SEVERN EMBRYONIC TECHNOLOGIES SCHEME

Severn Tidal Fence Consortium Final Report

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1 EXECUTIVE SUMMARY

As part of the Severn Embryonic Technology Scheme (SETS) proposal, the Severn Tidal Fence Consortium (STFC) has studied the technical feasibility of an innovative approach to extracting energy from the tides. The STFC have proposed the use of a 'tidal fence system' as a method of extracting tidal power from the Severn Estuary whilst minimizing impact to the natural environment and shipping and importantly not impeding future commercial shipping developments.

The key findings from this initial analysis of the 'tidal fence system' are a 19km scheme located between Aberthaw and Minehead, utilising between 680 and 780 turbine units in a twin fence arrangement. The scheme rating is estimated at 400MW, generating 0.88TWh and saving 37,700t of Carbon that is delivered at a cost of £2.3bn returning cost of energy at £226/MWh. The scheme will have a 650m gap to allow free unimpeded two-way navigation for shipping and is considered to have low environmental impact with a loss of intertidal area of <0.5%. These findings are different from the original estimation of scheme rating and electrical generation as the simplified modelling undertaken in this investigation redirected the study to consider free stream kinetic flows only, with no flow augmentation through blockage effects.

The STFC considered two possible locations or the tidal fence, an inner location between Lavernock Point (Wales) and Brean Down (England) via Flat Holm and Steep Holm islands; and an outer location between Aberthaw (Wales) and Minehead (England). The outer fence location was chosen during the early stages of the project due to its preferable bathymetry and correspondingly higher extractable energy.

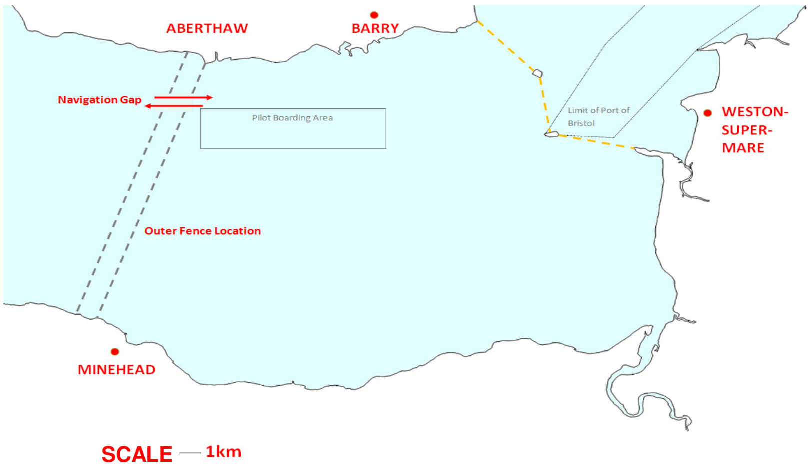

Figure 1: *Schematic showing the proposed fence locations – Outer (double, grey, dashed lines) and Inner (single, yellow, dashed line)*

The configuration of the chosen fence has been selected to minimise impact on the natural environment and to minimise impact on the free passage of shipping traffic in the Severn Estuary. The concept began with a strategy to install sufficient blockage in the fence to increase the flow through the tidal generation devices in the fence but with the intent to provide an open shipping channel. However, the initial simple hydraulic modeling showed that the two aims were not compatible and that unacceptably high velocities would flow through any gap.

The strategy at this stage was therefore modified to maintain a primary objective of unimpeded navigation for all large commercial vessels through reducing blockage effects. It is considered that this is a conservative approach that requires further study. In order to achieve an increased level of confidence it is required to undertake further more sophisticated hydrodynamic modelling to understand to achieve an improved level of refinement and improved understanding of where the optimised and acceptable of blockage effect lies.

The strategy of low environmental impact and free navigational passage by all large commercial vessels was maintained. A key finding of the study was that by introducing a second fence system the flow velocities through the navigational channel could be reduced.

Information was initially sought from sixteen Tidal Energy Converter (TEC) technology developers which narrowed down to seven who were asked for detailed responses. Detailed information sheets were received from five technology developers who agreed to supply information on their devices. All developers who responded submitted data on their devices designed for tide races with peak velocities in excess of 3 m/s, which are higher than those found in the Severn. The best two devices were considered in detail and these were a twin rotor horizontal axis turbine (Marine Current Turbines Ltd - MCT) and an oscillating foil turbine (Pulse Tidal Ltd - Pulse).

Due to the lower flow velocity in Estuary, 1.9 m/s at peak spring tides, verified by the survey results from 1980[1], a lower flow turbine concept was also considered based upon the horizontal axis turbine concept similar to the MCT Seagen unit, in effect a re-rated turbine sized appropriately for the Severn using the same geometry and overall numbers of devices. It should be noted that a small variation in flow speeds impacts significantly the power out and this is an area where greater confidence is required. The fence system, using the MCT and re-rated arrangement consists of 782 machines of appropriate sizes for the water depth, for the Pulse TECs it amounts to 678. Power outputs are: 383MW peak springs and an average over the tidal cycle of around 104MW for the horizontal axis turbines.

Preliminary civil and electrical designs for the fence were carried out and independently reviewed. This approach to costing was undertaken with the express objective of achieving defendable, realistic estimates. Cost estimates priced in all logical recommendations from the reviews increased the overall £2.3bn cost by £50m.

Operating expenditure amounts to an average of 0.8% of capital cost per annum, this rises in specific years (e.g. major equipment change-outs) as high as 4.3%. The downtime is representative of the advice from technology developers giving availabilities in the range 92-96%.

The Cost of Energy was calculated to be £226/MWh for the central Case with a range from £204 to £259/MWh in the low and high cost cases. Although the Capex is slightly above the £200/MWh target, it is based on capital costs that have some measures of technology and construction risk priced in. The STFC believes that engineering development will produce the necessary cost reductions in the course of the Route Map Programme.

The aim of the Route Map is to achieve a development programme that realises acceptable costs and risk exposure at the relevant stages. It includes 2 years of preliminary studies and surveys, accounts for 6 years for general tidal technology development and also the 'fence system' development including the lower flow re-rated tidal turbines. It estimates that a Severn fence requires 2 years of detailed engineering design and four years construction. A construction start date of 2019 with completion in 2023 is set down. The main aim of the route map being to achieve an acceptable programme cost and risk exposure. A higher risk strategy for the route map would be to carry out certain activities in parallel such that, having seen the prototype deployed and having an acceptable operating performance, the design work for the main project would be commenced as the remainder of the pre-commercial array are deployed. This would result in a construction period starting in 2015 and completed in 2018/19. It must be emphasised that the risks involved are more significant with the early commitment to project design ahead of a period of operation of the whole pre-commercial array.

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[1] Bondi Severn Studies (HRS reports). EX966 Observations of tidal currents, salinities and suspended sediment concentrations:Jan1981. 13 pages of text, 4 tables, 43 figures and 4 plates. EX959 Measurements of tidal currents over offshore banks: November 1980. 9 pages of text, 4 tables, 4 figures and 6 plates

2 AIMS AND OBJECTIVES

The DECC funding programme was launched in April 2009 with the aim of promoting the use of embryonic tidal technology as a further option alongside barrage and lagoon solutions for the extraction of energy from the Severn Estuary. Specifically the objectives set were:

- Developing new proposals to outline design stage
- Increasing confidence in their output, costs, impacts and technical feasibility
- Establishing a 'route map' to take to deployment stage, proposals with the potential to generate significant amounts of energy affordably and with acceptable impacts on the natural environment and regional economy.

The Severn Tidal Fence Consortium (STFC) was formed by the Severn Tidal Fence Group (STFG - originally made up of partners IT Power, NaREC, University of Edinburgh, Pulse Tidal, Marubeni and BMT Fleet Technology) and CleanTechCom (part of Woodshed Technologies with partners Sigma Offshore ltd, University of Edinburgh, Metoc) to consider an innovative Tidal Fence arrangement in the Severn. The overarching goal for the fence is to provide a strategic source of electrical generation without significantly impacting the natural environment and commercial activities already established in the Severn.

Within the scope of this study the STFC were to determine the preferred location of the fence and to determine the cost and economics, with development route map for the preferred Tidal Fence location. Specifically the study would determine:

1. An outline design, consisting of the selection of the appropriate location for the fence, together with the selection of tidal stream turbine types that could be feasibly available for power generation.
2. Definition of a support structure for the tidal devices and a bridge that could function as a service road for operations and maintenance.
3. Definition of an electrical system to transmit power generated to the most suitable location for acceptance to the grid as well as any other facilities required for safe and efficient operations.
4. To enroll a number of technology developers in the process of suggesting how their particular devices could fit into the scheme by providing information on performance, configuration, size, power generation characteristics, cost and a projection of how a large number (500 +) devices could be manufactured in a suitable timescale.
5. To prepare very preliminary models that represent tidal flow in the estuary and the extraction of energy using the range of devices for which information was provided.
6. To carry out sufficient basic engineering to provide a capital cost estimate of around 15% accuracy and an understanding of the confidence in that accuracy for the devices, fence structure and all associated systems.
7. To utilize the engineering and cost data to determine O&M costs including an understanding of generation lost due to maintenance, breakdown and system losses.
8. To minimize impact on the environment and Estuary users by minimizing change in water levels and providing an opening in the fence for the free passage of shipping.
9. To review the impacts of the fence on the environment – this was a limited exercise due to the SEA being developed by DECC.

10. To develop a route map that embraces both the development of technologies suitable for the fence and the consenting, planning, funding and execution of the design and implementation of the fence in a realistic timescale.
11. To carry out a risk analysis exercise around the project costs and method, the technology and project development to identify key risk areas and suggest mitigation that will provide adequate confidence in the overall proposal.

3 METHODOLOGY

In conjunction with DECC, the STFC assembled a set of work packages (consisting of multiple sub-tasks) to assess the viability of the tidal fence concept in the Severn Estuary context. The progress through this plan was closely monitored by DECC (and advisor Parsons Brinckerhoff) with monthly gateway review meetings. The STFC have kept closely to the plan despite the late start of the project.

The consortium brings together a number of industry experts in tidal energy conversion, civil design and construction, electrical design, project cost and risk assessment and environmental and shipping impact assessment. This work has then been reviewed and verified formally by respected third party consultants from the mechanical, civil and electrical engineering industry.

The assembled consortium consists of the following companies, and the shorthand name to which they are referred to in this report and the key strengths they have brought to the project:

IT Power ltd. (ITP) – tidal energy conversion expertise (mechanical and electrical) and project management

CleanTechCom ltd. (CTCL) – tidal energy conversion expertise, engineering management and costing expertise

University of Edinburgh (UoE) – hydraulic modelling expertise

Sigma Offshore ltd. (Sigma) – expertise in civil works design and costing

Metoc plc. (Metoc) – expertise in the impact of large scale engineering projects on the natural environment

Marubeni Europe plc. (Marubeni) – expertise in project cost and risk analysis

British Maritime Technology, Fleet Technology ltd. (BMT) – expertise in shipping and navigation

NDSL National Renewables Energy Centre (NaREC) – expertise in electrical design and costing

3.1 Hydraulic Modelling

In order to assess the possible energy yield from the tidal fence concept above and beyond the work already completed, Professor Ian Bryden (University of Edinburgh) was commissioned to produce a one dimensional (1 D) hydraulic model of the fence. The model is also referred to as a one and a half (1.5 D) dimensional model to account for the fact that it approximates variation in flow over the width of the river by cutting the river into sections length-ways and performing a one dimensional calculation on each section, thus giving a pseudo two-dimensional impression of the cross channel flow profile.

In this report, the model is referred to as a hydraulic rather than a hydro-dynamic model to reflect the non-dynamic nature of the calculation it performs. The model is a significant simplification of the actual hydro-dynamics of a tidal fence, and conclusions drawn from it should be read accordingly. The model is suitable to the time and budget available for this project.

The model assesses the cross channel flow modification caused by the extraction of energy and by the natural boundary roughness at the fence location. This cross channel flow profile includes the affect that the fence has on the navigation passage through the fence, a key piece of work in determining the ultimate configuration of the fence. The model also investigates the affect of the flow retardation caused by the fence on the filling and emptying of the basin upstream of the structure.

The model was calibrated using bathymetry and flow speed information provided by STFC partner Metoc plc. Flow speed information confidence has since been improved by further information provided by Parson's Brinckerhoff. There is however significant variation depending on the source of the information, and any further work on the fence will required a thorough survey of the available resource.

3.2 Tidal Energy Converter (TEC) Technology Selection

In order to select the most suitable energy conversion technology for the tidal fence (available at the date of writing), a shortlist of the fourteen of the market leading technology developers was agreed. Of these fourteen, seven were selected in consultation with the consortium and contacted for information. Developers were paid a nominal fee in order to ensure that due attention was given to the information provided. The following developers were consulted:

- Marine Current Turbines (MCT)
- Verdant
- Pulse Tidal ltd. (Pulse)
- Lunar
- OpenHydro
- Hammerfest Strom
- Atlantic Resource Corporation (ARC)

Of this seven, two developers declined to be involved (Hammerfest Strom and ARC).

Using the information collected from the five engaged TEC developers, the bathymetric data and flow regime generated by Professor Bryden's work, a numerical model was developed by IT Power to formulate a physical arrangement for the fence. This process considered single TEC type schemes for each of the technologies, and the best optimised combination of the TECs available.

