Weston scheme in terms of construction, electricity generation, and operational costs. Scaled figures were applied in the present work to the Shoots scheme. The STPG [21] report described in detail a capital cost breakdown over 6 year pre-construction period. This was compressed to fit the construction period of 5 year period envisaged by DECC [11]. The maintenance costs were again approximated at 70% of the M&E generating plant every 40 years, with a maintenance period of 2 years for the Shoots barrage. The annual operation cost of the barrage was taken as 1.75% of the total construction cost for the scheme. This is in line with the estimates made by DECC [11], although they state that in the case of the Cardiff-Weston barrage they estimated an annual cost of just 1.25%. The cost of decommissioning the Shoots barrage has again not been accounted for in the present study.

Compensatory habitat. An additional allowance for compensatory habitat has only been included in the most recent studies. For the Shoots scheme, depending on how the total scheme would be funded, there is a potential for this to be provided by the private sector. The impact of the Shoots on the Severn Estuary (see Figure 1 above) is much less significant than for the larger Cardiff-Weston scheme, and therefore the best financial case assumed no compensatory habitat was required. These compensatory habitat costs for the Shoots barrage ranged from £0.32 bn to £0.96 bn.

Discounted cash flow. The *Levelised Unit Electricity Cost* (LUEC) is typically employed to compare the economic performance of different power generators. This is the price at which electricity must be sold in order to recover all costs incurred during generation. The net present value (NPV) of the sum of the capital cost, maintenance and operational costs and, potentially, decommissioning is calculated over the life of the project, along with the NPV of the total electricity generated. This yields the LUEC in *pence per kilo-watt hour* (p/kWh$_e$) for the Shoots barrage, which can then be compared to that for alternative power generators. Consequently, by using this method, different energy options with a variety of lifespans, capital costs, and efficiencies can effectively be compared so that the most cost-effective option can be determined. The discounted cash flow over the life of each project (here assumed to be 120 years) is calculated as follows:

$$\text{Discounted Cash Flow} = \sum_{t=1}^{t=120} \frac{R_t}{(1+\text{TDR})^t} \tag{3}$$

where R_t is the net receipts (income less cost); t is the time in years for the total foreseen life of the project, and r is the discount rate. In the case of public sector investments a so-called *Test Discount Rate* (TDR) is utilised. It is typically derived from a comparison with private sector discount rates (or *Weighted Average Cost of Capital* [WACC]). In the UK, HM Treasury [33] recommends that the TDR for projects with durations of less than 30 years should be taken as 3.5%, then falling in line with the profile indicated in Table 2 below.

Table 2. The declining long-term UK test discount rate [33]

Period of years	0-30	31-75	76-125
Discount rate	3.5%	3.0%	2.5%

The results obtained by DECC [11] do not use these TDR values, as they believe that it would not satisfactorily manage all of the risks associated such a project, and will only represent the case of the scheme being entirely funded through the public sector [5]. The LUEC values presented by the DECC [11] employed a discount rate of 8%, which they regard as reflecting the WACC that would enable the project to be financed by the private sector.

RESULTS AND DISCUSSION

Energy analysis

Cradle-to-site analysis. Embodied energy associated with the material requirements for the Shoots Barrage were obtained from the ICE database [15, 16]. The highest

contributor in terms of the energy requirements for the barrage was rock (Figure 5), with 97% of this being due to the energy consumed during transportation between the quarry and the barrage site. The assumption made in the gate-to-site analysis was that rock was shipped from the *Glensanda* super quarry in Scotland. The *Severn Barrage Steering Committee* identified this quarry as an alternative option, if it was not possible to source the rock locally in Wales. When investigating items such as crushed aggregate in this study it was found that shipping items from this Scottish quarry was more energy efficient owing to the poor freight train connections in Wales, along with the high energy requirement for moving freight by road. *Glensanda* has its own shipping port, and hence no movement of goods by road occurs.

