SEVERN EMBRYONIC TECHNOLOGIES SCHEME

CONCEPT DESIGN OF A VERY-LOW HEAD DUAL GENERATION TIDAL SCHEME FOR THE SEVERN ESTUARY

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NOTICE

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EXECUTIVE SUMMARY

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Rolls-Royce plc in partnership with Atkins Ltd have progressed the development of a bi-directional turbine and very-low head dual generation tidal scheme proposed for construction and operation in the Severn estuary to the outline design stage. The scheme is referred to as a tidal bar throughout the remainder of the report. The work package is funded under the Severn Embryonic Technologies Scheme (SETS) supported by the Department for Energy and Climate Change (DECC), Welsh Assembly Government, South-West Regional Development Agency, and the Department for Environment, Food and Rural Affairs (DEFRA).

The tidal bar concept addresses the principal objective of the SETS programme to develop strategically important and economic power generation options exploiting the tidal range of the Severn estuary but offering potentially less impact on the natural environment than conventional barrages and lagoons.

The present study takes the work undertaken by the University of Liverpool and Proudman Oceanographic Laboratory “Tapping the Tidal Power of the Eastern Irish Sea” completed under North-West Regional Development Agency funding as its technical basis. These studies have shown that comparable or greater energy yield may be extracted in a dual generation scheme when the turbine flow capacity is substantially increased. The turbine is assumed to be a double regulated bulb turbine in which the performance deteriorates to 80% of its design point capability in reverse mode. This assumption is considered to be optimistic in that:

- Dual-generation bulb turbines would require upstream and downstream diffusers to effectively recover dynamic head which would increase the width of the barrage structure and cost of the scheme or incur a further performance penalty. The complex flow conditions around the bulb of the turbine would likely require a difficult diffuser design to prevent flow separation when operating in reverse mode.

- The high solidity rotor design is optimised for uni-directional operation; it is unlikely that the blades could be adequately re-pitched to provide the required reverse mode efficiency.

The current study looks at the design of a high efficiency bi-directional turbine and development of a tidal bar solution for the Severn estuary however much of the work in the turbine design will be complementary in effectively exploiting worldwide tidal resource. Scheme alignments at Cardiff-Weston and Minehead-Aberthaw are considered.

Rolls-Royce has produced two separate turbine design concepts to address the very-low head operating conditions and bi-directional generation requirement. The first is an axial flow fixed speed machine with two contra-rotating blade rows that rotate to face the on-coming tide. The second is an axial flow variable speed machine with rotor and stator blade rows and produces bi-directional power by rotation of the turbine assembly. Both designs eliminate the requirement for downstream diffusers. The hydraulic efficiency of the designs is expected to be greater than 90% across the operating range.

Rolls-Royce prefers the contra-rotating turbine configuration as in-service reliability and flexibility is considered to be superior with no detriment to fish survivability.

Preliminary hydrodynamic, mechanical and electrical design has been completed and the turbine integrated with the barrage civil design within the SETS funded programme. Technical development risk has been evaluated and an estimate of the development programme required to deliver a production turbine design has been included in the study.

Both configurations produced are designed to reduce the mortality rate of fish passing through the bar. Axial flow and rotor blade speed are kept well below current operating low head turbines, blade-to-blade spacing and blade chord maximised, and substantial clearances maintained between subsequent blade rows. These characteristics should minimise the damage to fish on the basis of the four principal mortality mechanisms defined and are expected to yield an order-of-magnitude decrease in mortality rate relative to a conventional bulb turbine.

Atkins have developed scheme designs for both Cardiff-Weston and Minehead-Aberthaw alignments compatible with the turbine configurations produced by Rolls-Royce. Estuary cross-sections of these alignments were studied to estimate available turbine swept area and the designs have incorporated lock structures in the path of existing navigation channels. Zero-dimensional non-linear basin models were used to evaluate net energy yield from the barrage and loss of intertidal habitat. The consortium has considered features within the design that improve installation and maintenance due to the large number of turbines required.

Cost and commercial models were developed with capital cost estimations developed using component supplier data where appropriate. Estimates of refurbishment and maintenance, lost habitat allowance, and financing were incorporated with the net energy yield to determine the cost of electricity for both solutions. The key results are summarised in the table below.

