Your Ref: Avon flood management and tidal power

Our Ref: 70024175/L002

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CONFIDENTIAL

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Dear Robin,

Subject: Tidal Power Assessment for the River Avon Flood Management Project

Thank you for your instructions to prepare a desk-top report on the opportunity for tidal power from the Avon working in conjunction with the potential tidal barrier sites.

The views expressed in this paper are based on the principles of tidal power design as applied to the basic characteristics of the River Avon from a high-level strategic viewpoint. Before feasibility of the proposal could be confirmed, additional study would be required on ground conditions, tidal and river flows, costs of construction and operation and the acceptability of the proposed method of operation from technical, environmental and hydrological perspectives.

Summary

Although significantly smaller than its neighbour, the Severn Estuary, the River Avon shares the same tidal range and therefore has similar potential to generate low carbon energy if its waters can be impounded to create a difference in level between the river and the sea. On the basis of the principal characteristics of the River Avon between the limit of tidal dominance at Netham Weir and Avonmouth, namely the area and volume impounded and the tidal range, and correlating these with other studies undertaken in the Severn Estuary, there is a relatively large energy resource in the tidal stretches of the Avon that can be captured by tidal power.

Using the data made available from Google Earth and the short-list flood defence options report prepared by Aecom for Bristol City Council (May 2016), a conservative approach would involve installing a 12 MW bulb turbine in either of the two tidal barrier proposals at Avonmouth or Ham Green. This could generate 25GWh/yr, yielding a potential annual revenue of over £2.25m for a capital investment, including optimism bias of 60%, of some £30m. With annual operating costs of £300k included, this would yield an IRR of over 5% before inflation, or 7% if future inflation averaged 2% per year.

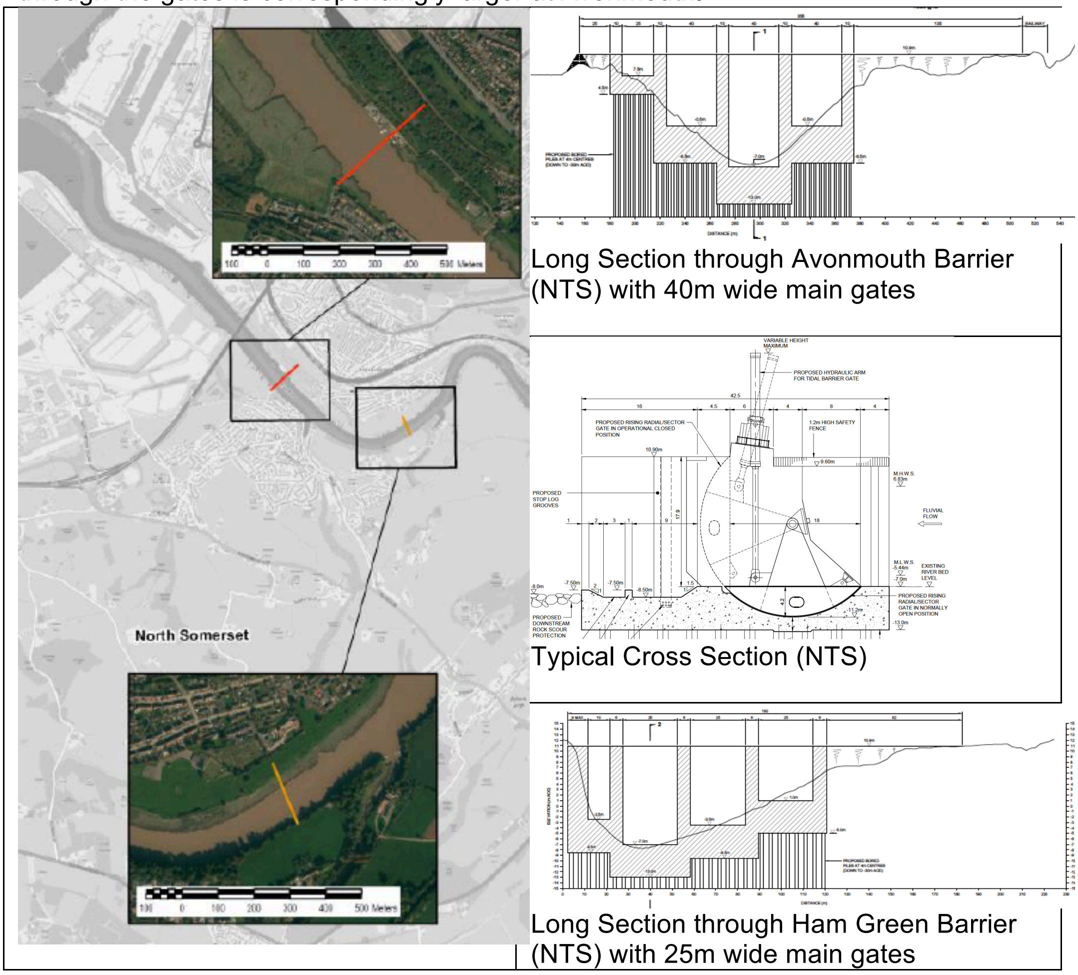
A 12 MW tidal power facility could be integrated into the existing tidal barrier proposals at Avonmouth or Ham Green but significantly more work would be required to consider the detailed costs, installation and access requirements, the benefits and impacts before an optimum capacity and configuration could be confirmed. Generating tidal power does not require a rigid barrage but could utilise the rising sector gates in the existing tidal barrier proposals to impound the River Avon for 4 hours in every 12. This