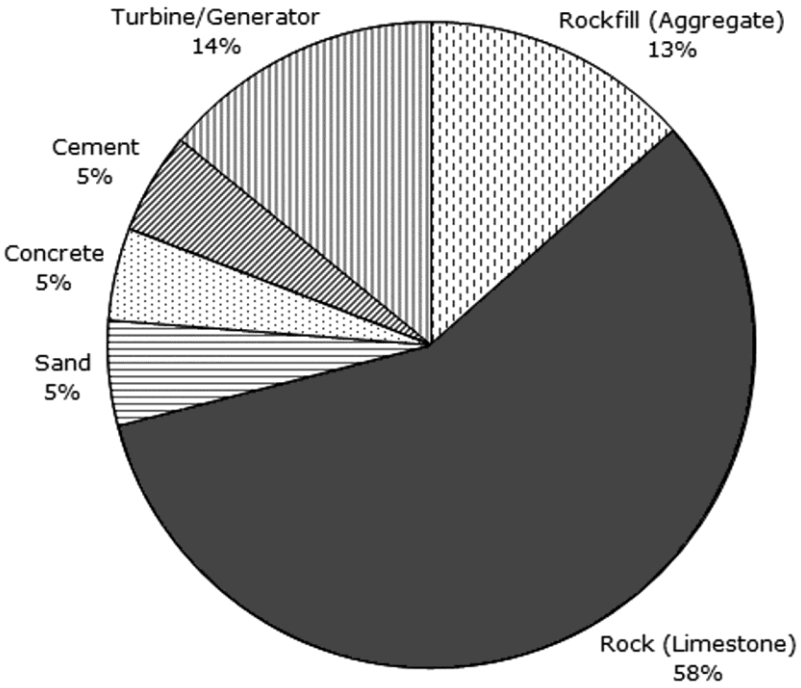

Figure 5. Cradle-to-site energy analysis: Shoots barrage material inputs

Total energy requirements. Energy requirements for commissioning and operation of the Shoots Barrage were analysed. The major element of the total energy consumed was found to arise due to operational energy requirements for the barrage. This suggests that the assumptions made about the commissioning of the scheme have a relatively minor influence on the overall energy requirements. The energy required to fabricate the individual components and the barrage itself was therefore neglected in the present study.

Energy Gain Ratio (EGR). Table 3 displays the EGR calculated using assumptions outlined above. The final energy gain ratios have been put into context by comparing them to other electricity generation plants. It has been possible to recalculate the EGRs for conventional nuclear and coal power plants so that they do not include plant construction or decommissioning energy requirements. These figures can then be more easily compared to the present ones (in Table 3). The EGR for the Shoots Barrage scheme is approximately double that of the coal plant investigated by White *et al*. [26]. The Shoots Barrage gives rise to a slightly better EGR than nuclear (fission) power stations. The EGR for wind, despite taking into account the energy consumed during construction and decommissioning, is higher than those of the Shoots Barrage. An average value has

been taken for the results of the above cradle-to-site analysis, and the EGRs were calculated at three different possible lifespans - from a full lifespan of 120 years down to 40 years [which is slightly less than the 44 year lifespan of the La Rance barrage (located on the estuary of the Rance River in Brittany, France); the longest proven lifespan for this technology to date]. The Shoots Barrage EGR fell to 19.44 for an 80 year life, and 14.00 for one of 40 years.

Table 3. Estimated 'Energy Gain Ratios' (EGRs) for Alternative Power Generators

Scheme	EGR	Lifespan [years]
Shoots tidal barrage	22.31	120
Coal-fired power plant	10.8 (10.8*)	40
Nuclear power station	17.8 (16.4*)	40
Wind turbine (without storage)	(23*)	25

NB: Data for alternative power generators taken from White and Kulcinski [26]. Numbers with an asterisk (*) indicates EGRs with the inclusion of plant construction and decommissioning.

The opportunity cost convention. This convention was been applied to the EGR estimated for a 120 year (default) lifespan. It then rose to be between 22.31:1 and 57.9:1. In terms of energy, this obviously makes the Shoots Barrage scheme a highly attractive power generation option on a like-for-like basis.

Energy Payback Period (EPP). The EPP indicates the time taken, in months following first operation, for the amount of energy generated by the Shoots Barrage to equal the energy consumed during commissioning and operation up to that moment in time. It should again be noted that not all of the energy consumed during this phase could be accounted for in this study, and hence it should be assumed that the current figures are optimistic. The EPP for the Shoots scheme is 50 months from first commissioning; assuming just a 50% power generation capacity in year one. Taking a construction period of 5 years, this equates to a total energy payback of 9.16 years. This is slightly longer than that of the much larger Cardiff-Weston scheme, but this difference is not significant over a lifespan of 120 years. By applying 'opportunity cost' convention, the EPP for the Shoots barrage was only 6.60 years, which indicates a strong case (in energy terms) for the implementation of such a scheme.