The TEC technology has been scored on the basis of its weighted energy and environmental performance to arrive at a physical arrangement or anatomy for the outer fence location. Environmental performance was scored using Metoc's fish impact report, which can be found in *Annex D, filename: 091028_Task_5.2_Fish_V1.3*.

As part of the TEC selection process, a hypothetical, re-rated TEC model was developed by IT Power, based on the twin rotor MCT design. The purpose of the design was to de-rate the structural elements of the design in order to produce a more cost effective, and appropriated device for the low flow Severn environment.

The model, and a full description of the way in which it is set up can be found in *Annex D, filename: 091019 STFC TEC Energy Model V5.4.* Please note that this model is not editable.

3.3 Capital Cost Method

A first draft capital cost estimate was prepared at the outset of the work by CleanTechCom Ltd (CTCL) using in-house data gathered from other projects and specialist software or websites for rates on steel and concrete construction. This initial cost was updated throughout the work as design activity and vendor data provided more relevant cost estimates. Control of the cost estimate was maintained by CTCL as part of the engineering management function, ensuring that interfaces between technical disciplines were managed throughout. All costs are determined as at January 2010 and used as the basis for all discounting.

The following aspects have all contributed to evaluating the capital cost of the proposed tidal fence:

1. Hydraulic model of the fence provided the estimated extractable power available. Data from technology developers was used as described in 3.2 (above) by ITP to select potential providers whose technology indicated best generation performance. The basic cost estimates for the turbines were provided by the developers contacted. These costs are for the manufacture of various numbers of devices up to 500 units. This information allowed STFC to interpret the way in which the Experience Curve[2] had been utilised by the developer. A percentage breakdown of the cost of key components was also given which allowed these elements to be analysed for the O&M cost method (see section 3.4).

2. Civil engineering carried out by Sigma defined the sizes of the piles and bridge structure and its abutments to the shores at each end. Costs were developed by Sigma using a combination of specific quotes from vendors for materials and marine plant hire, industry rates for fabrication of steel and concrete components, and from the most recent Spon's Guide[3], a reputable standard reference for civil engineers. As contractors involved in development of solutions for offshore engineering in the oil and gas industry, Sigma have a comprehensive data base of costs for a wide range of civil/structural work.

   Civil engineering and construction costs were reviewed by SLP Group Ltd who are fabricators in the oil and gas and wind industries and have carried out a range of installation studies in the marine renewable energy sector.

3. The overall electrical system configuration was selected by Narec as that with the least power losses incurred (see section 3.6). A system design capacity was selected that was adequate to handle the likely generated power available from the turbines. Narec interrogated a large number of vendors to provide budget quotations for the cables, switchgear, transformers and junction boxes that comprise the overall electrical system. Whilst many could not offer the correct items or declined to quote in the timescale, a price was obtained for all cables and equipment from at least one experienced and competent vendor in every case. STFC consider this to be a firm basis for the electrical costs. Key items, such as cables, were checked against historical costs, brought up to date from published inflation indices for the construction industry.

   Narec developed a bill of materials for all the above items from which costs were incorporated into the estimate.

   The electrical report and cost estimate was submitted to Senergy Econnect Ltd (SEL) – an experienced renewable energy electrical consultant for independent review.

[2] http://cost.jsc.nasa.gov/learn.html (Note that this may need to be accessed via Wikipedia from the search engine as it is not available direct on the main NASA site)

[3] Spon's "Civil Engineering and Highway Works Price Book – 2010"

4. Installation and Indirect Costs were estimated by CTCL. Installation costs utilised marine vessel rates from the current market with which CTCL is familiar from other work in the marine renewable sector. Durations of offshore related activities were derived by creation of step-by-step bar charts based on experience of offshore construction activity. Reference was made to Offshore Hook-up Norms utilised by Shell on offshore projects for electrical cable pulling and hook-up of devices and substations where relevant. Labour and technical manpower rates were derived from current market rates for the disciplines involved. Civil engineering installation was estimated by Sigma.
5. A zero-based approach was taken by CTCL for estimation of all elements of indirect costs including project and construction management teams, design and engineering staff, environmental assessment, surveys, legal, land purchase, computer modelling, offices, telecoms and computer facilities and similar.
6. The largest single element of the capital cost is for purchase of tidal energy generation devices. Costs were provided by technology developers. However developers provided their present designs of device which were intended to operate in tidal streams in the 3 – 3.5m/s range at peak spring tides. Investigation has shown that the velocities in the Estuary[4] are closer to 2m/s at peak springs and a de-rating of the turbines is required to ensure operation takes place at a reasonable load factor. This will clearly save cost of the power take-off including gearbox, generator and possibly electrical systems. Also the devices can be reduced structurally due to lower force loadings. ITPL have developed a method to estimate these savings[5] and this has been used to prepare estimates of cost based on two approaches using the Experience Curve method, a conservative approach based on the cost of the 30th machine cost and a 92% experience curve (the central case) and a more optimistic case using the 50th machine cost and a 90% experience curve (as used by MCT in their response).
7. The economics of the scheme were calculated based on a 120 year model prepared by Marubeni which combines the data on capital costs described above with the estimated O&M costs (see section 4.4 below). The model is based on the same premises as those used by Parsons Brinkerhoff in the main studies for the Severn Barrage & Lagoon options. The cost of energy has been calculated using the standard approach practised by the Carbon Trust[6] which involves summing the present values of capital and operating costs and dividing by the discounted energy produced.

The above approaches have been used to develop a series of capital cost estimates covering four cases:

Horizontal Axis (MCT type turbines) – High Cost case

Horizontal Axis (Re-rated turbines – Realistic Costing) - Central Case

Horizontal Axis (Re-rated turbines – Optimistic Costing)

Oscillating Blade Turbine (Pulse Energy) – Alternate High Cost Case

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[4] HR Wallingford Report No. Ex 943 "The Severn Estuary – Recording of Tidal Levels in 1980", Sept 1980

[5] ITPL, "Fence Configuration Model Cost Report" ITP/1087

[6] www.carbontrust.co.uk/technology/technologyaccelerator/mea.htm

3.4 Operation and Maintenance Cost Method

The approach taken was to envisage the types of interventions required, both planned and unplanned and to estimate both the cost of them and the loss of generation incurred.

The types of intervention considered (based on MCT type devices) are given below.

Around devices:

- Change out of all nacelles after 20 years of operation, they will be refurbished /re-bladed as required and replaced in service.
- Routine inspection – by diver/ROV on cables from nacelles to power system and inspection of yoke and blades/nacelles.
- Allowance for delayed access to devices on all routine interventions and waiting-on-weather.
- Allowance for structural change-out of devices.
- Other operational downtime. This is handled by adding a decreasing additional downtime element to the first 10 years of operations.

Around electrical systems:

- Routine Inspections and breakdowns have been allowed at 8 hours each per device per year.
- Electrical change-out (per device) assumed to affect 5% of devices per year plus a 25 yearly change-out of all electrical switchgear in a four year campaign.
- Allowances for sub-station routine maintenance and substation breakdown
- Substation change-out –shutdowns carried out every 25 years

In the maintenance calculation, all downtime has been assessed as an average MWh per hour of lost generation.

The costs of all the above interventions have been estimated in summary terms for manpower, plant and equipment, marine vessels and spares. Other costs including connection charges to the grid have been included. Costs of device subsystems were derived from the

An additional allowance for miscellaneous spares has been made. In addition, where it is necessary to build up a significant number of spare components (eg for the exchange of nacelles) a build up of additional spares has been allowed over the first ten years of operation when, after initial failures, the failure rate would be expected to reduce in the typical "bathtub" curve recognised by reliability professionals.

The above assumptions are based on experience from industry in an offshore environment, as there are no detailed vendor recommendations or marine renewable guidance on maintenance at this early stage. However STFC believe the figures given above represent a credible scenario.

Other operational costs have been included for suitable staffing of the operating team, own use of power, insurance of the assets, legal and other professional services.

The costs and loss of generation has been aggregated into the Cost of Energy model as they occur in time for discounting purposes.

3.5 Civil Engineering Design Approach

Sigma Offshore developed a concept for a light bridge with pre-cast reinforced concrete spans, supported on steel piles. These in two lines set a distance to thicken the fence. The pile lengths provide an air gap to cope with 1 in 50n year waves and other requirements such as water level increase due to climate change.

Additional similar piles have been specified where an electrical substation is to be supported on the bridge and the access road is conveyed around the substation. The roadway is expected to carry mobile cranes, lorries and light vehicles conveying spare parts and personnel.

Piles are protected by aluminium sacrificial anodes which will need to be replaced at roughly 20 year intervals.

The bridge also carries a cable rack section sized to allow operator access along the length of the bridge and with appropriate separation for heat dissipation from cables. It is recognised that additional appurtenances to the structure may be required but these are a matter for detailed design as there is no technical basis to specify them at this stage. The pile caps are suitably sized to accommodate an additional level within which electrical and control equipment associated with each device can be installed. A volume for this equipment was provided by technology developers and it is possible to accommodate this in the structure.

The abutments to land are piled and an allowance of rock fill has been identified to reduce flow close to the shore but to be adjusted, subject to sedimentation studies, to ensure appropriate sedimentary movement at the shoreline for the avoidance of untoward erosion or deposition.

Roads have been specified linking the proposed local temporary construction and storage sites as well as the ends of the two fence lines. The permanent operating sites accommodating control and switchgear rooms and external transformer yards as well as offices stores and workshops are also allowed for in the scheme. Details of the layout have not been developed as they are wholly dependent on the exact topography of the selected sites. These cannot be identified without survey, further study and submission to the usual planning and consenting processes.

Access to the sea has been allowed for by provision of two quays in a suitable water depth, one on each bank. This will facilitate personnel movements and much of the routine movement of materials and equipment in both construction and operations. Major works (as well as initial construction) will require use of additional port facilities including quayside access, cranes and storage. It is understood that these may be found in the ports of the Cardiff and Bristol areas which have been reviewed in a preliminary way as part of the navigation safety study (see section 4.8 below),

Geotechnical data was extracted from the appropriate British Geological Survey's maps covering the Severn Estuary. Advice was also sought from sedimentologist Dr Robert Kirby on expected sand/silt cover of the rock head, Dr Kirby has a unique body of data on the area collected from many years of rigorous study.

An independent review of construction and construction costs has been carried out by SLP Group.

3.6 Electrical Engineering Design Approach

The Narec design for the electrical system was initially studied using "ERAC"[7] software for three configuration options. They differed in the way in which the collection circuits were transformed to 400kV. The numbers of devices were determined by the ITPL model (described in section 4.2 above)

[7] ERA Technology Ltd, Leatherhead , Surrey

based on the hydraulic model, (see section 3.1). The losses for each configuration were calculated and the lowest loss configuration adopted as the base case. The collection circuits are brought together in substations on each fence line; these are connected northwards to the Aberthaw landing point where the transformers to the grid are situated. The electrical layout of a bridge is shown schematically below in Figure 2.

The gaps in each fence will be interconnected by subsea cables trenched into the seabed and protected by rock dumping. The cables are large diameter, single phase, so that three cables are laid in parallel across each gap.

A large number of enquiries were issued to possible vendors for equipment and cables, quantities were measured from a schematic layout and the system costs calculated.

Senergy Econnect conducted an independent review of the system and costs.

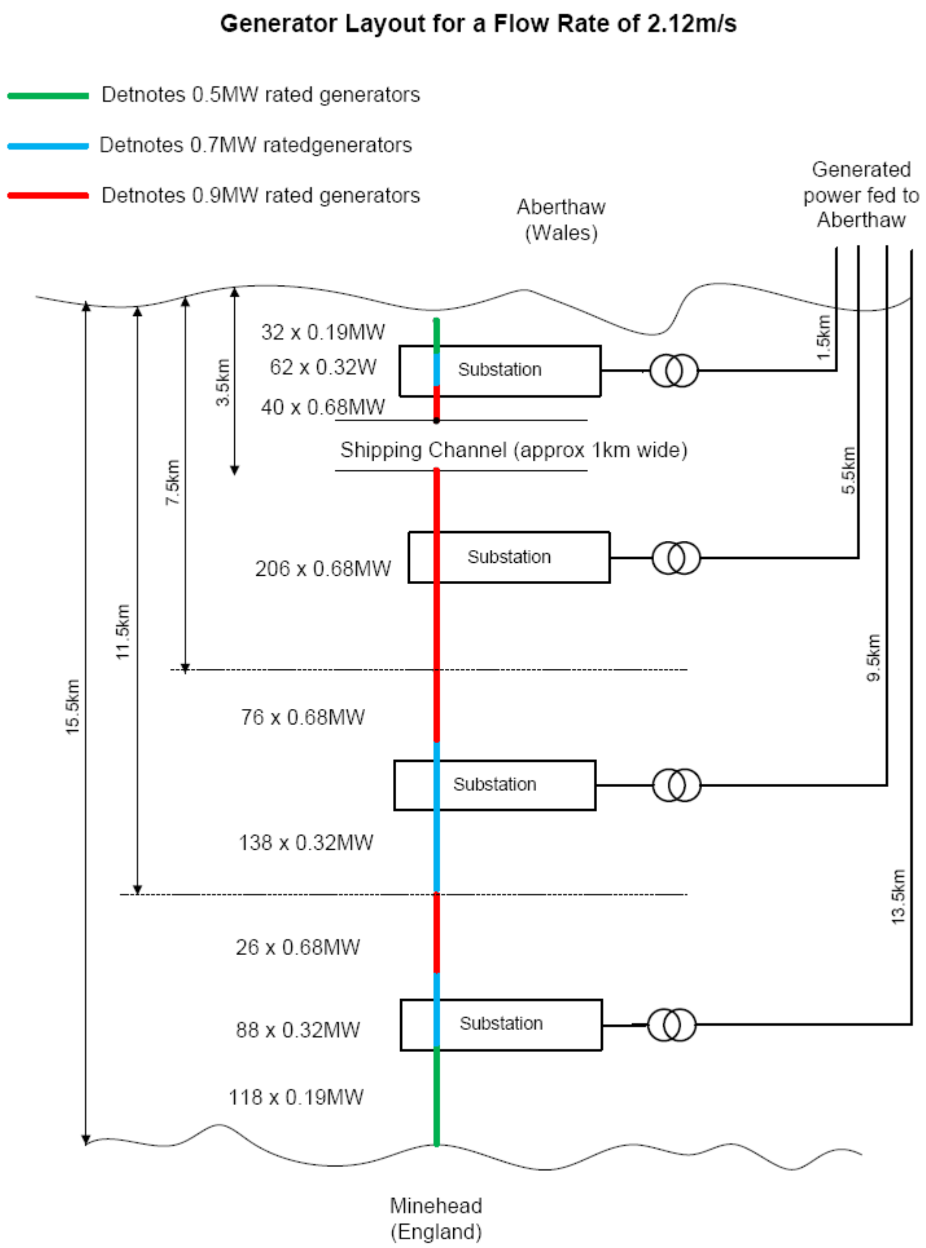

Figure 2: *Schematic electrical layout for the tidal fence*

3.7 Environmental Impact study

Estuaries are amongst the most productive ecosystems in the world, and the STFC, and the wider Severn Tidal Power group recognise that the Severn Estuary is no exception. The STFC has been proposed as an idea that allows flexibility in the delivery of a suitable compromise between environmental impact and energy production. Within the scope of the SETS project the following three high-level studies have been conducted by Metoc:

1. *Task 5.2 Turbine Study: Environmental Impacts:* focuses particularly on the potential impact and associated, required mitigating measures of the proposed fence scheme on fish species. *Annex D, filename: 091028_Task_5.2_Fish_V1.3.*
2. *Task 7.2 Key Drivers for Construction:* provides and overview of the impacts of the likely infrastructure requirements associated with the construction of the tidal fence scheme. *Annex D, filename: 7.2 - P1250_RN2241_REV2.*
3. *Task 8.2 Tidal Fence Turbine Impact Studies on Wider Environment:* provides an overview of the impact of the deployment of a tidal fence in the Severn, with particular reference to hydro-dynamics, waves, sediment transport , geomorphology and water quality. *Annex D, filename: 091202_Task_8.2_V1.2.*

The studies have been used to inform the selection of TEC technology, to comment on and influence the method of fence scheme construction (proposed by Sigma) and to comment on the impact of the fence scheme on the larger Severn environment.

The studies enable the STFC to assess the environmental impact and associated compensatory and mitigating measures at a broad overview level. The STFC recognises that these studies are very high-level and need significant further work to better quantify and conclude the use of a tidal fence to extract energy from the Severn.

Work conducted by Professor Bryden on the changes to water levels in the estuary, a point of particular environmental concern that has subsequently been used to approximately quantify the change to inter-tidal area.

3.8 Navigation Impact Study

With a two-way, continually free passage (non tide dependent) navigation gap in the fence, the scheme poses very little impact to current and planned large-scale ship movement in the Severn estuary. This is considered to be a key characteristic of the fence and has an important influence on the chosen configuration (as discussed in sections Hydraulic Modelling3.1 and 3.2).

The navigation impact study was undertaken by BMT, experts in shipping and navigation. In order to understand the impact of the two potential fence locations on shipping lane locations, flow velocities through a (potential) navigation gap in the fence and the impact on port access (including impact mitigation costs), the study was separated into three main bodies of work:

- Navigation impact: To report on the on predicted impacts on shipping from turn around times through the ports of Bristol, and cost estimates for both hard (marking, beacons, training walls) and soft (VTS systems) which may be required.
- Collision Impact: To assess the ship impact measures to be designed into the system structure
- Permeability. To optimise the permeability of the structure (the depth and width of channels, depth over structure, etc. with the navigational impact.

Five major ports upstream of the proposed outer fence location were investigated in this study. BMT, CleanTechCom and IT Power visited the offices of the Bristol Port Company (owners and operators of Avonmouth and Royal Portbury Docks) over the course of the project, to understand the requirements of this key stakeholder in any future development of the Severn.

BMT conducted a broad overview of commercial traffic movement in the Severn. Information was not available from DECC or Parson's Brinckerhoff for this aspect of the study. A lack of vessel type and frequency information meant that a collision impact study could be meaningfully completed. Instead, engineering judgement was used to assess what could be practicably applied to protect the fence from vessel collision.

A PIANC[8] study was also completed by BMT to assess the implications of a two way passage through the fence on navigation. This study was conducted by simulating a ULCS (to represent future shipping) passing through the gap at the same time, but in the opposite direction to Portbury Dock's largest container vessel.

It should be noted that the study was conducted with a 'thin' or single-row fence configuration as this represented the fence design when the study was made. A double-row fence, as finally agreed upon represents a less stringent requirement on movement through the gap as flow speeds are reduced by the presence of the double row.

Given the importance of the free passage navigation feature of the fence, further work is required beyond this study to better quantify the limitations of ship passage through the navigation gap at different flow speeds.

3.9 Route Map

The development route map has been assembled by IT Power, Marubeni and Narec, and provides a plan for development of the tidal fence concept from its state at the end of the SETS project to full commercial deployment in the Severn Estuary. The route map begins hypothetically in October 2010 and describes the proposed project through the following key work streams:

1. Further work required to assess the feasibility of the fence concept, ensuring key, detailed information is gathered at the outer fence location, and that hydro-dynamic modelling is used to better understand the navigation gap and ultimate power output of the scheme.
2. Development of a de-risking tidal fence demonstrator project.
3. Construction of the full scale, double-row fence proposed by the SETS project work.

In addition to detailing the sub-tasks of the above work streams, the route map also quantifies the anticipated timescales of the full scale project, the potential time contingency required against high risk tasks, and the specific risks to which that area of work relates. The latter links the route map to the Risk Assessment of the Route Map body of work produced by Marubeni.

The route map also comments on the strategic potential of the tidal fence scheme to establish commercial maturity in the tidal stream market.

3.10 Risk Assessment of the Route Map

The Risk Assessment of the Route Map, produced by Marubeni, gathers together information provided by the whole consortium on the future Severn Tidal Fence project in addition to Marubeni's expertise on the subject of risk management.

[8] PIANC is the global organisation providing guidance for sustainable waterborne transport infrastructure for ports and waterways

Risk information from the consortium has been gathered over the course of the SETS project, using a live risk summary sheet stored on a shared FTP site, and updated by all members of the consortium as the project progressed.

The Risk Assessment also concludes the risks associated with the development of the tidal stream market outside of the tidal fence project, specifically the development of technology appropriate to the application and development of the necessary commercial setting for the project.

The Risk Assessment provides a full analysis of the Route Map, and the two documents should be read in parallel.

3.11 Project and Engineering management

The STFC has been driven by project management from ITP and engineering management from CTCL. The work process was facilitated by a full consortium kick-off and close-out meeting, fortnightly teleconference meetings, strategic face to face meetings between consortium partners and monthly Gateway Review meetings with DECC and Parson's Brinckerhoff. A FTP file exchange was set up to ensure that all partners had access to the latest partner documents.

4 RESULTS

4.1 Scheme Configuration Overview

The STFC project set out to assess the use of tidal fencing to extract power from the tidal movement in the Severn Estuary whilst reducing impact on the environment and passage of ships. As a result of the work carried out, a scheme with the following characteristics has been proposed (TEC – Tidal Energy Converter):

Location:	Results from the hydraulic modelling exercise place the most suitable fence location at the outer, Aberthaw to Minehead route.
TEC Type:	Marine Current Turbine's (MCT) twin rotor device and Pulse Tidal ltd's (Pulse) oscillating hydrofoil device have been selected as the best choice of TEC machinery (at this juncture) when considering ability to extract energy and potential impact on fish mortality.
TEC Quantity:	A two row fence consisting of between 678 and 782 (Pulse and MCT numbers respectively) in total. The two rows of technology have a stream wise separation of 1000m.
Environmental Impact:	Whilst wide ranging, the environmental impact of the proposed fence scheme on the Severn would be low in comparison to tidal impoundment schemes. Loss of inter-tidal area is estimated at <0.5% of existing.
Navigation Impact:	A 650m wide, free passage (at all tides), two-way navigation channel for shipping at the deepest point in the estuary at the outer fence location.
Mode of Operation:	The fence operates during ebbing and flooding tides, with power output being directly proportional to flow speed (approximate sine wave form).
Rated Power:	The scheme has a rated (operation at peak spring tide) power output of between 383 MW or 389 MW (MCT and Pulse respectively).

Annual Energy Yield: The annual energy delivered by the fence is between 0.88TWh and 0.84TWh (MCT and Pulse respectively – please note the switch in magnitude from rated power).

The variation in scheme cost and a summary of the key information is given in Table 1 over leaf.

Table 1: *Scheme summaries given for varying cost cases*

Name of scheme(s) and alignment(s)	Power Output (MW)	Annual Output (TWh)	Construction Cost (Inc comp habitat@ 2:1 and contingency @15% but exc optimism bias)	Energy Cost (£/MWh)	Annual Carbon Saving (CO_2 pa)*	Environmental Impacts (Key impacts on Fish/Birds/habitat etc)
High Cost Case (MCT)	383	0.88	2,305,930	259.03	380,000t	Please see section: 4.5
Realistic - Central Estimate Case (MCT)	383	0.88	1,969,202	225.96	380,000t	Please see section: 4.5
Low Cost Case (MCT)	383	0.88	1,751,071	204.54	380,000t	Please see section: 4.5
Alternate High Cost Case (Pulse)	389	0.84	2,038,838	252.59	360,000t	Please see section: 4.5

* - Carbon Trust multiplier: 0.44kg/kWh

4.2 Technology selection and mode of operation

In order to develop the flow profile for the transect (spanwise section) of the Severn at the outer fence location, the bathymetry shown in Figure 3 was provided by Metoc and used to calibrate Professor Bryden's model. The bathymetry shown is for lowest astronomical tide (LAT). LAT depths were used to ensure that all TEC machinery remains submerged throughout the year.

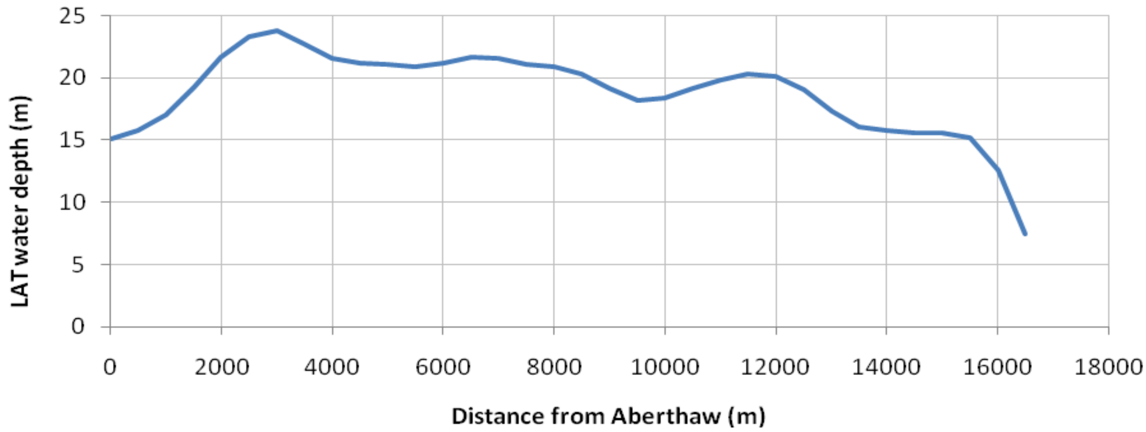

Figure 3: *Outer fence location bathymetry*

The Bathymetry was used to plan the number and sizes of TEC devices that could be accomodated across the transect. In order to make best use of the full width of the channel, machines provided by the supplier were scaled to provide larger and smaller versions. The characteristics of these machines were extrapolated accordingly.