	Cardiff-Weston	**Minehead-Aberthaw**
Net energy yield	20.8 TWh	30.4 TWh
Habitat loss	5,200 hectares	6,000 hectares
Cost of electricity - excluding habitat allowance (IOAR basis)	£92.7 / MWh	£104.0 / MWh
Cost of electricity - including habitat allowance (IOAR basis)	£93.5 / MWh	£106.9 / MWh
Cost of electricity - excluding habitat allowance (SETS basis)	£51.0 / MWh	£59.3 / MWh
Cost of electricity - including habitat allowance (SETS basis)	£52.4 / MWh	£60.6 / MWh

Table 1 Output summary for Cardiff-Weston and Minehead-Aberthaw very-low head dual generation tidal bar schemes.

The tidal bar has the advantage of a lower peak capacity than the equivalent Cardiff-Weston ebb-only barrage with similar annual energy output. The result is a higher capacity factor for the turbine equipment and a more consistent power export to the grid.

The capability of the turbines to operate as pumps to further limit intertidal habitat loss and increase net energy yield allows the barrage to import excess power from the grid and act as a temporary energy storage system to reduce instabilities from intermittent supplies. A recent study at the University of Liverpool and Proudman Oceanographic Laboratories suggest that the longer generating window of dual model schemes would enable co-ordination of North-West and Severn tidal schemes to provide a more stable grid input.

The consortium has progressed development of a tidal bar scheme to the outline design stage but has identified that the following risks associated with the turbine and bar require further treatment beyond the SETS programme:

1. Validation and acceptance testing of turbine passage fish passage rates.
2. Physical confirmation and acceptance testing of turbine hydrodynamic performance (including pumping) and control strategy.
3. Government and financial commitment to development programme.
4. Turbine blade supply chain development and availability.
5. Design, manufacture and validation of a production turbine.

Within the context of the current study the consortium concludes that:

1. A tidal bar requires lower capital investment than the Severn Tidal Power Group (STPG) ebb-only barrage at Cardiff-Weston.
2. A tidal bar substantially reduces the loss of intertidal habitat relative to the STPG ebb-only barrage at Cardiff-Weston.
3. A tidal bar provides greater energy yield than the STPG ebb-only barrage at Cardiff-Weston.
4. A tidal bar provides competitive or better economics than an STPG ebb-only barrage, tidal stream or offshore wind generation.
5. A very-low head bi-directional turbine with high, reversible efficiency is technically feasible and no new technology or engineering methodology is required.
6. A very-low head bi-directional turbine design can eliminate the requirement for downstream diffusers.
7. Turbine passage fish passage rates can be significantly improved over existing bulb turbines and a feasible design developed on the derived operating conditions.
8. A tidal bar could reasonably be in service by 2020 - 2030 subject to planning consent and commercial commitments.

Scheme and alignment	Tidal bar at Cardiff-Weston	Tidal bar at Minehead-Aberthaw
Rated power output	5800 MW	10,000 MW
Annual energy output	20.8 TWh	30.4 TWh
Construction cost	£16,856 m	£26,267 m
Cost of electricity (IOAR basis)	£93.5 / MWh	£106.9 / MWh
Cost of electricity (SETS basis)	£52.4 / MWh	£60.6 / MWh
Carbon offset	9.3 mt CO_2 / yr	17.2 mt CO_2 / yr
Estimated year of first generation in Severn	2020 - 2030	2020 - 2030
Environmental impact	• Significant reduction in power generation carbon emissions. • Significant reduction in intertidal habitat loss relative to Cardiff-Weston STPG ebb-only scheme. • Reduction in through turbine fish mortality.	• Significant reduction in power generation carbon emissions. • Significant reduction in intertidal habitat loss relative to Cardiff-Weston STPG ebb-only scheme. • Reduction in through turbine fish mortality.

Table 2 Summary of results for dual generation Cardiff-Weston and Minehead-Aberthaw schemes.

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AIMS AND OBJECTIVES

1 AIMS AND OBJECTIVES

Rolls-Royce plc in partnership with Atkins Ltd have progressed the development of a very-low head dual generation scheme to the outline design stage proposed for construction and operation in the Severn estuary. The scheme is referred to as a tidal bar throughout the remainder of the report. The work package is funded under the Severn Embryonic Technologies Scheme (SETS) supported by the Department for Energy and Climate Change (DECC), Welsh Assembly Government, South-West Regional Development Agency, and the Department for Environment, Food and Rural Affairs.