Carbon accounting

Cradle-to-site emissions. Two earlier cradle-to-gate studies of the carbon emissions have previously been completed by the SDC [12] and by Woollcombe-Adams *et al.* [27]; the data obtained during the present study was compared to these two previous sources. These employed an embodied energy value for rock that was slightly higher than that adopted here, but the material type was confirmed by a member of the *Severn Barrage Steering Committee*. The carbon coefficient for extracting the material from the quarry is taken in the present study from a more recent version from the ICE database (v2.0) [16]. Data from previous studies slightly underestimate the GHG emissions from that raw material. The extraction of the required quantities of cement produces the greatest quantity of carbon emissions. Only the SDC study [12] - undertaken for them by Black & Veatch - has published detailed results, and these do not compare well with those from present study (Figure 6). Variances are likely to be mainly due to different assumptions

about the material content of the barrage, and to a lesser extent to the fact that Black & Veatch used an older version of the ICE database (v1.5).

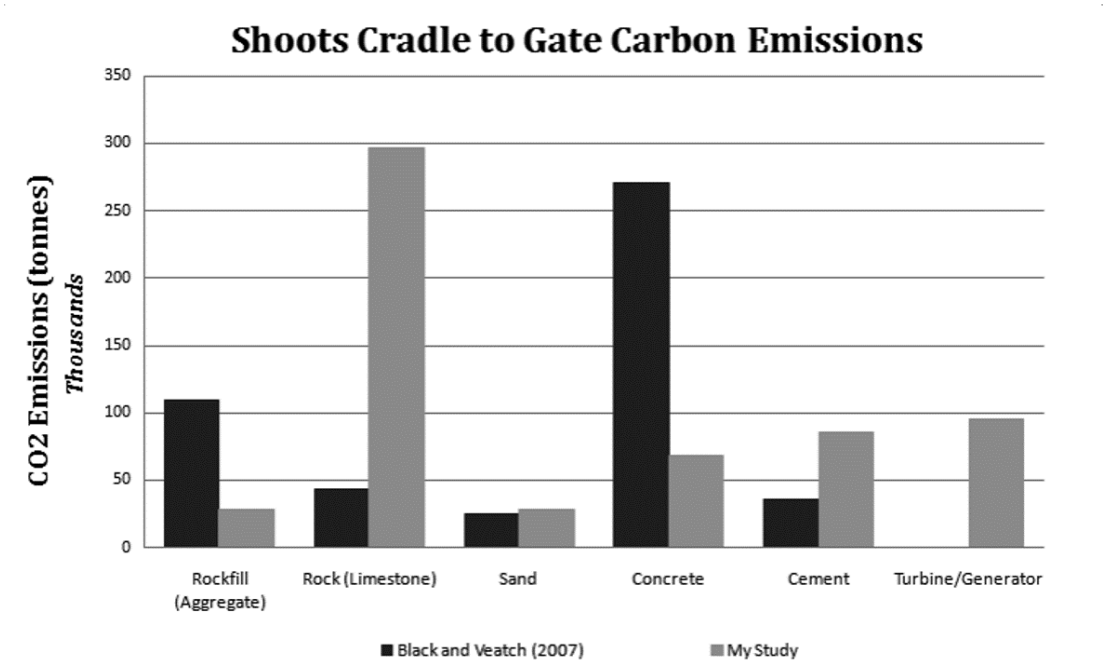

Figure 6. Shoots barrage: Cradle-to-gate carbon emissions
(Sources: Black & Veatch for the UK *Sustainable Development Commission* [12]; 'My Study' represents the present work)

Total carbon emissions. The highest carbon emissions occur during the operational phase of the Shoots Barrage (around two thirds), as in the case of the energy requirements calculated above. The assumption of 1.75% of the total emissions during construction has been taken from the financial model first made by the DECC (11). It is far higher than in earlier report by the STPG (21). However, the proportion of 'on-site' carbon emissions is smaller than that found in the energy analysis above. This was in part due to items, such as towing energy requirements, being ignored in the present analysis. The total carbon emissions over the assumed 120 lifespan were some 2.75 $MtCO_2$.

Carbon dioxide emissions per unit of electricity. Estimates of the carbon dioxide emissions per unit of electricity generated (in gCO_2/kWh_e) were made assuming a lifespan of 120 years. The range of CO_2 emissions was calculated by applying the range of data obtained at the cradle-to-gate phase. The overall results show that the Shoots Barrage scheme would emit about 8.0 gCO_2/kWh_e. That is attractive in terms of a low level of carbon emissions. But it should be noted that not all of the sources of emissions could be accounted here, and the actual results would consequently be slightly higher in reality.