would require some re-design of the rising sector gates to enable them to be resilient when they are operated twice a day, every day and to be able to withstand differential water levels in both directions. If the scale of a tidal range facility at 12MW is considered to be too ambitious, a tidal stream alternative may also be feasible although this would be significantly smaller , with a higher cost of energy (the unit cost of producing each kWh) given the relatively low currents in the River Avon. On the other hand, further studies may show that a 12MW facility is sub-optimal and that a better return could be achieved using a larger installed capacity.

Background

One of the options being considered for the enhanced flood protection of Bristol from potential sea level rise is a tidal barrier. This would operate in a similar manner to the Thames Barrier with rising sector flood gates allowing free water passage until they are raised to prevent tidal water ingress into the Avon. There is the potential to use this mode of operation more flexibly in conjunction with tidal power generation.

Two sites have been considered for a tidal barrier as shown in Figure 1. The most expensive is a 355m wide option just upstream of the M5 Avonmouth Bridge. A second, less expensive option is approximately half the width at 180m in a location further upstream close to Ham Green, A third site, at Cumberland Basin, was also considered. It is noted that the reinforced concrete elements, the primary indicator of cost, are 195m wide at Avonmouth and 118m at Ham Green. The free flow area through the gates is correspondingly larger at Avonmouth.



Long Section through Avonmouth Barrier (NTS) with 40m wide main gates

Typical Cross Section (NTS)

Long Section through Ham Green Barrier (NTS) with 25m wide main gates

Figure 1 Location and Sections through Potential Tidal Barriers (© Aecom, 2016)

A tidal barrier, by comparison with other options of raising linear defences along the protected area, will always have a higher cost in net present value terms because of it's capital intensive nature and the requirement to construct it "up-front". Improvement to linear defences such as flood embankments and walls, by contrast, can be programmed over a longer period of time, deferring costs into the future and thus reducing their cost in net present value terms. However, each has a different inflation profile, with the inflation risk and cost associated with a barrier being confined to its relatively short construction period whilst a long programme of linear defences is exposed to inflation risk and cost over a more prolonged period. It would be beneficial to run a sensitivity analysis with future inflation assumptions to understand the impact of inflation of the net present value of the different options.

All options have different impacts with tidal barriers involving work in the river and with associated impacts on the river basin environment, whilst linear defences, particularly at water-front locations, have the potential to cause widespread loss of quality in landscape and amenity terms.

Even if the different inflation profiles are accounted for when comparing options, tidal barriers are still likely to be more expensive (in NPV terms) than linear defence improvements but have the potential to achieve greater benefits, although not all these benefits are necessarily of value to the project's prime purpose of flood defence. Amongst these additional benefits, for a tidal barrier on the Avon, is the incorporation of a road crossing (the economic case being the removal of local traffic wishing to cross the River Avon at Avonmouth from the congested M5 between junctions 18 and 19) and the generation of low carbon power using the benefit of the structure provided by the barrier (the subject of this paper).

Incorporating a road crossing into a tidal barrier (with or without power generation) reduces the cost compared with a "stand-alone" road crossing as the foundations are essentially provided by the reinforced concrete elements of the flood barrier. The detailing of the structural elements would require some amendment to accommodate a swing or lift bridge over the main navigation channel and the cost reductions (compared with a stand-alone structure) only arise if the tidal barrier is on or close to the preferred road alignment given the cost of associated road connections to the Portishead road to the South and the Portway to the North. A road crossing would involve running the road on the embankments either side of the tidal barrier and running a rigid bridge deck between the piers of the non-navigable tidal gate channels. The navigation channel (the tidal gate channel co-incident with the deepest part of the natural channel) would require a swing or lift bridge of 25m or 40m depending upon which location was adopted. A swing or lift bridge would be required by a stand-alone structure assuming a lower cost design was preferred with occasional interruption for navigation. The alternative of a higher bridge with clearance for shipping would be more expensive and neither tidal barrier location would offer any advantage as the gradients required to achieve acceptable navigation clearance would require an elevated carriageway many tens or hundreds of metres away from the tidal barrier, meaning that a higher bridge would effectively be a "stand-alone" structure whether or not it was co-incident with the tidal barrier alignment.

If a tidal barrage was considered as an alternative to a tidal barrier, the practical differences from the perspective of a road crossing would be minimal as bridge decks would still be required to span between the sluice gates that would be needed to pass the peak river flow from the River Avon into the Severn Estuary. The only difference between a barrage and a tidal barrier at Avonmout or Ham Green is the depth of the gates – a tidal barrier has full depth gates whereas a barrage has shallower gates based on the fact that water levels in the Avon would be impounded permanently. This would be challenging given the environmental implications of impounding water levels permanently, and there is no advantage of a barrage over a barrier providing full depth flood gates (capable of operating on a daily basis if power generation is adopted) can be economically sourced.