With the bathymetry data in place, the hydraulic model then calculates the transect flow profiles during spring and neap tides. These profiles are shown in Figure 4. The spike in flow speed represents the location of the navigation gap. It should be noted that the resolution of the hydraulic model only allows for a 500m wide gap to represent the 650m gap proposed. The gap is situated 2500m from Aberthaw at the position the deepest channel

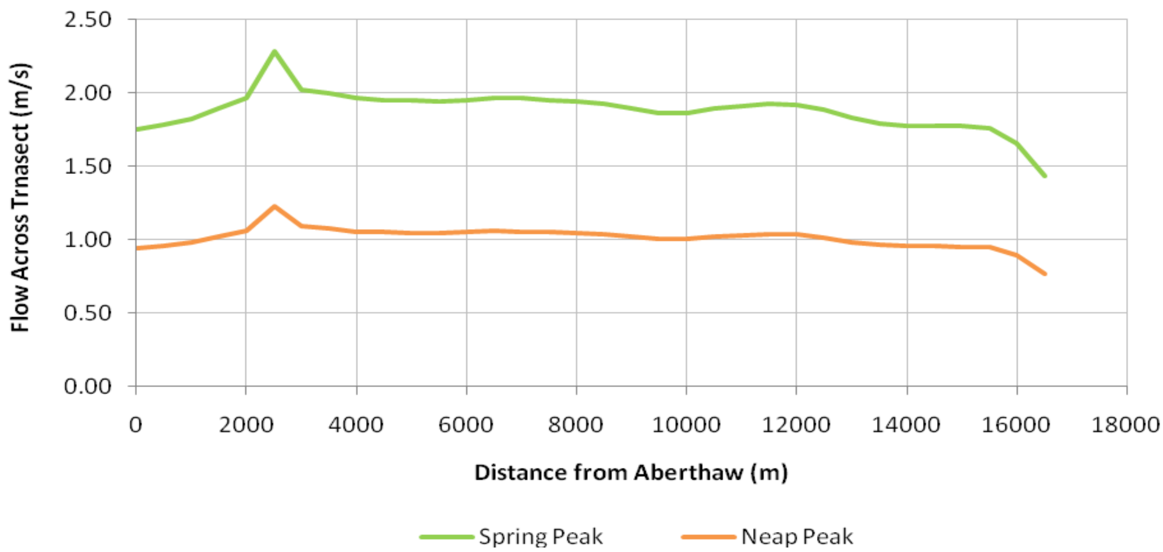

Figure 4: *Outer fence location flow profile across transect*

The STFC proposal sought to test the concept of developing blockage with a low porosity fence, whilst retaining the free navigation gap. The pre-study preliminary modelling undertaken had correctly indicated that introducing blokage effects would result in head being generated across the fence, allowing capture efficiencies to exceed kinetic energy extraction limits (Betz criterion – theoretical extraction limit of approximately 59%).

In this study the simple modelling of Professor Bryden's work showed that there was a significant relationship between the gap width and the speed of flow through the gap, and hence a relationship between the power conversion and the gap width. Increased gap width results in a reduced gap speed but also results in reduced power conversion.

With a gap in the fence, it was not possible to maintain a head greater than a few centimetres across the fence. By generating head, and consequently increasing impedance of the flow through the fence, the total energy flux is reduced and this, in turn, results in a higher head difference and a consequential increase in flow speed, which acts to maintain the level within the basin.

The result is that according to current hydraulic modelling (not hydrodymanic), any increase in blockage generated by the fence only serves to accelerate the flow in the navigation gap without significantly improving power output. As a result, with the hydraulic modelling conducted under this study, it has been concluded that the fence must operate using kinetic energy exctraction only, if the navigation gap is to remain navgiable. Further work is required to test this critical question over the fence.

In order to improve the energy output of the fence, in light of the inability to benefit from potential indicated by current modelling, a double row fence was considered. A study of the impact of the 'thickness' (term coined to express the distance between the rows of the fence) on the peak velocity through the navigation gap showed that a reduction in the peak flow speed occurs with increased separation of the two fence lines and maximises energy extraction from the tidal stream.

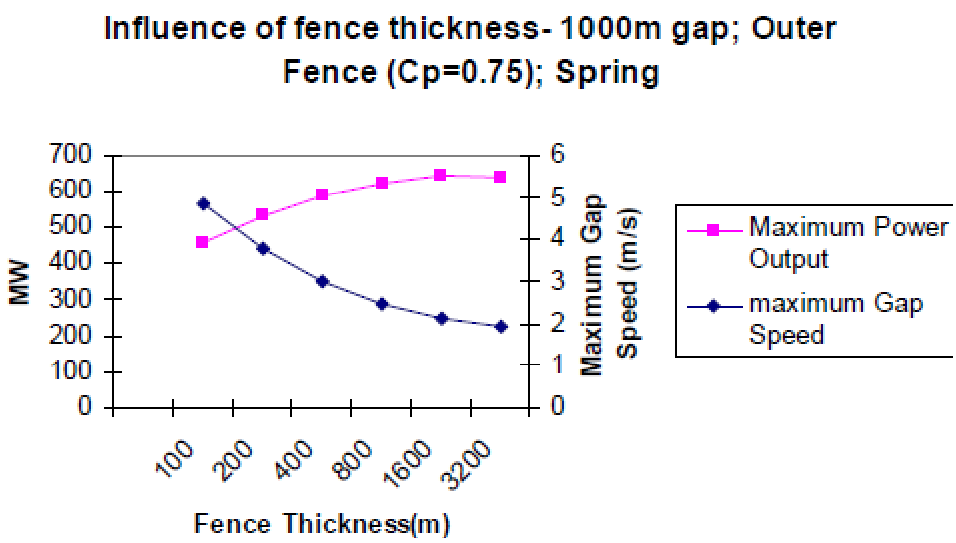

Figure 5: *Shows how the flow speed through the gap decreases with increased thickness of the fence.*

The double row fence increases the power output of the fence by a factor of two, and has the added benefit of reducing flow speed in the gap, although this result requires further investigation. By placing the rows of the fence 1km apart, there is sufficient distance for the wake from the first row to dissipate, meaning the second row can absorb the same percentage of energy from the flow as the first.

The 1km separation of the double row fence results in an acceptable peak velocity of the tidal stream through the 650m gap of 2.5m/s (5knots) at peak spring tide. This is considered a practical level of by the navigation study.

With a scheme configuration in place, the transect flow profiles and their calibrated variation over the tidal (time period to completing a full cycle from peak ebb to peak ebb) and lunar cycle (time period completing a full cycle from peak spring to peak spring tide) were run through the TEC configurations fitted to the bathymetry.

Figure 6 shows the ebb and flood flow velocities as positive values. As the fence operated in both ebb and flood, the direction of the flow is removed for calculation purposes. The power output during a spring tide cycle and a lunar cycle for the MCT and Pulse configurations can be seen in Figure 7 to 7.

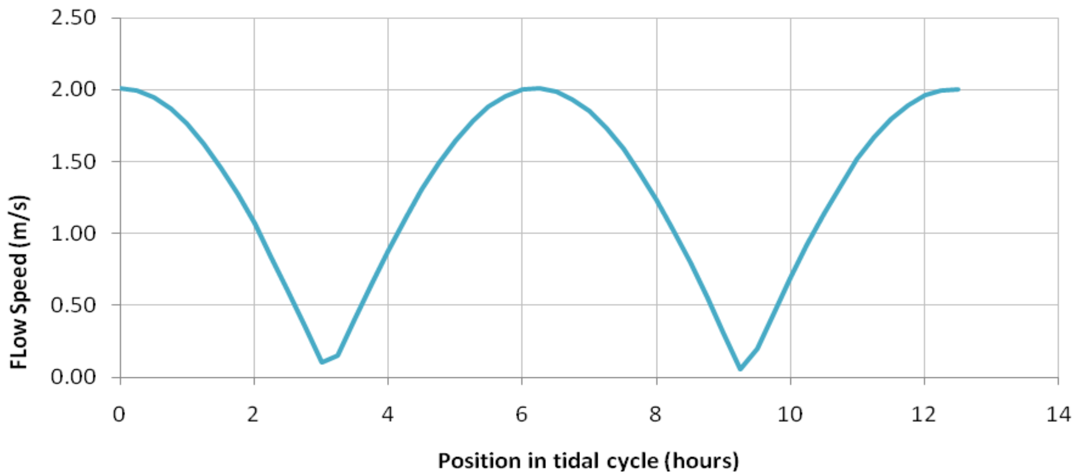

Figure 6: *Flow speed over one tidal cycle (12.4 hours approximately) during peak spring tides*

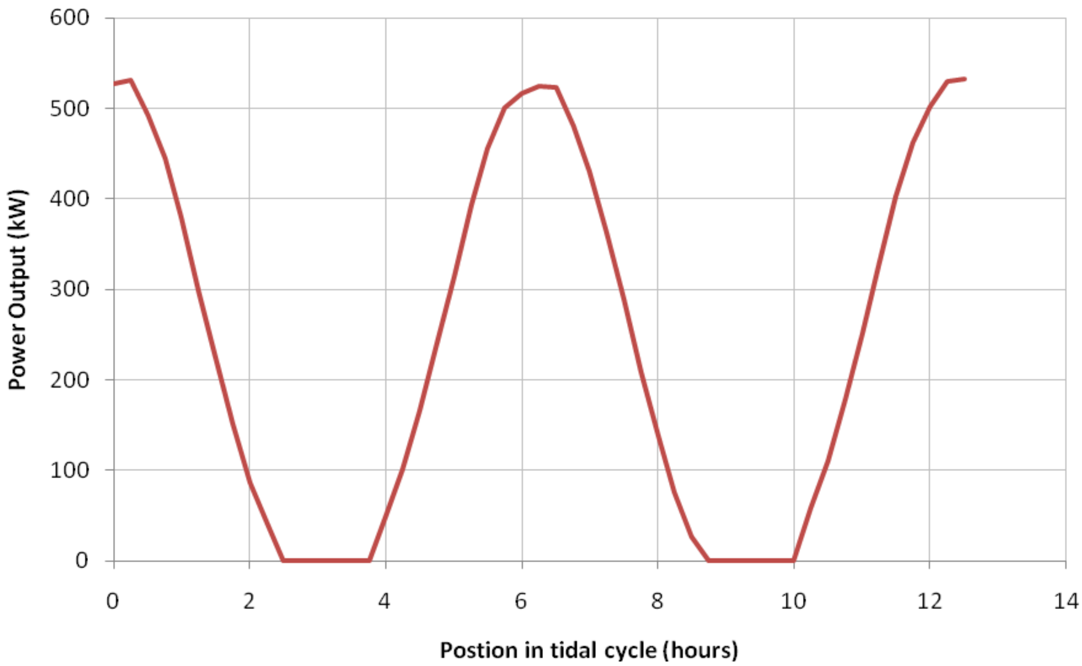

Figure 7: *Power output from an MCT (Deep – 14m diameter rotor) type TEC device over one tidal cycle during peak spring tides*

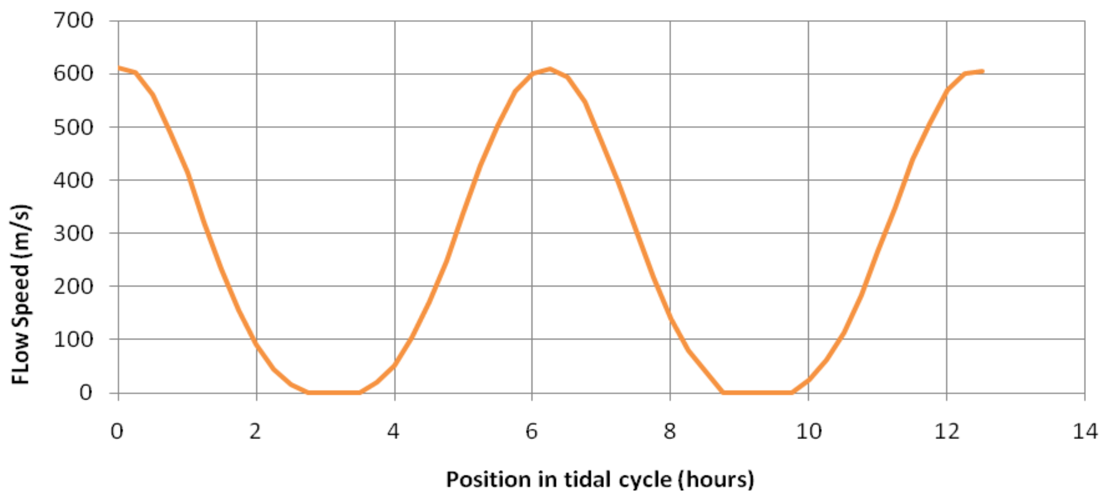

Figure 8: *Power output from a Pulse (Deep – 12m stroke length) type TEC device over one tidal cycle during peak spring tides*

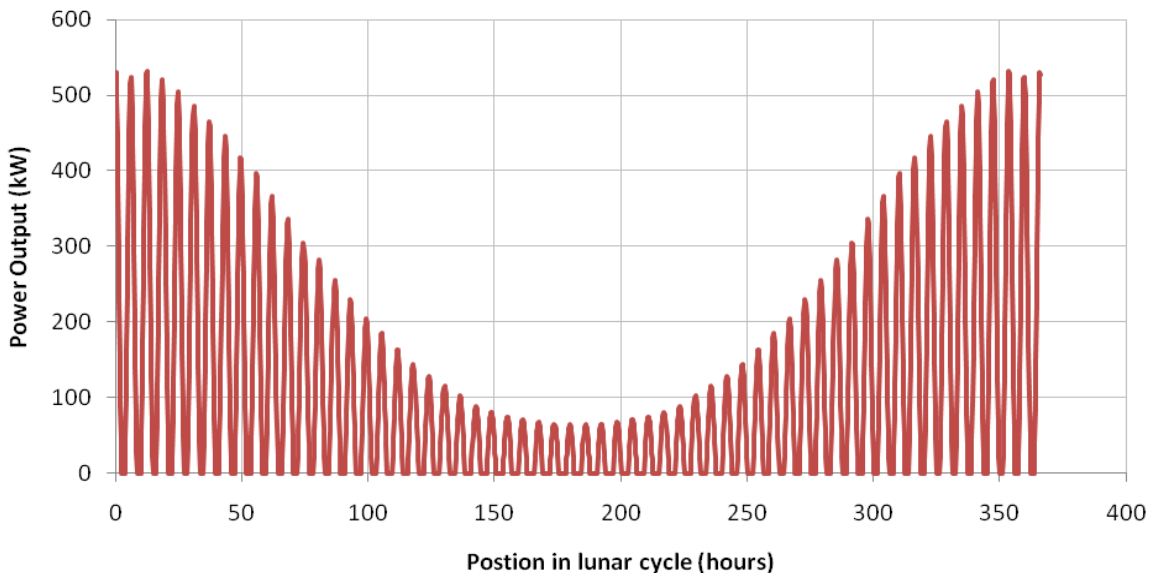

Figure 9: *Power output from an MCT (Deep – 14m diameter rotor) type TEC device over one lunar cycle (spring to spring – 366 hours approximately*

Please refer to the full configuration report for results on the scheme output for the alternative technology suppliers.