The tidal bar addresses the principal objective of the SETS programme to develop strategically important and economic power generation options exploiting the tidal range of the Severn estuary but offering potentially less impact on the natural environment than conventional barrages and lagoons. The stated aims of the SETS programme are to:

- Develop new proposals to the outline design stage.
- Increase confidence in output, cost, impact and technical feasibility.
- Establish a route map 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 embryonic study completed by Rolls-Royce and Atkins has taken the form of a requirements capture and concept design programme. The project team has actively sought to establish functional requirements, develop and characterise solutions, and identify, sentence and where possible mitigate risks in the technology and product development process. The stated objectives of the Rolls-Royce / Atkins programme are:

- Develop the concept design of a bi-directional tidal turbine operating in appropriately defined flow conditions.
- Select all turbine sub-systems from ‘water to wire’.
- Trade off a number of fundamental design architectures to identify the optimum configuration.
- Estimate the research and development time scales and costs to deliver new technology for the chosen concept design and to then take this through a robust product development programme to entry into service meeting necessary standards and external agency certification rules.
- Develop barrage caisson designs to include structural and installation calculations and match the optimum turbine power system.
- Refine power and energy calculations for the very-low head dual generation scheme at Cardiff-Weston and Minehead-Aberthaw alignments.
- Publish peak and mean power, energy yields, and cost of electricity data for Cardiff-Weston and Minehead-Aberthaw alignments.

The consortium’s progress against the published deliverables has been reviewed throughout the programme by representatives from the Department of Energy and Climate Change and technical advisors from Parsons-Brinckerhoff.

SECTION 2

METHODOLOGY

2 METHODOLOGY

The present study takes the work undertaken by the University of Liverpool and Proudman Oceanographic Laboratory “Tapping the Tidal Power of the Eastern Irish Sea” [1] completed with North-West Regional Development Agency funding as its technical basis. The Dee, Mersey, Ribb estuaries as well as Morecombe Bay and Solway Firth were investigated by the University of Liverpool using a combination of zero and two-dimensional hydrodynamic modelling to estimate energy yield and changes to intertidal range under ebb, flood and dual generation schemes.

These studies have shown that comparable or greater energy yield may be extracted in a dual generation scheme when the turbine flow capacity is substantially increased. The turbine is assumed to be a double regulated bulb turbine in which the performance deteriorates to 80% of its design point capability in reverse mode. This assumption is considered to be optimistic in that:

- Dual generation requires operation at a lower peak and mean operating head passing a large volume flow rate to capture energy effectively on both the ebb and flood tides.
- Lower head operation reduces the tolerance of the system to exit flow losses requiring a very-high turbine swept area to achieve the high volume flow rate at low velocity.
- Conventional bulb turbines pass high volume flow rates through a small turbine swept area requiring a downstream diffuser to recover kinetic energy from the turbine exit flow. A dual generation scheme would require up and downstream diffusers substantially increasing the required width of the barrage.
- Bulb turbines do not have the necessary pitch range to fully reverse the blades resulting in the turbine (in reverse mode) presenting a thin leading and thick trailing edge and incorrect blade twist to the flow resulting in poor efficiency from radial sections of the turbine stalling.
- The role of the rotor blades and stator vanes in reverse mode operation is interchanged reducing turbine efficiency: in forward generating mode the stator vanes introduce swirl to the flow while rotor blades remove flow, in reverse generating mode the rotor blades introduce swirl while the stator vanes remove swirl.

The reverse mode water-to-wire efficiency of a bulb turbine installation without dual diffusers may be lower than 50% compared to greater than 80% in forward mode. The turbine developed by Rolls-Royce within the SETS programme provides the following characteristics water-to-wire efficiency of 80% or greater in both flow directions without the requirement for diffusers.

The above is evidenced by operational data from La Rance in which only 2 – 6% of the total barrage output is generated in flood operation. Nevertheless the merits of dual-mode generation both in net energy yield and minimising disruption to the natural tidal cycle are recognised in the University of Liverpool / Proudman Oceanographic report. The current study looks at the design of a bi-directional turbine and development of a dual generation tidal bar solution for the Severn estuary however much of the work will be complementary in effectively exploiting North-West tidal resource.

A very-low head bi-directional turbine design is a completely unknown product worldwide. A concept preliminary design study has been completed to progress the technology to the outline design stage. The design is complicated by a requirement to minimise the environmental impact of the turbine, notably the disturbance and attrition rate of migratory fish, while maintaining a design that may be economically manufactured in the required volumes to meet Government renewable energy targets. A critical consideration is understanding the technology maturity and development risk required to deliver the design as well as the required timeframe to establish a supply chain and manufacturing facilities.