The incorporation of a bridge and associated road links provides an advantage for the tidal power installation as it provides an engineered access route and the ability to mobilise a mobile crane as and when maintenance is required, rather than providing in-situ craneage.

This short paper looks specifically at the tidal power opportunity presented by the Avon, and whether it is possible to integrate this with a tidal barrier. It is important to clarify one issue. Tidal power does not need a fixed barrage to generate power from the tidal range – a tidal barrier as proposed for the Avon, operated on each tide, can perform the same function of impounding water in the river before releasing it through turbines back into the sea.

Tidal Power Requirements

The River Avon has a tidal range in excess of 14m at peak spring tides and the mean spring tidal range is over 12m. The River Avon is tidal from Netham Weir to its most downstream point at Avonmouth. A flood barrier, if appropriately designed, provides the opportunity to impound water within the River Avon basin at high tide and release it through turbines to generate power as the tide falls. Operating the flood gates towards the end of the generating cycle would allow the basin river levels to fall to close to the natural low tide mark on ebb tides with the river basin being recharged as it is today on the flood tide.

There are two types of tidal power:

- Tidal range relies on impounding a volume of water at high tide and discharging it through turbines to generate power when a difference in water level exists between the impounded water and the sea level, as the tide falls. The power generated is a direct function of the level difference and the volume of water than can be stored and discharged through the turbines. A minimum tidal range at mean high water springs (MHWS) of 5m is required.
- Tidal stream[1] turbines which operate in a similar manner to wind turbines, using the water current to generate power. The power generated is a function of the cube of the current speed and the swept area of the propeller. For this reason, large diameter propellers and currents at MHWS of 2.5m/s or higher are required.

Tidal stream turbines may, subject to confirmation of currents, be feasible although they typically require deep water below the Lowest Astronomic Tide (LAT). Tocardo in the Netherlands has developed a design that can be lowered into the water to generate when the river is not being used for navigation and when water levels and currents are suitable for generation but their pilot site in the Netherlands has a relatively low tidal range and high currents.

The River Avon, at Avonmouth, has one of the highest tidal ranges in the world and given the more attractive economics of tidal range over tidal stream, even at high currents, this paper focuses on the opportunity from tidal range. A recent review[2] of tidal currents during extreme spring tide events at Bedminster Bridge confirms that tidal currents in the River Avon are low (at less than 1m/s) but that significant tidal flows of 250 cubic metres per second are achieved some 10km from the tidal barrier sites. The low currents mean that tidal stream technologies are not suitable for the Avon at Bedminster Bridge or further downstream at the two barrier sites. Tidal stream technologies are therefore not considered further in this paper. Whilst tidal currents will

[1] Tidal stream turbines have a much lower power density than tidal range turbines and therefore produce significantly less energy than their tidal range equivalents in the same location

[2] Bristol Avon Flow Monitoring, Report J3450/0, Hydro-Logic Services, September 2015

be similar throughout the tidal Avon, flows will increase as the channel widens and deepens.

The potential tidal power generation depends upon the tidal range at the point of generation, the volume of water impounded upstream of the barrier and the ability to accommodate a submerged turbine below LAT. There is also the issue of integrating the tidal power facility into the tidal barrier.

The energy generated (in kW in one hour) equals the flow (cumecs) x net head[3] (metres) x acceleration due to gravity x water density x electrical efficiency. The nameplate capacity of the turbine - generator is the maximum amount of kW that can be generated in 1 hour.

Tidal power turbines are generally propeller turbines with adjustable guide vanes and propeller angles – typically double regulated Kaplan turbines of which there are many examples installed on rivers throughout Europe and elsewhere in the world. Generators are typically direct coupled and contained in a watertight bulb in line with the turbine with the shaft aligned horizontally. They can be fixed speed (synchronous) or variable speed in which case voltage control is required. The latter is now preferred because of reduced cost and lower average turbine speeds. These configurations are known as a bulb turbine. Turbidity levels are relatively high in the Severn and Avon and the turbine materials, bearings and seals would need to be designed to suit the local conditions. Technical advice from established turbine manufacturers such as Andritz Hydro for other potential tidal power sites in the Severn has indicated that this is a matter of design detail rather than influencing site selection.

An alternative arrangement is to use a gearbox to enable the generator to be mounted above the turbine in the powerhouse (a pit turbine). Pit turbines are more suitable for smaller installations but have the disadvantage of a gearbox with high torque loadings and short operating lives.

The option assumed by this paper, because of the difficulty of surface access, is a bulb turbine configuration, located in a reinforced concrete structure, as used at La Rance in France and as proposed for the Swansea Bay Tidal Lagoon. Assuming that the tidal power element is being integrated into a tidal barrier, the extra-over cost is approximately £1.5m/MW of installed capacity for an ebb generation scheme. There are no other examples of tidal power installations being incorporated into a tidal barrier (ie where power generation is secondary to the main purpose of flood defence) but the technologies proposed are well established and understood. Tidal power installations at la Rance in France and Anapolis Royal in Canada have been operating for many decades for example.