It can be seen from Figures Figure *7* and Figure *8* that the peak power output from the both MCT and Pulse TECs is significantly lower than the rated power output of these machines (1.4MW and 1.2MW respectively – note these figures are approximate). This means that the machinery as specified by the suppliers is operating at a low load factor (ratio of energy delivered at actual operation over energy delivered at rated operation). A low load factor indicates that the machinery is not well matched to the resource.

Current developments in TEC technology are aimed at more energetic tidal races than are found in the Severn Estuary, typically geared towards flow speeds in excess of 3 m/s. At the outer fence location, peak flow speeds (according to available data) average at 1.9 m/s. This discrepancy in flow speeds results in the low load factors observed: 8 – 11% for the various sizes of MCT and Pulse devices. In order for TEC technology to be commercially viable, it is widely understood that load factors should exceed 20%. TEC developers were only able to supply information on current technology.

In order to appropriate the available technology to the Severn resource, IT Power conducted an exercise to de-rate the structural aspects of the TECs, accounting for the reduced thrust loads experienced at lower than rated flow speed. Rotor dimensions, speed and corresponding capture efficiencies were not modified (this is considered a false economy). By de-rating the technology, cost savings are observed and consequently credible load factors appear that exceed 20%.

This approach to shifting the TEC technology market carries significant risk. It should be noted that a move to low pressure TEC technology would also result in increased technical risk. In order to absorb this risk, the STFC have proposed a tidal fence demonstrator scheme as part of the route map. The cost of this demonstrator project fall outside the cost of the full scheme, and will be financed separately

4.3 Civil Engineering

The hydraulic analysis indicated benefits to energy extraction of a thicker fence and a reduced velocity through the navigable gap, 650m wide, with reinforced dolphins to protect the fence ends, allowing shipping to pass unhindered. Hence two fence lines will be constructed with a separation of approx. 1 km.

Sigma Offshore developed a concept for a light bridge with pre-cast reinforced concrete spans, supported on steel piles 2.5 m in diameter which will be drilled and grouted from self-elevating barges some 7-10 m into the seabed. The average pile length is c. 57m but the variation in length is between 50 and 65m. Wall thickness is at least 25mm plus corrosion allowance.

SLP Group provided an independent review of the construction method and costs. Their total suggested changes would increase construction costs by some 11.8%, however Sigma had received quotes from vendors and held extensive conversations with suppliers which show that not all the suggested cost increases should be taken into the estimate. STFC have therefore accepted a number of the recommendations, specifically concerning pile wall thickness, materials for the dolphins, where the expendable sections included a larger inventory of concrete and increased labour rates for welding of pile caps. The total increase on the account resulting from the changes is 7.8% which STFC believes is an acceptable adjustment in the light of design information available.

The full civil design and construction report is available in the appendices.

4.4 Electrical System

The selected option for the lowest loss circuit configuration which had collection circuits running at 11 or 33kV transformed up to 132kV and on to 400kV onshore. The case was then analysed further for three different power loads corresponding to different velocity regimes in the Severn Estuary. The chosen levels were 1.51m/s, 2.12m/s and 2.51m/s, of these, the closest to the expected peak spring velocity is 2.12m/s, which has a power capacity of 714MW for two fence lines, almost double the electrical rating of the turbines. The number of turbines (both fences total) was determined as 782 for the horizontal axis devices and 678 for the oscillating foil devices. This electrical system can be optimised in detailed design with appropriate savings.

An independent review of the proposed system was carried out by Senergy Econnect. This indicated a potential benefit in the reduction of the system Fault Currents by upgrading the collection system from devices to 66kV. It also resulted in an increased space requirement in the substations and in total a cost estimate increase of around 18% was recommended which is believed to be a robust figure.

Optimisation of the electrical system in design is expected to reduce overall costs and avoid drawing on contingency funds. There is also a strong possibility that the power can be delivered into the local grid at 275kV rather than the National Grid at 400kV which will produce additional savings. This aspect will be determined in detailed design.

The full report on the electrical system is in the appendices.

4.5 Environmental Impacts

The impacts of placing a tidal fence in the Severn Estuary are wide ranging, from impacts to seascape/landscape character and biodiversity, to reduction of the tidal flow and the knock on effect this would have on migratory passage and water quality. Key impacts on fish will include:

- direct impacts on fish passing through the turbines, e.g. stress and injury, both for the seasonal migration and the daily movement of estuarine species
- indirect effects of changes to the hydrodynamics and geomorphology of the estuary, e.g. changes to migratory cues and routes, availability of food, spawning areas and holding up areas

While some small changes in water level and current speed are expected, the porous nature of the tidal fence will reduce these impacts to a low level. It is considered unlikely that there would be significant impacts on sediment transport, morphology and water quality in the Severn Estuary. Impacts on migratory cues and routes, availability of food, spawning areas and holding up areas would therefore be low.

Each fence line will present partial blockage of the channel (approximately 40% at LAT), with open areas between, below and above the turbines, and the 650m navigation gap providing clear areas for free fish passage.

The turbines rotate slowly, compared to pressure turbines (used in an impoundment type scheme), and present a much lower risk of injury to fish. The causeways at each end of the fence will present a potential restriction to fish movement along the coastal margins of the estuary, particularly in the intertidal areas. However, they are unlikely to significantly restrict fish movement, being similar to a small rocky headland, and will provide additional areas of habitat and shelter for migrating and juvenile fish.

The work conducted on the environmental impact of the scheme during construction makes the following key observations:

- Loss of shingle/sand/mud in the inter-tidal regions will be required for the causeways and the quaysides at either end of the fence. Deposition of significant quantities of rock and sheet piling will also be required to form these structures.
- Noise levels from the sheet piling activities may cause disturbance to intertidal wading birds fish and marine mammals, but this activity is reasonably limited in extent and duration.
- Piling of the TEC device foundations will be localised but, depending on tidal state, geotechnical conditions and depth of pile, could have the potential to create an impact to migrating fish and marine mammals. The piling method, percussive, drilled or vibropile, would be determined at the detailed design stage together with any site specific mitigation required.
- The construction yards and contractors' laydown areas at the English and Welsh ends of the fence would require careful siting as a result of local environmental designations at the proposed fence landfalls.

- Movement of materials and construction workers is possible by road, rail and marine transport, although there are specific constraints in the Minehead area relating to rail and road access.

Large areas of the Severn Estuary are designated as a Special Protection Area (SPA) and as a Site of Community Importance (SCI) under the Habitats Directive, for the intertidal and subtidal habitats and migratory fish species. A number of parts of the estuary are designated as a Site of Special Scientific Interest (SSSI). The estuary is also recognised as a wetland area of international importance and is designated as a Ramsar site. Although the impact is likely to be small in comparison to impoundment schemes, these Severn-wide environmental credentials will be impacted by the fence in a number of ways:

- Reduction in upstream water levels of up to 5 cm corresponding to a loss of inter-tidal area of less than 0.5% of existing
- Reduction in peak tidal velocity of between 0.1m/s and 0.15m/s (approximately 7% reduction)
- Some increase in sediment deposition is expected but significant changes are considered unlikely
- Modification of estuary hydro-dynamics is not expected to lead to significant changes in salinity, temperature or water quality

4.6 Navigational Impact

There is a significant amount of both coastal and deep sea commercial traffic in the Severn Estuary, and this is only expected to increase in the coming years. The Bristol Port Company has a particular interest in major developments in the Severn Estuary due to their proposed Deep Sea Container Terminal (DSCT) facility due to commence construction in 2010 (plan to be operation in 2015). The DSCT would enable the Severn Estuary to accept Ultra Large Container Ships (UCLS), which would need to be able to pass through any scheme proposed down stream of the Avonmouth Docks.

The fence scheme has been proposed with a 650m, two-way, open gap allowing traffic to pass un-hindered at all stages of the tide. This proposal is likely to have very little impact on navigation of vessels to the major ports in the Severn.

The navigation study included a brief study of ship to fence collision impact measures. The study found that there is no practicable, cost effective way of protecting the fence from direct collision with a large vessel. Mitigation measures against collision will consist of vessel routing management, emergency anchoring rules, standby tugs and emergency response.

The proposed location of the fence will necessitate the relocation of the pilot boarding area, currently located outside of the Barry Docks. The area will need to be moved downstream of the fence so that vessels can controlled by pilot vessels prior to passing through the fence.

For small vessels and leisure craft, provision of two simple locks, one close to each bank could be possible to facilitate their passage at any time of day. At this early stage of the fence study, this work has fallen outside of the project scope, and as a result has not been allowed for in the cost estimate.

4.7 Costs

Capital Costs – A central case based on re-rated horizontal axis turbine technology, with a conservative approach to device costs has a supply and construction cost of £1.96bn. The range of costs is from the Optimistic case at £1.75bn (-10.7%) to the High Cost Case at £2.3bn (+17.3%). The oscillating foil case was at £2.04bn (+4.1%) . All of these costs include the 15% contingency and indirect costs which are around 16% of the supply and erect cost.

The overall cost has had technology risk, material quantity risk and technology risk priced into it. STFC believes that the conservative approach taken to costs will result in reductions as the design definition and technology development proceeds

O&M Costs - averaged annual costs over 35 years of operation were:

- £18.4 million for the horizontal axis turbines and £20.6million for the oscillating foil device

O&M costs will peak in the years that major change-out of equipment to £100.3million per year for horizontal axis and £46 million per year for the oscillating foil case. This places the O&M costs between 0.8% and 4% of the capital costs annually, depending on the precise activity in any given year. STFC believes this is in accord with a near-shore operation where much of the access for intervention can be via the maintenance bridge.

The allowances in the O&M costs for maintenance activities is summarised briefly below.

- Rate of change-out is about 200 devices per year over a four year campaign and is reckoned to take 13 hours per device (10 hours in the case of oscillating foils). Change takes place after 20 years of operation – this is the assumed outcome of technology development and testing over a 6 to 7 year period shown in the Route Map. *Annex D, filename: 091222 Task 9.1 SETS Route Map V2.5.*
- Technology developers predict initial availabilities (post-commissioning) down to 92% which they expect to improve over a period of years (10 years assumed in this study) to somewhere in the 96-98% range (depending on developer). A decreasing additional downtime allowance has been added over the first ten years of operation to reflect this.
- Routine electrical inspections and breakdowns have been allowed at 8 hours each per device per year.
- Electrical change-out (per device) calculated to take 24 hrs and assumed to affect 5% of devices (39 per year) plus a 25 yearly change-out of all electrical switchgear in the sub-stations in a four year campaign.
- Sub-station routine maintenance (8 hours per device per year) and substation breakdown (8 hrs per device per year).
- Substation change-out – an average 25 items of switchgear to be replaced in full week (168 hrs) shutdowns carried out every 25 years

All the above are reflected in the Cost of Energy model and associated data book (see appendices)

Cost of Energy - The Central Case Cost of Energy (CoE) is £226/MWh , that of the Low Cost Case £204 /MWh and £259 / MWh for the High Cost Case. The Oscillating Foil Case CoE is £253/MWh.

These are outside the £200/MWh target but are derived from conservative costs and based on a programme that allows scope for significant technology development, therefore STFC consider that they are sufficiently close to viability to be taken forward with further investigations.

Re-rated technology - This is described in the report (*Annex D, filename:* 091111 *Fence Configuration Model Cost Report V1.7)* which argues the quantitative case for reducing the cost of an horizontal axis turbine system to adapt it to extract and generate a lower power commensurate with the lower tidal velocity (2.0m/s at peak Spring tide). The re-rated costs have been used to formulate the Central and Low Cost cases. This is justifiable in STFC's view because a seven year development period has been allowed in the Route Map to design, build and deploy an initial prototype to be immediately followed by say, four more devices as a pre-commercial array which would be operated for 2 or more years. From this experience, including the production engineering aspects of manufacture, STFC believes the costs forecast in this study will be evaluated for the devices. In addition valuable O&M experience will have been accrued.

4.8 Route Map

The route map exercise was used to asses the scope of work required to take the fence project from its state at the end of the SETS project to full commercial deployment and operation in the Severn Estuary.

A key observation from the route mapping exercise is influence that the technology readiness levels of what available in the market at present has on the ultimate delivery of the scheme. The route map and associated risk analysis proposes to remove this risk and the associated cost by providing a 5 to 10 machine demonstrator scheme prior to significant investment in the Severn fence. The demonstrator will also allow time to observe the development of the tidal stream industry as a whole, allowing technology with a twenty year life to be delivered.

The demonstrator scheme would be preceded by a package of work (see section - 6 Recommendations) to better understand the Severn resource, and to set the requirements for the demonstrator.