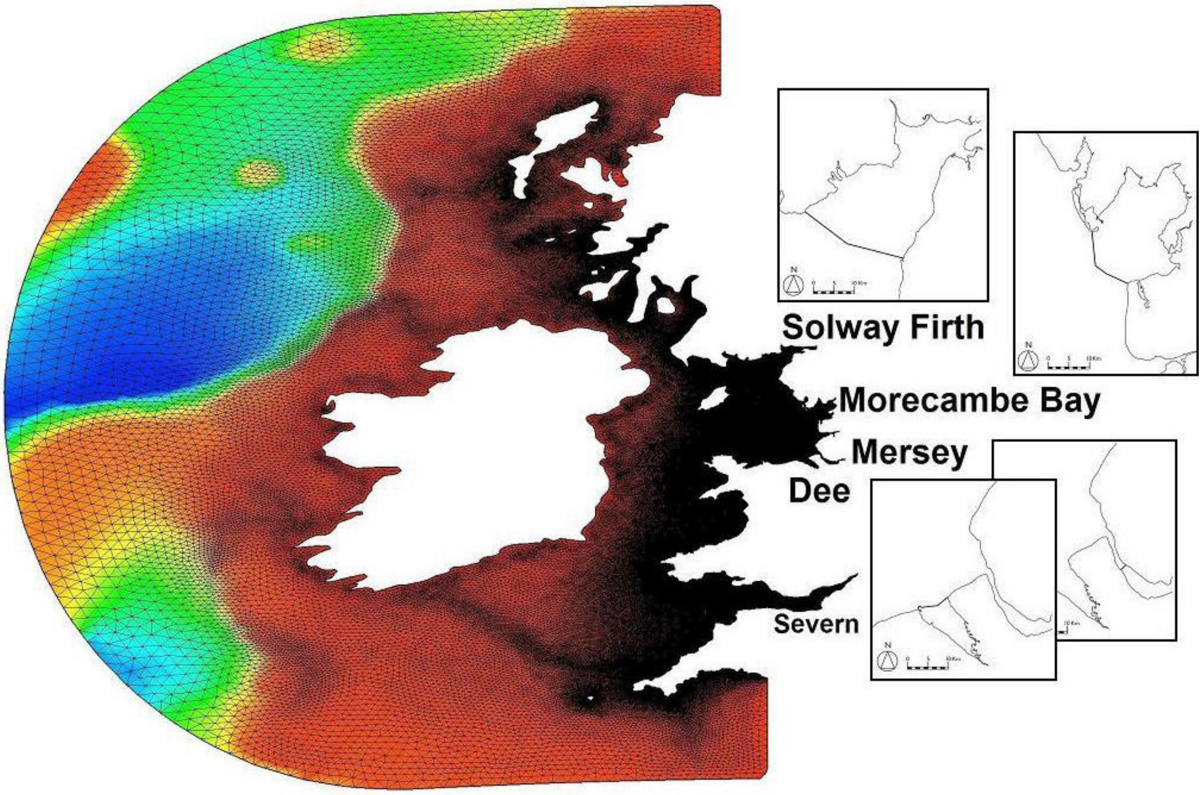

Figure 1 Two-dimensional unstructured grid used in computation of Irish Sea tides in the University of Liverpool / Proudman Oceanographic Laboratory studies of North-West estuaries (inset).

The project consortium gratefully acknowledges the support of Assystem UK, BMT WBM, Allen Gears, and Converteam in the development of the turbine solution whose expertise in associated design, analysis, and manufacturing areas have assisted in evolving and de-risking the turbine design.

Rolls-Royce and Atkins have addressed the following in the development of a very-low head tidal dual generation bar solution:

- Requirements capture.
- Concept identification, evaluation and selection.
- Hydrodynamic turbine and duct design.
- Structural and mechanical shaft line design.
- Equipment health monitoring, control and instrumentation.

- Electrical conversion and grid connection design.
- Alignment and civil works design.
- Energy yield modelling.
- Cost and commercial modelling.
- Manufacturing, logistics and supply chain.
- Installation, removal and maintenance.

The content of each work package is described under separate headings in the following text.