Options that can generate in both ebb and flood mode are more expensive at c £2m/MW, requiring longer draft tubes and higher unit costs for turbines. For an installation such as the Avon, there is no advantage in ebb and flood generation, particularly if the turbine can be used in conjunction with the sluice gates to reduce water levels at the end of the generation cycle to close to the natural level. Ebb and flood generation has the ability to generate more energy than an ebb only scheme providing it is possible to significantly increase the number of turbines. This is problematic for tidal barriers or barrages which are generally located to minimise their length and cost. However, tidal lagoons, with their longer impounding structures, are able to accommodate more turbines at the appropriate depths and produce more energy from the area impounded. The capital cost increases and the capacity factor reduces (from 25% to less than 20%) but the future value of the additional energy generated nevertheless improves the IRR. However, incorporating ebb and flood

[3] Net Head is the difference in m between the upstream and downstream water levels at the turbine, after deduction of frictional losses.

generation for either barrier would not increase generation because of the limited depth and opportunity to accommodate additional turbines.

The costs quoted represent the incremental costs (ie they assume the tidal power facility is constructed as an integral part of the tidal barrier) and include the turbine structure and hydraulic passages, the bulb turbine and associated gates, and the electrical switchgear and control systems. Additional costs would be required to cover dredging and scour protection, project management and contingency.

For the Avon, the preferred operational mode is therefore based on generation taking place on the ebb tide with the gates lowered towards the end of the generation cycle to reduce river levels further, following which the Avon would recharge naturally on the flood tide before the gates are raised to maintain the river basin at a higher level as the tide drops.

River Avon Options

The details of the two potential flood barrier locations identified by BCC's consultants (shown in Figure 1) and the upstream river characteristics are presented in Table 1 below. These are assumptions based on the data that has been made available. If more detailed data is available from existing hydraulic models available to Bristol City Council, the figures below will need updating. Chart Datum of -6.5mAOD has been used at Avonmouth to convert nautical data to Ordnance Datum.

Table 1 - Summary Details of Tidal Barrier Options and Associated River Characteristics

Option 1 – Avonmouth / Pill		
Overall Width (m)	355	of which 160m is embankment
Design Crest Level (mAOD)	+10.9	
Formation Level (m AOD)	-13	
Gate Area	1136 sq m	@MHWS of 6.8mAOD
River Cross Sectional Area	1500 sq m	@MHWS of 6.8mAOD
River Length	14km	Length to Netham Weir
Average channel cross section	750 sq m	Based on 1,500sq m at Avonmouth, 1030sq m at Ham Green and 250 sq m at the New Cut
Impounded Volume (est)	10 million cubic metres	Average CSA x Length
Live Volume for tidal power	6 million cubic metres	60% of total impounded volume assumed based on ebb generation
Option 2 – Ham Green		
Overall Width (m)	180	Of which 62m is embankment
Design Crest Level (mAOD)	+10.9	
Formation Level (m AOD)	-13	
Gate Area	840 sq m	@MHWS of 6.8mAOD

River Cross Sectional Area	1030 sq m	@MHWS of 6.8mAOD
River Length	12.5km	Length to Netham Weir
Average channel cross section	625 sq m	Based on 1,030sq m at Ham Green and 250 sq m at the New Cut
Impounded Volume (est)	8 million cubic metres	Average CSA x Length
Live Volume for tidal power	4.8 million cubic metres	60% of total impounded volume assumed based on ebb generation

Operating Sequence
The operating sequence for power generation during a typical 12.8 hour period from tidal peak to tidal peak is shown in Table 2. This assumes that an ebb generation project would generate for approximately 8 hours per day.

Table 2 – Operating Sequence

Tide State	Hours after Peak Tide	Operation
High Tide	0	Flood Gates prevent tidal ingress, no generation
Standing Period	0 to 1.5	Flood Gates prevent tidal ingress, no generation, level difference created between the Avon and the Severn
Ebb	1.5 to 5.5	Turbine generates using the level difference between the River Avon and the Severn Estuary, flood gates raised
Ebb to Flood	5.5 to 6.4	Flood gates retracted, River Avon continues to discharge into the Severn, lowering level to close to the Severn
Flood Tide	6.4 to 12.8	Flows from the Severn pass through to the River Avon, re-filling the river basin
High Tide	12.8	Flood gates raised before the cycle above is repeated.