The Severn specific fence project is planned to commence one year through operation and testing of the demonstrator scheme. If a late 2010 start is achieved for the project, Severn specific work (excluding initial feasibility work stream) would start mid 2015, with a phased installation and system power output starting at the beginning of 2011, with a fully operational scheme delivered early 2023. Please note that this plan is subject to worst case contingency, quantified in the route map document.

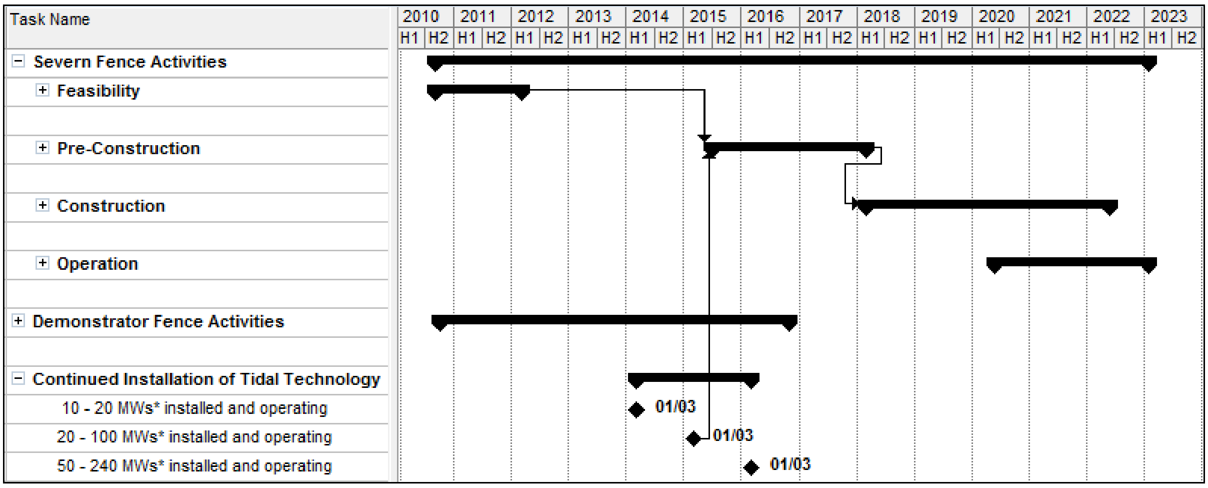

Figure 10: *High level route map plan. Note 'Continued Installation of Tidal Technology' figures are taken from: BWEA Marine Renewable Energy, State of the industry report - Oct 2009*

Please note that a comprehensive risk summary document (produced by Marubeni) is supplied with this report and provides a comprehensive understanding of the risks associated with deploying a fence in the Severn Estuary.

5 CONCLUSIONS

5.1 Fence Configuration

A tidal fence scheme in the Severn Estuary as proposed by the STFC has the potential to provide power to over half a million homes with electricity (assuming 0.6kW average rate of consumption) at a conservative, competitive (future) cost of between 20.4 and 24.5 p/kWh.

The scheme would produce in excess of 380MW with an annual energy delivery of 0.88TWh/year, and an associated annual carbon saving in excess of 380,000 tonnes of CO_2.

The fence configuration was determined to be two lines of 391 devices (MCT case) or 339 devices (Pulse Generation case). The two lines need to be separated by 1 km which results in an acceptable peak velocity of the tidal stream through the gap to be 2.5m/s.

Study of the impact of the “thickness of the fence” on the peak velocity through the navigation gap showed that a reduction in the peak flow speed occurs with increased separation of the two fence lines and maximises energy extraction from the tidal stream.

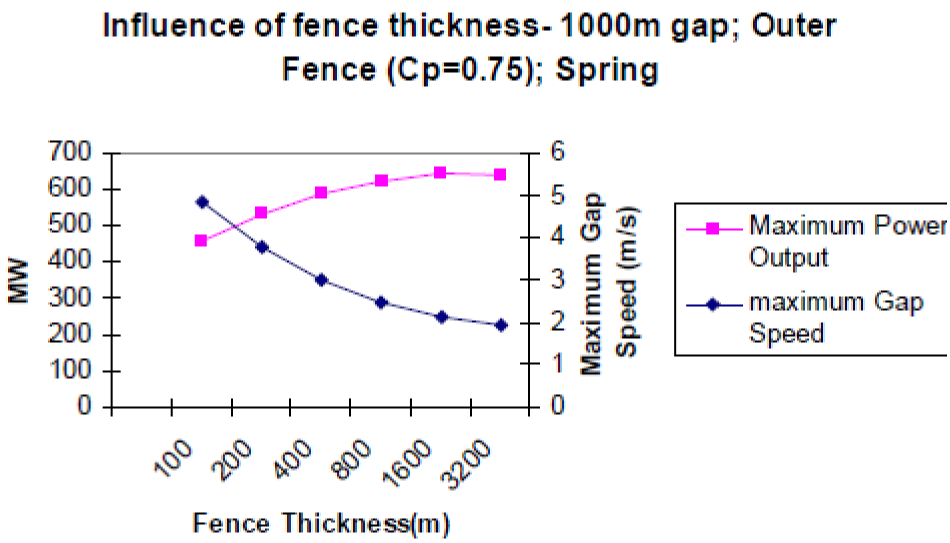

Figure 11: *Shows how the flow speed through the gap decreases with increased thickness of the fence.*

Source: Bryden, I “Hydraulic Model Description”, January 2010

The 1 km separation was therefore chosen so as to obtain close to the maximum power with a peak tidal velocity in the gap that does not limit the passage of larger cargo vessels.

Gap for navigation – 650 m – expected to allow free passage for all large vessels in both directions capable of 12-15 knots, coastal vessels capable of 9 -10 knots may be restricted to periods of about 3 hours in every tide. For small vessels and leisure craft – provision of two simple locks, one close to each bank could be possible to facilitate their passage at any time of day. At this stage these have not been allowed for in the cost estimate.

These conclusions from the model need to be tested with further, more sophisticated modelling work. It should be noted that the current conclusions do not match with modelling work conducted on the tidal fence concept previous to the SETS project. As a result these conclusions require further work if they are to be fully validated. For the purpose of this project, the results produced by Professor Bryden’s work represent a conservative approximation of energy conversion, and hence can be considered as a baseline from which STFC expects to improve as understanding of the hydro-dynamics of the fence is improved.

The civil structure of the fence is a simple, cost-effective solution to the problem, and facilitates operation and maintenance economies of scale by enabling all devices to be accessed by common lightweight roadways (two separate sections, either side of the navigation gap, for each row). The fence will also be served by two quays at either side of the river, enabling effective use of maintenance vessels when required.

The civil and electrical works can be installed in a phased scheme to enable the fence to start generated power and revenue early in the construction process. Four phases corresponding to four pairs of electrical sub-stations.

The civil super-structure enables all electrical cabling (excluding the navigation gap link), sub-stations and switchgear to be housed out of the water on the maintenance bridge. This significantly reduces the cost of the system, through reduced specification and ease of operation and maintenance.

The electrical system is sized, at present, such that the scheme will connect to the National Grid through the District Network Operator. This will change if it is possible to increase the output of the scheme.

5.2 Environmental Impact

Although large enough to have far-reaching effects on the Severn Estuary and surrounding landscape, the magnitude of the impacts on the environment and associated mitigating measures would be minimal. This can be concluded from the following key points:

- The fence would utilise slow moving (slower than impoundment scheme pressure turbines) resulting in reduced likelihood of fish mortality
- The fence would cause less than 0.5% reduction in inter-tidal areas
- The fence would reduce flow speeds local to the fence by no more than 7%

It can be concluded that, whilst reductions in tidal range could lead to a partial loss of the inter-tidal mud flats, which support large numbers of resident and over wintering birds, such losses are expected to be very small when compared to the total area of mudflats within the estuary. Given an estimated 5 cm change in low water level, the loss in the total area of mud flats exposed at low water on a spring tide is conservatively estimated as <0.5%. This would give a typical reduction in the width of inter tidal mud flats exposed at low water (i.e. measured perpendicular to the shoreline from high water to low water) of between 2 and 25m, depending on beach slope. Such a small loss in mud flats would not be expected to have a significant impact on feeding birds.

Environmental impacts due to construction would not be un-due for a construction project of this size, and would need further investigation as the project proceeds, and the SEA is developed by DECC.

5.3 Navigation Impact

With the proposed navigation gap in the fence, the fence would have very minimal impact on shipping activity in the estuary and economics associated this. The fence also presents a future proof scheme, by catering for the largest vessels associated with the planned developments in the estuary.

It is believed that a scheduling study and better information on vessel movement would enable a change in gap size or the employment of gates / locks, and as a result, could ultimately allow the fence to access more energy.

5.4 Capital Costs

The base case is £1.96 bn representing a realistic cost forecast of the optimised horizontal axis turbine with lowest cost £1.75bn (-12.1%) and highest - £2.3bn (+17.3%). The degree to which de-rating and cost reduction of devices can be achieved in mass manufacture has been interpreted in a realistic fashion using the initial cost of the 30^{th} machine based on the de-rated device assessment and a 92% Experience Curve. The more optimistic lowest cost option was evaluated starting from the 50^{th} de-rated machine cost

5.5 Operation and Maintenance Costs

The average at £18.4 million per year to £100.3 million per year for the axial device, and £20.6million to 46 million for the oscillating foil device lie in the range that offshore industry experience would suggest is reasonable. The allowances made are credible assumptions for the expected performance of devices and fall within the views expressed by developers of technologies.

5.6 Economic benefits

The scale of the Tidal Fence Scheme is such that considerable employment would arise in both SW Region and Wales, both in the construction and operational life of the facility. The direct jobs created during the manufacturing/construction period will be of the order of 10,000 over the four years and it is reasonable to assume that 40% would be created in the local regions. Further each direct job will give rise to a potential 2 support jobs (hotel, catering, accommodation and other services) bringing the total regional jobs close to 12,000.

In the O&M phase, an ongoing 300 jobs should be available with peak working rising at times into the 1,200 to 1,500 range with manufacturing jobs elsewhere in the UK for supply of some device components.

5.7 Cost of Energy

The Base Case for Cost of Energy (CoE) at £218/MWh has variation cases which are +18.8% and -6.6% of the base case figure. The risk analysis and the independent assessments of the capital costs indicate the level of confidence in this initial estimate as being suitably conservative for the status of engineering to date and support STFC's expectation of improved economics as the fence systems are better defined.

Financing

The Tidal Fence Scheme represents a good opportunity for the private sector to finance the main project, subject to a clear government commitment to the development. Ahead of the project itself, is a smaller amount of "higher risk" expenditure required to execute the studies that will remove risk from the overall project. Some of this expenditure is reflected in the recommendations for further work below; another additional tranche is given in the CoE model phased expense for years between 2012 and the start of the project c 2017. Finally the pre-commercial array of de-rated devices will need to be funded in a similar manner to those being deployed currently.

5.8 Market Opportunity

The ability to extract energy from the lower velocity tide races offers an excellent new market area in the UK and in other parts of the world. Technology that can be successful in tides peaking around 2m/s will increase the available tidal resource areas by a factor of between four and eight times the high energy tide race areas. As a significant export opportunity could exist for the UK in this respect, the development of such technology should not be ignored.

With minimal impact on tidal flow in the estuary and negligible impact on water levels, the fence scheme could be successfully combined with other power extraction schemes to provide the best compromise of stakeholder impact and delivery of energy.

The route map and associated risk analysis conclude that the fence scheme could be delivered in a manner that minimises risk to the government whilst accelerating the tidal stream industry as a whole (through the ordering of more than 600 units). The scheme has the potential to cement the UK's position in the world as the home of tidal stream technology development.

6 RECOMMENDATIONS

STFC recognise that a number of additional activities are required to reduce the risk around technology, construction and estimated costs. The following items are considered to be the minimum:

- ACP survey for current profiles in the Estuary (8 -10 positions) - £100k
- Swathe bathymetry of route(s) - £150k (by a recognised survey company possibly including ACP deployment in package)
- Sub-bottom profiling to assist geological assessments - £100k (if deployed with swathe bathymetry)
- 2.5-3D model using Telemac or similar by HR Wallingford or equivalent - £500k
- Sedimentation studies and simulation for the shipping gap and channel and the coastal areas - £200k
- Preliminary geotechnical investigation plus "mini-coring" £400k (recognised geotechnical survey company. surveyors eg Fugro /Andrews/Gardline or equivalent)
- Onshore site surveys - £50k (Local surveyor practices)
- Provision of lump sums to say, three developers to produce concept design, cost and manufacturing report for re-rated turbines suitable for a 2m/s max tidal flow. - £150k (carry out update to developer selection first)
- Further design definition of the fence concept - £250k (including some possible elements of partly – funded man hours)
- Scoping EIA work and engagement with key stakeholders and planning authorities £200k (Maximising use of work already carried out for Barrage studies)
- Allowance for managing the above plus cost risk analysis & reporting to DECC etc - £200k
- Funding search/studies to establish potential private sector funding/insurance plan for whole development – £100k

Total cost £2.4million Duration thought to be – 18 months to 2 years from start

Outcome from these activities:

- Capex – more accurate with greater confidence limits
- More detailed Opex model and revised cost of energy
- Increased confidence of technology performance (plans/funding for deployment of prototype and proving in small array)
- Manufacturing report including commercial requirements for manufacture. Clear programme from technology trials to manufacture.

- Associated business issues will have been be analysed and investigated with potential investors, clear criteria determined to shape project objectives.

This work would answer the question “Is this project suitable to go ahead?”