Financial investment appraisal

Baseline LUEC. This analysis provides a baseline cost for the Shoots Barrage of 10.83 p/kWh_e (derived for a 120 year lifespan, using the STPG cost breakdown): see Figure 7. The results obtained using the DECC [11] investment appraisal approach with constant capital expenditure over the pre-construction and construction periods are

slightly higher than those using the more detailed breakdown derived from the STPG [21], although this does not represent a significant difference. The ultimate Levelised Unit Electricity Cost (LUEC) variation over a 120 year lifespan using the declining TDR (see Table 2; advocated by HM Treasury) produced a value of 4.72 p/kWh$_e$ for the STPG breakdown and 4.67 p/kWh$_e$ for that from the DECC study. When applying a TDR of 8%, this range rose to 10.83 p/kWh$_e$ for the STPG method (the baseline case as indicated above) and 10.42 p/kWh$_e$ from the DECC study. Differences in the LUEC determined by using a more detailed cost breakdown by the STPG [21] in comparison with than the constant expenditure model of DECC [11] produced a difference of only 0.41 p/kWh at a discount rate of 8% over a 120 year lifespan. The SDC-sponsored study [12] by Black & Veatch indicated LUEC values for the Shoots tidal barrage of 3.29 p/kWh$_e$ (with a range of 2.96-3.62 p/kWh$_e$) for a social discount rate of 3.5% or 6.8 p/kWh$_e$ (with a range of 6.08-7.52 p/kWh$_e$) for an investor discount rate of 8%.

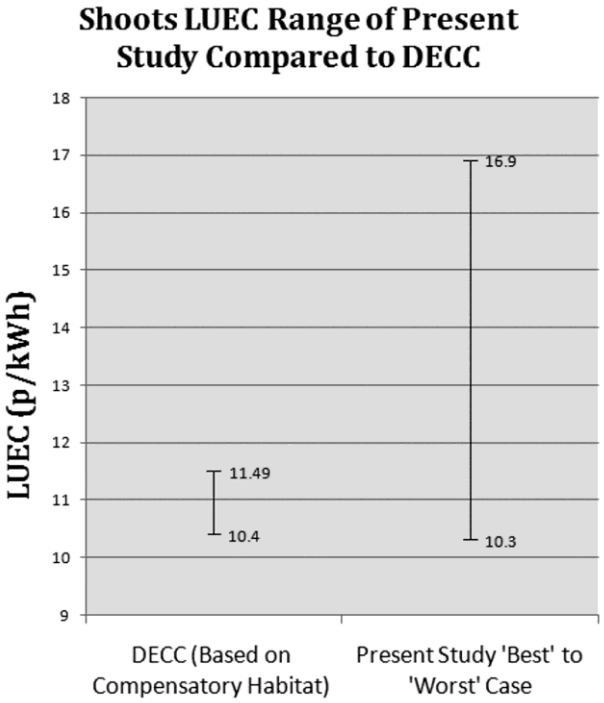

Figure 7. Shoots barrage: Comparison of the 'best' to 'worst' case ranges of LUEC studied here to that of DECC [11]

CONCLUSIONS

Several tidal power schemes have been proposed for the River Severn Estuary between the South West of England and Wales. Here the so-called Shoots Barrage scheme has been evaluated (see Figures 1 and 2) using various appraisal techniques to determine its net energy output, carbon footprint, and financial investment issues. It would located near the Severn road crossings in the United Kingdom (UK), involve an estimated to cost £3.2 bn to construct, and could generate around 2.7 TWh/yr [or just about 0.7% of UK electricity supply]. An energy analysis was conducted comprising a detailed investigation into the cradle-to-site, operation and maintenance energy consumption for the two schemes. The total energy output of the scheme over its foreseen lifespan of 120 years was calculated in order to determine the associated *energy gain ratios* (EGR) and *energy payback periods* (EPP). The former was found to vary from

19.2:1 to 23.8:1 (see Table 3), whilst the latter was estimated to be about 9.16 years. On an 'opportunity cost' basis the EGR rose to be between 22.3:1 and 57.9:1 with an EPP of about 6.6 years. Overall, the present analysis suggests that the Shoots scheme has relatively attractive 'figure of merit' in energy terms.