Assuming that the live volume would be drawn down over 4 hours (1.5 to 5.5 in the table above), the maximum flow through the turbines would be approximately 1.5 million cubic metres per hour (415 cumecs) or 1.2 million cubic metres per hour (333 cumecs) for Ham Green during MHWS tides. Flows would be significantly lower at neap tides. The mode of operation assumes that at the end of the generation cycle, the flood gates are lowered to reduce water levels as quickly as possible in the River Avon basin before the tide returns. As there is no generation on the flood tide, river levels restore themselves as quickly as they would without any power generation, the only inhibitor being the blockage caused by the presence of the tidal flood structure. The tidal power facility would be below the natural channel and would thus not block natural river flows. Assuming that a turbine smaller than the maximum possible would be installed (to reduce cost and integration challenges and provide a degree of conservatism given the absence of detailed data), a flow of 250 cumecs and a maximum operating head of 6m would suggest a turbine with an installed capacity of around 12MW. Further, more detailed studies may show that this can increased given the higher flows at Ham Green and Avonmouth but the potential loss of generation potential from fulfilling navigation demands also has to be taken into account.

The majority of vessels using the River Avon are light leisure craft with the occasional larger vessel such as the SS Balmoral or the Mayflower transiting to the Severn. The intensity of navigation movements is relatively low except for certain occasions such as the Bristol Harbour Festival. The implications for power generation are simple. When a ship chooses to navigate through the tidal barrier, power generation must cease and water levels adjusted either side of the barrier to enable safe passage. Fortunately, most shipping movements on the Avon leave the floating harbour/Cumberland Basin at high tide as the tide turns to ebb and this co-incides with standing high water (0 to 1.5 hours in Table 2). Assuming they are able to pass through the barrier within this 1.5 hour window, there would be no impact on power generation. Returning from the Severn into the Avon is generally undertaken on the flood tide when no power generation takes place. However, there is the possibility that some generation ability may be lost if transit times are longer than 1.5 hours or the occasions when navigation is required outside the norms described above. The impact of this will be relatively low (of the order of a few %).

With the assumed flows of 250 cumecs through the turbines and the opening of sluice gates in the latter part of the generation cycle to release more water downstream to lower water levels within the basin to the natural low tide state, the different upstream and downstream water levels during a 24.8 hour period at spring tides is illustrated in Figure 2. The period of generation is indicated by the arrows and the tidal gates are lowered during the final phase of generation to reduce water levels to close to their natural level before the flood tide recharges the upstream levels. A standing period of 1.5 hours has been assumed but this would require some optimisation before being finally determined.

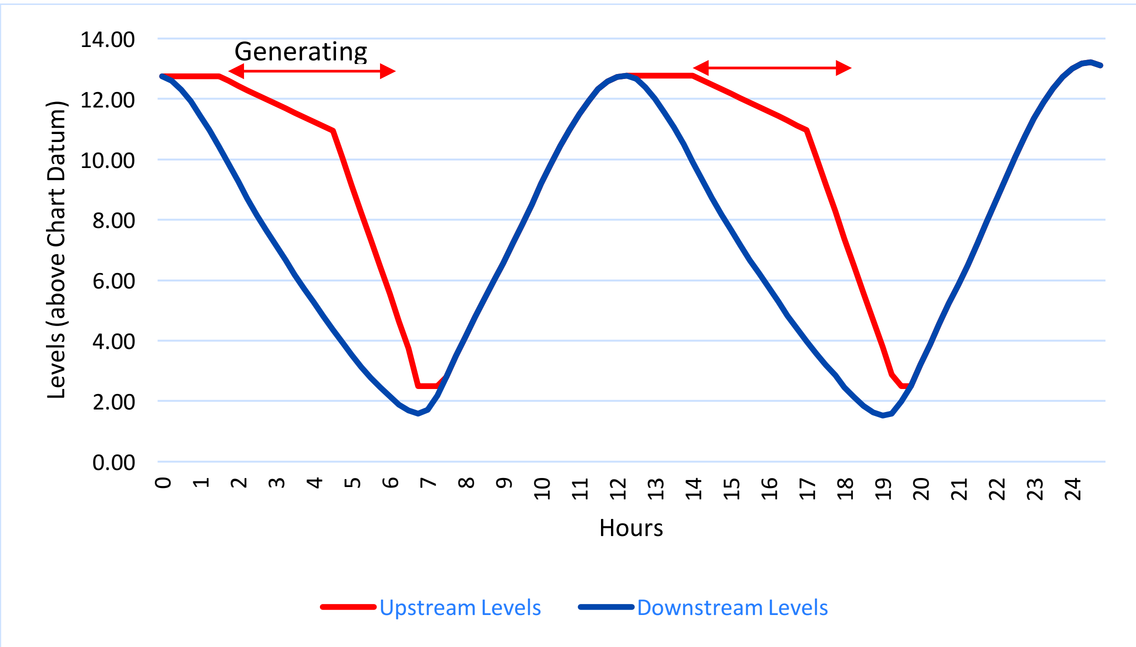


Figure 2 Upstream and Downstream Water Levels

Physical Integration

Integrating the turbine into the tidal barrier structure would involve some additional construction of a structure to house the turbine and draft tubes[4]. A 12 MW bulb turbine would require a 10m wide (50 metres in length) structure to be integrated into the tidal flood barrier, to the side of the central navigation / tidal gate structures. The inlet and outlets would be at either end of the 50m long structure and would be below the natural bed level. Some localised excavation/dredging would be required to allow free passage of water to the full cross sectional area of the inlet and outlet passages. It would be prudent to allow a 25m length of bed lowering at both the inlet and the outlet with an excavated depth of 5m. The breadth of the excavation need only be 10m but the actual depth would depend upon whether sheet piling is used to retain the difference in levels between the natural bank and the excavated section or whether this is achieved by a transition slope protected by rock armour. The area excavated would require scour protection. The turbine would be around 6m in diameter with a 3 bladed rotor with a typical rotating speed of c 60 rpm. A smaller diameter could be achieved at the expense of a higher rotational speed which may be problematic for fish passage.