7 ANNEXES

7.1 Annex A - Scheme Description

Please note that the following section contains information already presented in main body of the report, but is included for clarity on the scheme as a whole.

All technical drawings are taken from Sigma Offshore Ltd's final report: *Annex D, document filename: SOL-059 001-TN 004-RevC*. Please refer to original drawings for full detail.

The selected tidal fence scheme consists of two rows of Tidal Energy Convertor (TEC) devices extracting kinetic energy from the tidal flow in the Severn. The fence runs from Aberthaw (Welsh coast) to Minehead (English coast). This route represents a distance of approximately 19 km, o f which approximately 16.5 km of channel width is practicably available for the installation of TEC devices.

The two rows are separated by 1000m, and each include a 650m wide navigation gap located at the deepest point in the transect, 2500m from Aberthaw. The gap location corresponds to the present, dominant path of commercial shipping traffic.

The location of the fence is shown in Figure 12.

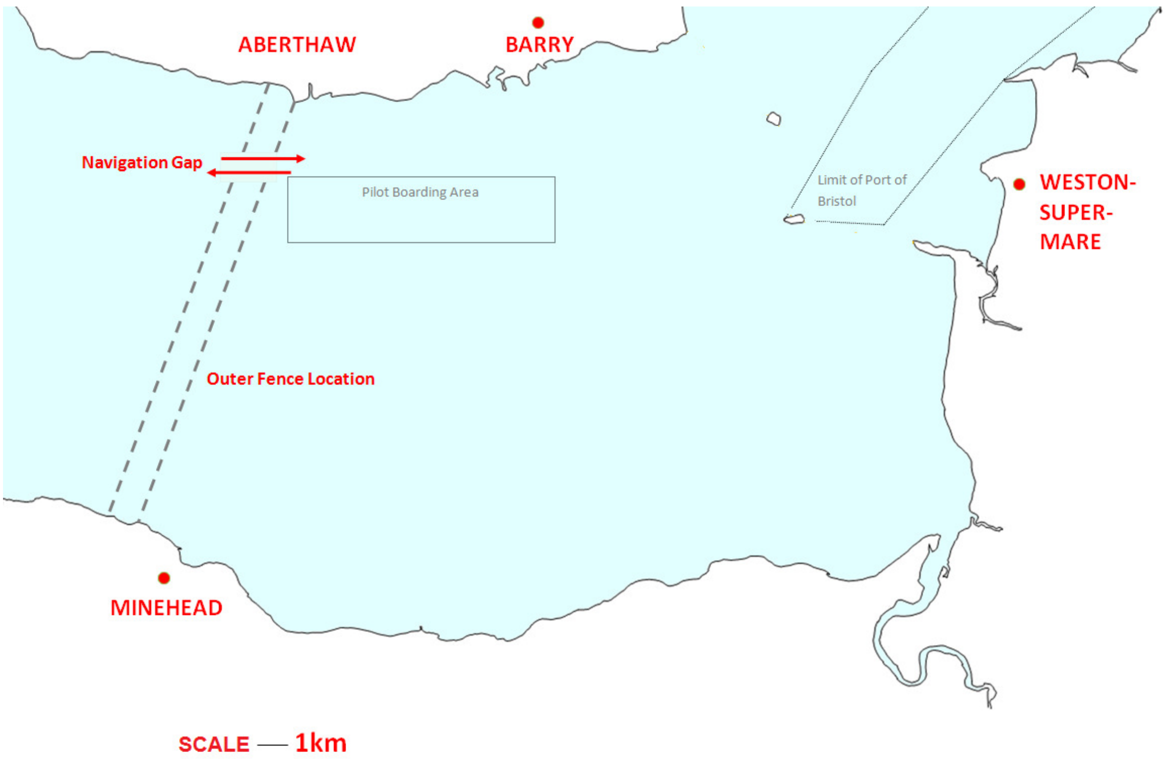

Figure 12: *Schematic showing the proposed location of the fence, the two rows of devices, and the navigation gap.*

Mechanical Engineering

Marine Current Turbine's (MCT) twin rotor device and Pulse Tidal ltd's (Pulse) oscillating hydrofoil device have been selected as the best choice of TEC machinery (at this juncture) when considering ability to extract energy and potential impact on fish mortality.

The fence consists of between 678 TECs in a Pulse configuration, and 782 TECs in an MCT configuration. TEC units will have a lifetime of no less than 20 years, a figure that is anticipated to rise as the tidal stream market develops. The scheme will have a lifetime of 120 years.

The fence demonstrator scheme will use pre-commercial / first generation commercial technology with an anticipated machine life of 10 years.

Civil Engineering

The civil structure of the fence consists of a 2.5m diameter piles, connected by a relatively lightweight concrete bridge deck. The piles act as the bridge deck support, but also as the connection points for the TEC units. The bridge deck serves as an operation and maintenance facility, providing expedient access to the TEC units, and also as a routing structure for the power export and control cabling and associated sub-stations, transformers and switch gear.

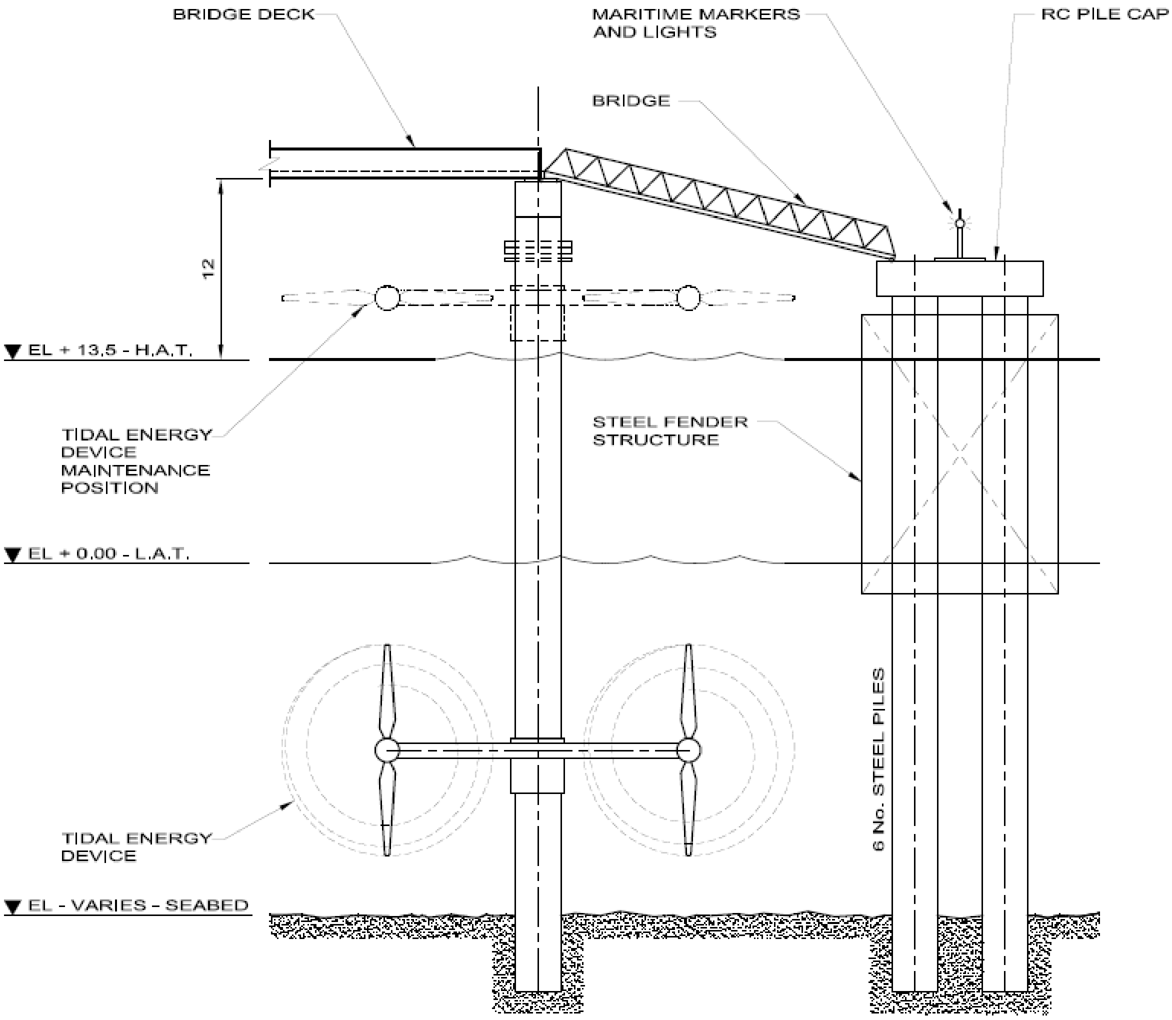

Figure 13: *Drawing showing an example TEC device located on the vertical bridge support piles. This particular view is taken at the termination of the fence at the edge of the navigation gap.*

The landfalls of the civil structure comprise of rock-filled causeways:

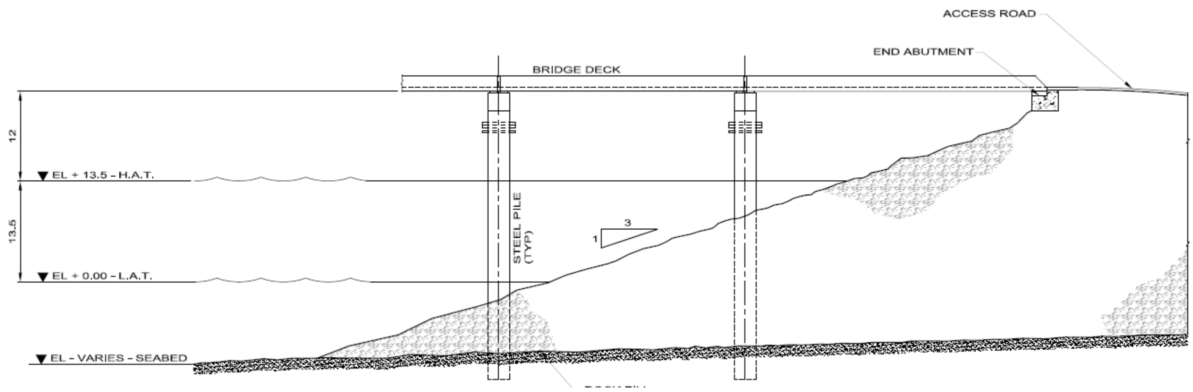

Figure 14: *Drawing showing an example landfall causeway at the end of the fence.*

At the terminations of the fence either side of the navigation gap, protective 'dolphins' have been used to protect the fence from minor impacts from vessels (see section **Error! Reference source not found. Error! Reference source not found.**), and to carry navigation markers. The dolphins are accessed by a gantry walkway.

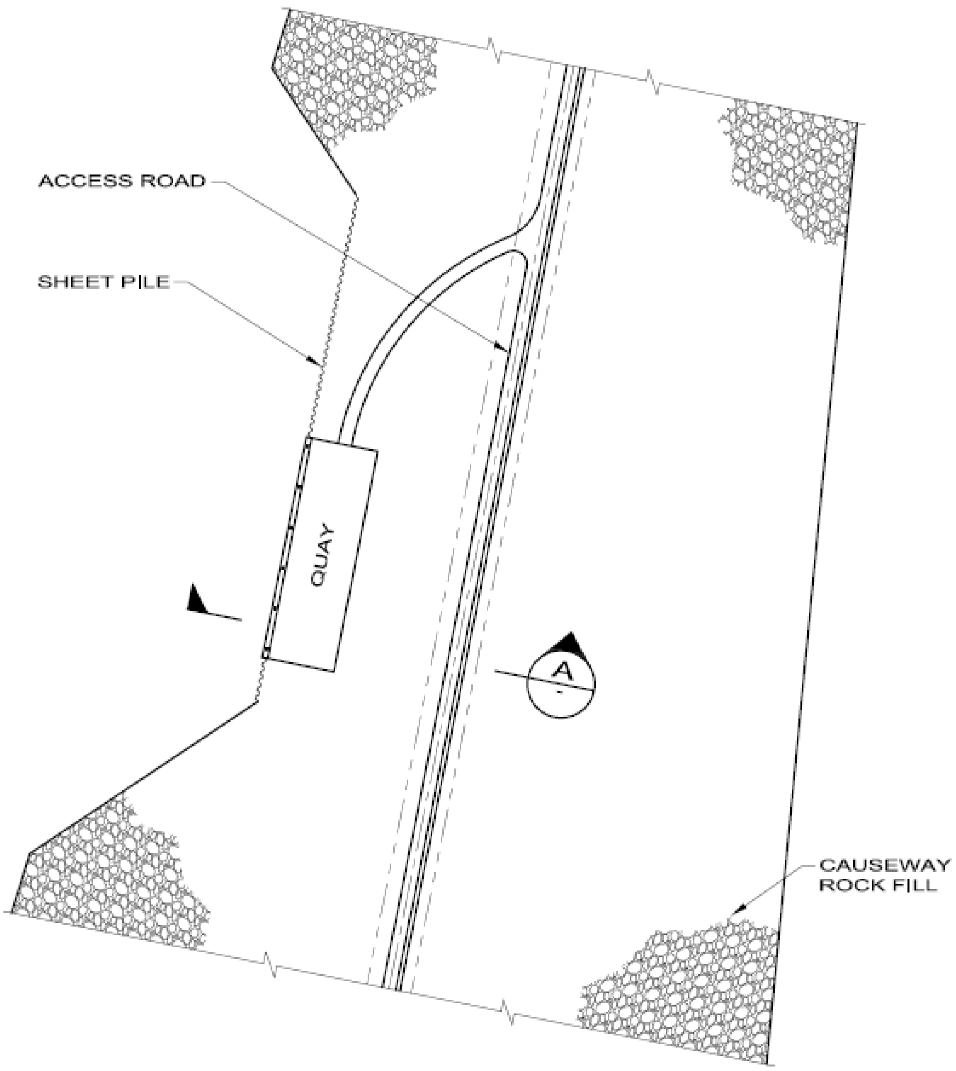

Figure 15: *Drawing showing an example quay built into the side of the landfall causeways. These quays (at either end of the fence) will serve maintenance vessels required when the access bridge is insufficient.*

Electrical Engineering

The electrical power take-off system of the fence consists of four substations and associated transformers on each fence, one on each section north of the navigation gap, and three of each section south of the gap. All power is exported to the Welsh side of the estuary to minimise local grid modification costs.