The above system boundary (see also Figure 4) was then applied for carbon accounting, and this yielded a 'footprint' of about 8.0 gCO_2/kWh_e. In both the energy and carbon analyses, the operational requirements/emissions of the Shoots Barrage were found to have the most significant influence on the final results (accounting for around two thirds of the emissions). It was not possible to include all of the energy requirements associated with the scheme or the sources of carbon emissions from the project, such as those emanating from the manufacturing of the turbines and caissons. However, they are unlikely to have a significant impact on the energy/carbon indicators estimated here. The Shoots Barrage is favoured by environmental groups, such as Friends of the Earth, due to its less severe environmental impacts than the larger, Cardiff-Weston scheme. Work sponsored under the auspices of the IPCC [34] indicates the carbon intensity of alternative power generators: coal (without carbon capture and storage [CCS]) ~1000 gCO_2/kWh_e; combined cycle gas turbines (CCGT; without CCS) - 443 gCO_2/kWh_e; nuclear - 66 gCO_2/kWh_e; solar PV - 32 gCO_2/kWh_e; and onshore wind - 10 gCO_2/kWh_e. Again, the present analysis therefore suggests that the Shoots scheme has displayed an attractive 'figure of merit' in terms of its 'carbon footprint': comparable with that of onshore wind over their respective life-cycles.

The economics of the Shoots Barrage scheme was evaluated in some detail. This suggested that the most likely *Levelised Unit Electricity Cost* (LUEC) value was 10.8p/kWh_e (using the HM Treasury declining TDR), which is a higher figure than that obtained by DECC [11], i.e., using a discount rate of 8%. This compares with the SDC-sponsored study [12] by Black & Veatch indicated LUEC values for the Shoots tidal barrage of 3.29 p/kWh_e (with a range of 2.96-3.62 p/kWh_e) for a social discount rate of 3.5% or 6.8 p/kWh_e (with a range of 6.08-7.52 p/kWh_e) for an investor discount rate of 8%. Relative to alternative power generators, this study has confirmed the conclusions of a number of earlier studies (such as that by the consulting engineers Mott McDonald Ltd. [35]) that the electricity generated by tidal power schemes is not commercially attractive in comparison with some of the alternative technologies. Mott McDonald [35] found, using a discount rate of 10%, the 2010 LUEC for a number of power plant types: gas CCGT - 8.03 p/kWh_e; coal (without CCS) - 10.45 p/kWh_e; nuclear - 9.90 p/kWh_e; onshore wind - 9.39 p/kWh_e; and offshore wind - 16.09 p/kWh_e. However, the impact of the selected *Test Discount Rate* (TDR) was found to be significant. No allowance has been made for the cost to decommissioning the barrage in the present study; this is due to limit data being available, the longevity of the project, and also to keep this study in line with other studies, such as those by DECC [11] and the STPG [21].

ACKNOWLEDGEMENTS

This is a revised and extended version of a paper originally presented at the *8th Conference on Sustainable Development of Energy, Water, and Environmental Systems* (SDEWES) in Dubrovnik, Croatia over 22-27 September 2013 (Paper SDEWES2013.0553). This work is part of a programme of research at the University of Bath on the technology assessment of low carbon energy systems and transition pathways that is supported by a series of UK research grants and contracts awarded by various bodies. In the present context, the first author (GPH) is the Principal Investigator and joint leader a large consortium of nine university partners initially funded via the

strategic partnership between *e.on UK* (the electricity generator) and the UK *Engineering and Physical Sciences Research Council* (EPSRC) to study the role of electricity within the context of '*Transition Pathways to a Low Carbon Economy*' (under Grant EP/F022832/1) over the period 2008 - 2012. The second author (CIJ) was funded in part under that grant before moving to the private sector. In 2012 the project was renewed with funding solely from the EPSRC under the title *'Realising Transition Pathways: Whole Systems Analysis for a UK More Electric Low Carbon Energy Future*' (under Grant EP/K005316/1). All the authors are grateful for the interaction with various consortium partners. Specific responses to technical queries were provided by Hayden Arrowsmith of *Lafarge Aggregates Ltd.*, Stephen Bool of *Bridgend Borough Council* in Wales (who also sat on the *Severn Barrage Steering Committee*), and Katie Gillingham of the UK *Department of Energy and Climate Change* (Office for Renewable Energy Deployment [ORED]). However, the views expressed here are those of the authors alone, and do not necessarily reflect the views of the collaborators or the policies of the funding bodies.

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Paper submitted: 07.03.2014
Paper revised: 06.05.2014
Paper accepted: 09.05.2014