Assuming a bulb turbine with a 6 m propeller, the centre line of which would need to be set 5m below MLWS, which would require a formation level of approximately about -18m AOD or some 5m below the lowest tidal barrier formation level (-13m). Tidal turbines need to be adequately submerged so that air is not entrained into the inlet at lower water levels. This prevents cavitation of the turbine blades where pockets of air at high pressure can cause pitting of the turbine blades.

The most sensible location for the turbines would be in line but below the gates adjacent to the deep channel gates, as illustrated in Figure 3 below. The central channel clear could thus be kept free for navigation and any vertical access arrangements could be incorporated without interfering with navigation access or water passage. Different options exist for the potential access arrangements. An elevated structure or bridge from the bank to the turbine caisson could provide access to the control gates on a permanent basis. Alternatively a floating platform could be used to provide temporary access as and when it was required. All aspects of the turbine control and operation would be undertaken remotely so it is only for routine maintenance that access would be required. A road crossing over the barrier would provide a comprehensive degree of access and provide for a mobile crane on the limited number of occasions this may be needed either for the power generation equipment or for the tidal gates themselves. Consideration of different access arrangements has raised the question of whether, in the tidal barrier, where only one navigation passage is required (using rising sector gates) and whether the other gates could be vertical drop gates as bulb turbines typically use vertical drop gates for their flow control.

The electrical control equipment and switchgear would be located on the bank somewhere between the tidal barrier and the grid connection point in a suitable building.

[4] Draft tubes are the steel lined water passages that direct water through the structure and into the turbine.

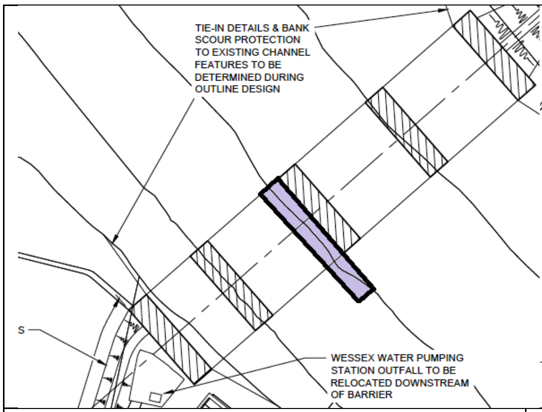
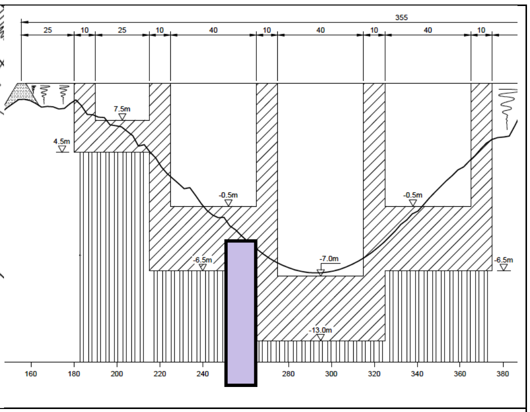
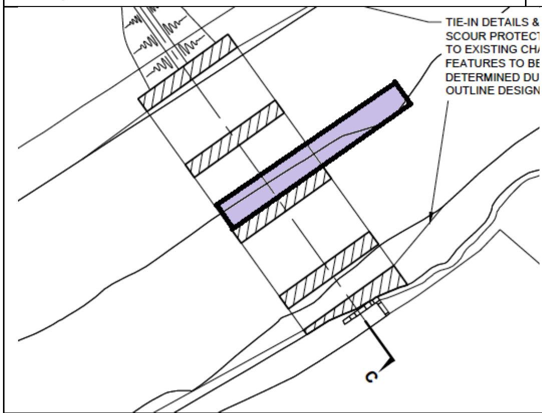
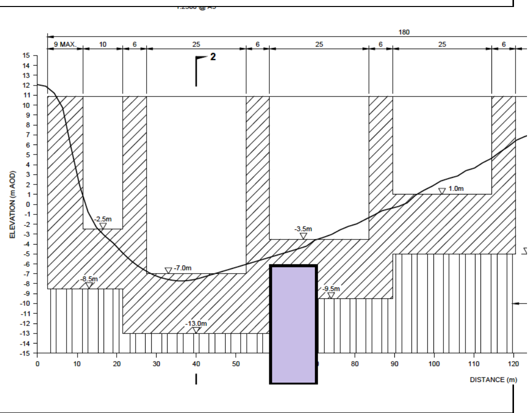
	
Plan on Avonmouth Barrier showing turbine structure location (indicative) - NTS	Long Section through Avonmouth Barrier showing turbine location structure - NTS
	
Plan on Ham Green Barrier showing turbine structure location (indicative) - NTS	Long Section through Ham Green Barrier showing turbine location structure - NTS

Figure 3 Indicative Locations for a 12MW turbine structure integrated into the tidal barriers (base figures © Aecom)

A typical arrangement for a similar sized bulb turbine is shown in Figure 4 proposed in 2010 for the Duddon Estuary (so details, levels and tidal range are different).