Connection to the TEC units is made at 11kV. This is stepped up to 66kV, then 132kV (twice to limit fault current) at the bridge transformers, and exported to shore at 132kV. At an onshore substation, the voltage is stepped up to 265kV for connection to the DNO network.

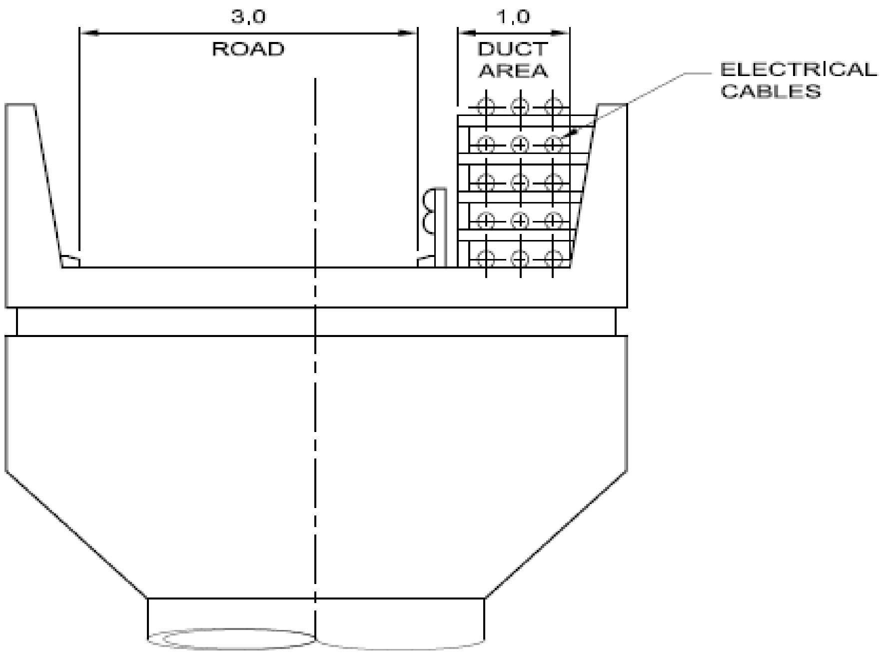

Figure 16: *Drawing showing accommodation of electrical cables along the bridge deck.*

Connection across the navigation gap is made via trenched cables.

Environmental Impact

Whilst wide ranging, the environmental impact of the proposed fence scheme on the Severn would be low in comparison to tidal impoundment schemes. Loss of inter-tidal area is estimated at <0.5% of existing.

Mode of Operation

The fence operates during ebb and flood tides, providing two distinct peaks of power output every tidal cycle (approximately twelve hours). Power output is proportional to tidal flow velocity, such that output is lower during neap tides.

Rated Power and Annual Energy Yield

Flow speeds a t the outer fence location are currently understood to be peak spring tide: 1.9 m/s and peak neap tide: 1.0 m/s.

The scheme has a rated (operation at peak spring tide) power output of between 383 MW and 389 MW (MCT and Pulse respectively).

The annual energy delivered by the fence is between 0.88TWh and 0.84TWh (MCT and Pulse respectively – please note the switch in magnitude from rated power).

7.1.1 Technical Risk

The key area of technical risk is the relatively untested tidal stream turbines. The STFC propose to mitigate this risk through the development of a 5 – 10 unit demonstrator fence scheme. The demonstrator will be installed in a location that simulates the Severn characteristics as closely as possible. This process is expected to take about 6 years in total. During this time, the tidal stream market is expected to develop to the point at which more than 100MW has been installed.

Other technical risk areas include the design of the support structures and finalising the use of the structure to facilitate the maintenance method for best cost/availability results. Life of assets must be evaluated in a rigorous manner.

The characteristics of the Severn Estuary must be fully measured and modelled including flow regimes, sediment movement (in the shipping channel and near the shores).

Addressing all of these risk areas will effectively reduce technical risk to a manageable level that will give confidence to investors for the Fence.

Please see the following documents (referenced by filename) contained in Annex D for further information:

Risk Assessment of Routemap v11

100125 STFC Risk Register V3.0

100121 SETS Route Map Gantt Chart V1.4

091222 Task 9.1 SETS Route Map V2.5

7.1.2 Cost and amount of energy

The range of cost of energy arrived at from this very preliminary study has produced a fully adaptable CoE model that can be used to monitor the effectiveness of all subsequent studies and design activity. The lower end of the calculated range falls within/close to the £200 /MWh target but it should be remembered that the design is far from optimised, detailed procurement enquiries have not been carried out to assess the benefits of bulk purchase.

Please see the following documents (referenced by filename) contained in Annex D for further information:

091111 Fence Configuration Model Cost Report V1.7

20100127 Maintenance Costs (FINAL)

20100127 STFC (FINAL)

20100127 STFC capital costs (FINAL)

*20100128 STFC - Data Book _FINAL_*

Outline Cost Method for the Outer Fence Rev 1

7.1.3 Impact on energy market and security of supply

The energy produced is of a level that can be accepted cost-effectively into the local DNO grid (delivered at 275kV) and no serious impact on the grid is envisaged for this case. It does provide a reliable, predictable albeit variable supply closer to a weaker extremity of the grid network. It allows a renewable supply of significant proportion to be introduced in conjunction with other sources including further fences, lagoons and barrages.

Energy supply is directly proportional to flow speed, irrespective of direction, meaning that the fence will deliver energy during both ebb and flood tides. A small amount of energy will be forfeited at very low flows due to TEC device cut in speeds (devices only start at a certain flow speed).

The Fence would effectively establish an enhanced international market for UK by providing technology that would address lower energy tide races which occur far more widely around the world (a factor of 4 to 8 depending on location), than the somewhat limited high energy tide races that are initially being targeted by technology developers. This market would extend the developable tidal energy sector in a very significant way.

Please see the following documents (referenced by filename) contained in Annex D for further information:

100125_PSA Study_VFinal

2382 Cleantech Severn Tidal Fence Review v1

7.1.4 Affordability and value for money

The proposed development should be affordable by the private sector providing Government is willing to share in and underwrite the much smaller (approx £20 million) investment into de-risking the project to a status where project finance criteria are met (Satisfactory rate of return at 3 ROCs, long project life and acceptable cost reductions are foreseen).

Please see the following documents (referenced by filename) contained in Annex D for further information:

Risk Assessment of Routemap v11

091111 Fence Configuration Model Cost Report V1.7

20100127 Maintenance Costs (FINAL)

20100127 STFC (FINAL)

20100127 STFC capital costs (FINAL)

*20100128 STFC - Data Book _FINAL_*

Outline Cost Method for the Outer Fence Rev

7.1.5 Environmental impact

The environmental impact of the scheme is shown to be minimal with the very small changes in water level (5 cm) predicted. This is understood to have minimal impact on loss of inter-tidal areas (<0.5%) and to allow free access for commercial shipping. Small scale locks adjacent to the shores are expected to be provided for small inshore and leisure craft.

Please see the following documents (referenced by filename) contained in Annex D for further information:

7.2 - P1250_RN2241_REV2

091028_Task_5.2_Fish_V1.3

091202_Task_8.2_V1.2

7.1.6 Regional level economic and social impacts

The regional impacts for the long term are thought to be positive, enhanced local power supply, short term jobs increase during construction (and to a lesser extent during technology development if executed locally). Whilst some increases in traffic around the construction period will be experienced, these reduce dramatically in operation and maintenance over the asset life.

Operation and maintenance represents a significant boost to local economies including long term employment relating to factories, provision of machinery, spares and equipment, logistics services, requirements for hotel accommodation, housing, port operations,

Furthermore, plans for new deep-water port facilities and other developments in the Bristol Cardiff ports will not be curtailed or inhibited by the Fence approach.

Please see the following documents (referenced by filename) contained in Annex D for further information:

General

7.2 Annex B - Development Route Map

The route map shows feasible execution and completion of the Fence by around 2023 and probably no later than 2025, even allowing for the development of de-rated TEC technology. Because the environmental impact is low, far less delay and difficulty should be encountered than would be the case of barrage options with much greater changes in water levels and the elimination of introducing further tidal power generation options.

Please see the following documents (referenced by filename) contained in Annex D for further information:

091222 Task 9.1 SETS Route Map V2.5

100121 SETS Route Map Gantt Chart V1.4

Risk Assessment of Routemap v11

7.3 Annex C - Risk Register

Please see the following documents (referenced by filename) contained in Annex D for further information:

Risk Assessment of Routemap v11

100125 STFC Risk Register V3.0

7.4 Annex D – Supporting Documents

This report should only be read in conjunction with the supporting documents folder: *100128 SETS STFC Annex D – Supporting Documents V1.2*. A schedule of documents contained in the Annex D is given below for information:

If you do not have access to this document folder, please contact:

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E-mail: ian.godfrey@itpower.co.uk
Direct Tel: +44 (0)117 9809449

Annex D - Schedule of Supporting Documents

This document catalogues the main deliverables of the project in final draft format

Note: Documents are listed in name order (use file browser to re-order accordingly)

Document Ref.	Report title	Filename	Issue no.	Source Partner
STFC 1	Key Environmental Drivers For Construction	7.2 - P1250_RN2241_REV2	2	Metoc
STFC 2	Design Review of Report	2382 Cleantech Severn Tidal Fence Review v1	1	Senergy E
STFC 3	Gateway Review 1	090908 GWR 1 Report V1.1	1.1	Consortium
STFC 4	Gateway Review 2	090929 GWR 2 Report V1.1	1.1	Consortium
STFC 5	TEC Energy Model	091019 STFC TEC Energy Model V5.4	5.4	IT Power
STFC 6	Turbine Studies: Environmental Impacts	091028_Task_5.2_Fish_V1.3	1.3	Metoc
STFC 7	Fence Configuration Model Report	091105 Fence Configuration Model Report V2.3	2.3	IT Power
STFC 8	Gateway Review 3	091105 GWR 3 Report V2.0	2	Consortium
STFC 9	Fence Configuration Model Cost Report	091111 Fence Configuration Model Cost Report V1.7	1.7	IT Power
STFC 10	STF Turbine Impact Studies on the Wider Environment	091202_Task_8.2_V1.2	1.2	Metoc
STFC 11	Gateway Review 4	091204 GWR 4 Report V1.1	1.1	Consortium
STFC 12	Route Map	091222 Task 9.1 SETS Route Map V2.5	2.5	IT Power
STFC 13	Gateway Review 5	100104 GWR 5 Report V1.3	1.3	Consortium
STFC 14	Gateway Review 6	100115 GWR 6 Report V1.1	1.1	Consortium
STFC 15	Route Map Gantt Chart	100121 SETS Route Map Gantt Chart V1.4	1.4	IT Power
STFC 16	STFC Risk Register	100125 STFC Risk Register V3.0	3	Consortium
STFC 17	Severn Tidal Fence Electrical Network	100125_PSA Study_VFinal	Final	Narec
STFC 18	Maintenance Costs	20100127 Maintenance Costs (FINAL)	Final	Marubeni
STFC 19	SETS Programme Task 5.4	20100127 STFC (FINAL)	Final	Marubeni
STFC 20	STFC Capital Costs	20100127 STFC capital costs (FINAL)	Final	Marubeni
STFC 21	Cost of Energy Model Data Book	20100128 STFC - Data Book _FINAL_	Final	Marubeni
STFC 22	Navigation report	BMT - Navigation Report V01 (Issued 8th Dec 09)	1	BMT
STFC 23	Construction of STF	Construction of STF - Comments B1	B1	SLP
STFC 24	Costing of STF	Costing of STF - Comments B2	B2	SLP
STFC 25	Outline Cost Method for the Outer Fence	Outline Cost Method for the Outer Fence Rev 1	1	CleanTech
STFC 26	Overall Fence Design Considerations	OVERALL FENCE DESIGN CONSIDERATIONS Rev 3_final_	3	CleanTech
STFC 27	Risk Assessment of Development Route Map	Risk Assessment of Routemap v11	11	Marubeni
STFC 28	Severn Fence Hydraulic Modelling	Severn Fence Hydraulic Modelling		UoE
STFC 29	Report on civil engineering strutures	SOL-059 001-TN 004-RevC	C	Sigma
STFC 30	Severn Tidal Fence Costing Review	STF Report - Review Comments B2	B2	SLP
STFC 31	STFC Design Philosophy	STFC Design Phil rev 1_final_	1	CleanTech
STFC 32	Tidal Power in the UK - Severn velocities	Tidal Power in the UK - Severn velocities		CleanTech