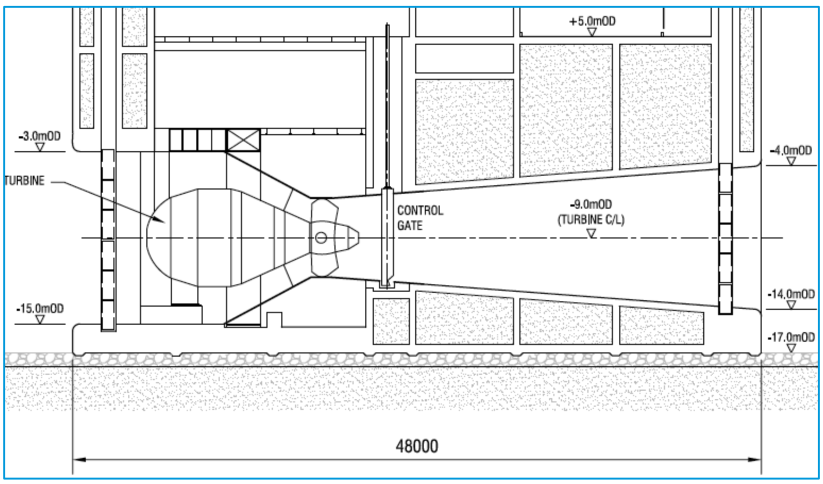


Figure 4 Cross Section through concrete structure and bulb turbine proposed for the Duddon Estuary (© Parsons Brinckerhoff, 2010)

Power Generation Potential
Although the tidal range is 12m or more, the maximum head for power generation purposes that could be developed is less. Assuming an average operating head of 6m and a conservative turbine flow of 250 cumecs[5] (the same has been assumed for both locations in this conservative assessment although flows and thus potential power will increase as the channel widens), the maximum power that could be generated on a spring tide is approximately 12MW. Tidal power projects operating in ebb generation mode typically have a capacity factor[6] of around 25%. If the maximum possible energy output from a 12MW generator is 105,120MWh (12MW x 365days x 24hours), then the annual energy yield from the Avon would be around 25% of this or 25,000MWh per year. This is the equivalent of a saving in carbon dioxide emissions of around 13,000 tonnes per year.

The capacity factor of 25% is taken from other studies[7] using ebb generating barrages (primarily the Cardiff – Weston Barrage @ 24% and the Shoots/English Stones Barrage @ 30%). The capacity factor is applied to peak output (ie the calculated output at spring tides when the maximum volume is available for generation) and takes account of the reduction in energy output for neap tides (when flows, heads and impounded volumes are less), the intermediate tides as well as the periods when no generation takes place (ie during flood tides and when water level differentials are insufficient).

The value of a MWh is around £40 on the wholesale market but under the Energy Act, low carbon generation can enter into a Contract for Difference which would mean that each MWh could be more than double this. Assuming that a Contract for Difference strike price of £90 could be negotiated (similar to new nuclear), the annual revenue from the power station could be £2.25m per year. Tidal range and new nuclear are both allowed to negotiate CfD terms such as contract length and strike price on a project by project basis, in contrast to other renewable technologies. A contract length of 35 years and strike price similar to new nuclear or offshore wind (target of £100/MWh) would be expected for a tidal range project.

Costs and IRR
The costs associated with incorporating power generation into the tidal defence barrier include the following:

i) Capex for the turbine, generator and mechanical and electrical equipment, including the grid connection and the civil engineering works required to accommodate a 12MW turbine (this would be of the order of £18m for an ebb only scheme based on the parametric[8] cost assessment of £1.5m/MW);
ii) Capex for amendments to the baseline flood barrier design including enhanced specifications for the flood gates on the basis that they would be required to operate on every tidal generation cycle and to be able to withstand differential heads in both directions and the costs of excavation to provide dredged water passages to the turbine inlet and outlet (an incremental cost of £3m has been assumed).
iii) Associated increases in contingency (60% OB has been applied to the £12m civil works - and 20% to the £9m turbine/generator/electrical works

[5] 250 cumecs is a flow of 250 cubic metres per second.

[6] the capacity factor is the ratio of the actual energy output over a year compared with the maximum possible output based on the generator rating.
[7] Severn Tidal Power Feasibility Study, DECC, October 2010 and Turning the Tide, Sustainable Development Commission, October 2007
[8] Parametric analyses have been undertaken using the reference costs established during the Severn Tidal Power Feasibility Study (DECC), the Mersey Barrage Feasibility Study (Peel Energy), the Duddon Estuary Tidal Power Feasibility Study and figures published by TLP for Swansea Bay Tidal Lagoon

given their long established nature) giving a total contingency figure of £9m.

iv) Total capex including contingency is therefore £30m.

v) Opex for the operation, maintenance, dredging, refurbishment and future decommissioning of the tidal generation equipment, as well as grid connection and balancing charges (approx. £300k per year[9])

The asset life of the civil engineering works would be regarded as in excess of 100 years for tidal power generation with the turbines requiring major refurbishment after 40 years and electrical equipment after 20 years. The IRR for a project with a capital cost of £30m spread over 2 years, operating costs of £300k per year and a revenue stream of £2.25m over 35 years would be around 5% before inflation or 7% assuming an inflation rate of 2% per annum. The NPV over 100 years has also been calculated using HMT's long term discount rates and is £27m. The equivalent figure after 35 years of operation is £8m.

Potential Issues

- Change of tidal characteristics upstream of the tidal barrier – the discharge into the Severn will take place over 4.9 hours rather than 6.4 on an ebb tide;
- Significant excavation / dredging will be required to accommodate the inlet and outlet channels for the turbine which has to be located below the Lowest Astronomic Tide (LAT) – this may be reduced by adopting two or more turbines of smaller diameter (similar energy but potentially more costly) but cannot be totally eliminated given the bathymetry of the River Avon at the two potential tidal barrier sites;
- Navigation needs to be reviewed but impacts should be acceptable if boats tend to leave on the ebb tide and travel up the Avon on the flood tide, some loss of generation would be inevitable to allow ship movements and this would need to be considered in more detail;
- The combined tidal defence and power generation barrier would have to be designed to ensure that both could function without compromise. It would be possible to reduce the size of the power generation facility to improve tidal defence functionality or reduce costs but with a commensurate reduction in energy generated;
- Environmental impacts, including micro-climate changes within the Avon Gorge will require review as will the impacts of any changes in water levels, water quality and potential fish passage through the turbine;
- Potential settlement during the 1.5 hour stand time after high tide would require careful evaluation. However, energy generation will provide a scouring effect and so settlement patterns are likely to be different rather than better or worse;
- The project would require, inter alia, a negotiated Contract for Difference. This can take up to a year with no guarantee of success. The project has to be developed in sufficient detail to allow firm cost estimates and energy predictions to be used in the CfD negotations.

Next Steps

If the opportunity to generate power from the tidal barrier is considered sufficiently attractive, the next steps would include but not be limited to, the following:

i) Confirmation of physical survey data assumptions used in this paper (eg river basin characteristics and currents);

[9] Annual opex costs from other tidal power studies on the Severn, the Mersey and the Duddon Estuary have ranged from 0.7% of capex to 1.5%. Given the simplicity of the Avon tidal power arrangement, its relatively sheltered location and the fact that it is integrated into another operating structure with its own operation and maintenance budget, a figure of 1% of the capex plus contingency has been used to estimate annual operating costs.

ii) Review of the current tidal barrier options with a view on how a power generation facility could be integrated, including whether all gates need to be rising sector gates or whether just the navigation channel requires a rising sector gate with others using a vertical drop gate;
iii) A high-level desktop assessment of the likely impacts on changes in hydraulics to understand changes potential changes in hydrodynamic levels, sediment movement and direct/indirect effects on the environment;
iv) Development of an outline design for the preferred technical option to assess the additional costs and requirements;
v) Review of navigation passage on potential energy yield;
vi) Review of fluvial flow requirements to understand flow capacities for various tidal states during power generation;
vii) 0-D modelling of the River Avon to estimate the potential power generation capacity and turbine requirements, potentially undertaken in conjunction with a shortlist of turbine suppliers;
viii) Development of a financial model to inform potential CfD requirements;
ix) Review of potential environmental impacts and potential mitigation measures, including informal negotiations with key environmental stakeholders and updating of financial model;

It is suggested that a gateway approach is undertaken so that each step is completed satisfactorily before the next step is initiated.

Conclusion
The River Avon has the potential to generate over 25GWh of low carbon energy per year. A 12MW tidal power facility could be integrated within a tidal barrier and the incremental costs and benefits of doing so could produce a higher Internal Rate of Return than HM Treasury Green Book requirements for the public sector. However, the integration of a tidal power facility with a tidal barrier requires further study to confirm its feasibility, particularly with respect to annual energy yield, dredging, construction costs, operational access and any impact on energy yield arising from navigational requirements. The locations studied have good potential connections to the electricity grid. There may be potential to rationalise the tidal barrier design in terms of the types of gates used for the non-navigable channels through the structure which may simplify integration of the tidal power facility. The tidal barrier gates will need to be designed for daily operation but the essential performance characteristics of the tidal barrier should not be compromised through the integration of the tidal facility, subject to increasing the operating specification for the flood gates. Potential environmental effects will need to be studied in detail, including impacts on the Avon Gorge micro climate, water quality and impacts arising from a changed tidal curve.

Yours sincerely,

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Encl.