2.1 Requirements Capture

Various requirement capture methods have been deployed in establishing requirements and stakeholder in the development of the tidal bar and very-low head bi-directional turbine. These tools include a functional analysis (Figure 2) diagrams, scenario analysis and context diagram (Figure 4). A database of functional requirements was established in the early phases of the project, which later incorporates lower level technical requirements related to specifics of the turbo-machinery concepts developed.

The objective of the SETS programme is to investigate and de-risk solutions that minimise the potential environmental impact of Severn tidal power generation but still provide a strategically significant source of electricity. These programme requirements shape the tidal bar functional requirements that define the design of the turbine:

1. Generate an economic and strategically significantly source of electricity.
2. Minimise the loss of intertidal habitat.
3. Minimise the attrition rate and impedance to both migratory and non-migratory fish species.

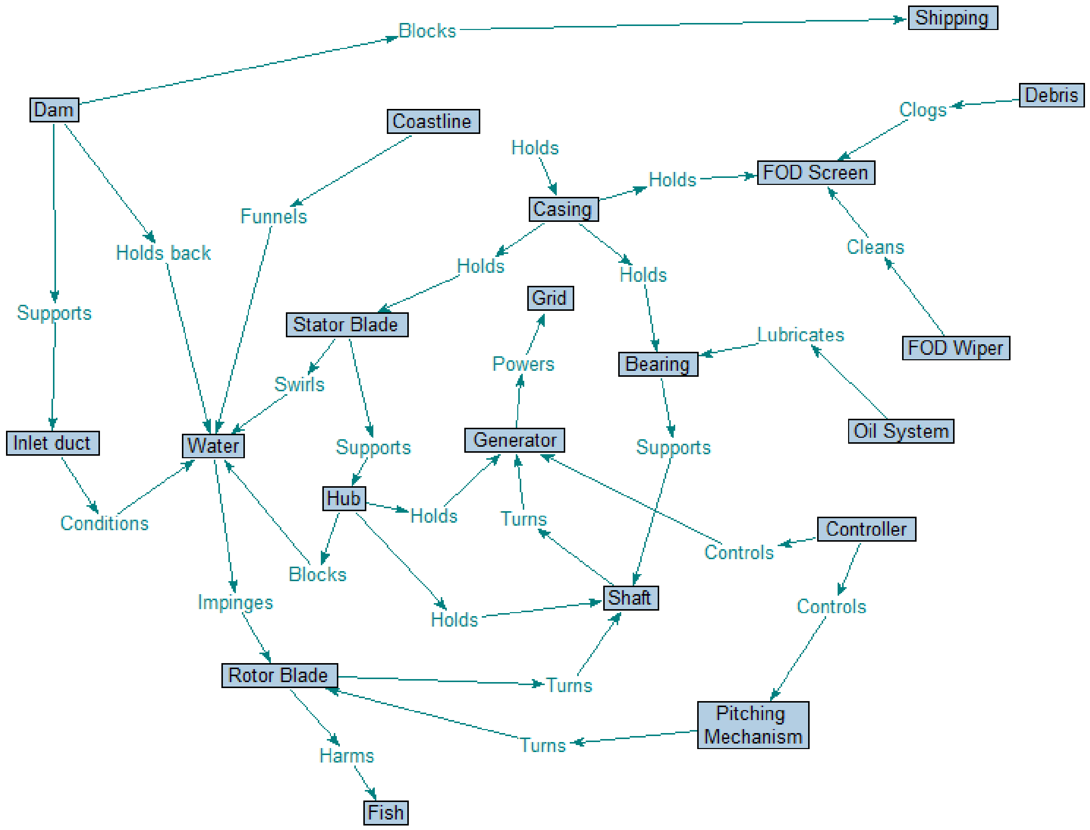

Figure 2 Functional analysis diagram showing the decomposition of a turbine system into its key components and illustrating their functional interactions.

Preservation of intertidal habitat requires the head across the bar to be as small as possible however reducing head makes generation of economic electricity difficult. Ebb and flood dual generation helps overcome this difficulty but infers that the turbine provides bi-directional capability.

Operating on a minimal head requires that losses through the barrage should be reduced to provide the turbine with the maximum net generating head. Minimising these losses is principally achieved by reducing the velocity through the turbine which results in an open structure with a large number of turbines.

The requirement for dual generation and high percentage of turbine swept area appears to conflict with the functional requirement for minimising the attrition rate to fish species inhabiting the estuary. The high turbine swept area and dual generation increases the probability of fish entering the turbine and minimises available area for separate sluices or fish ladders. The turbine must therefore minimise fish mortality by design.

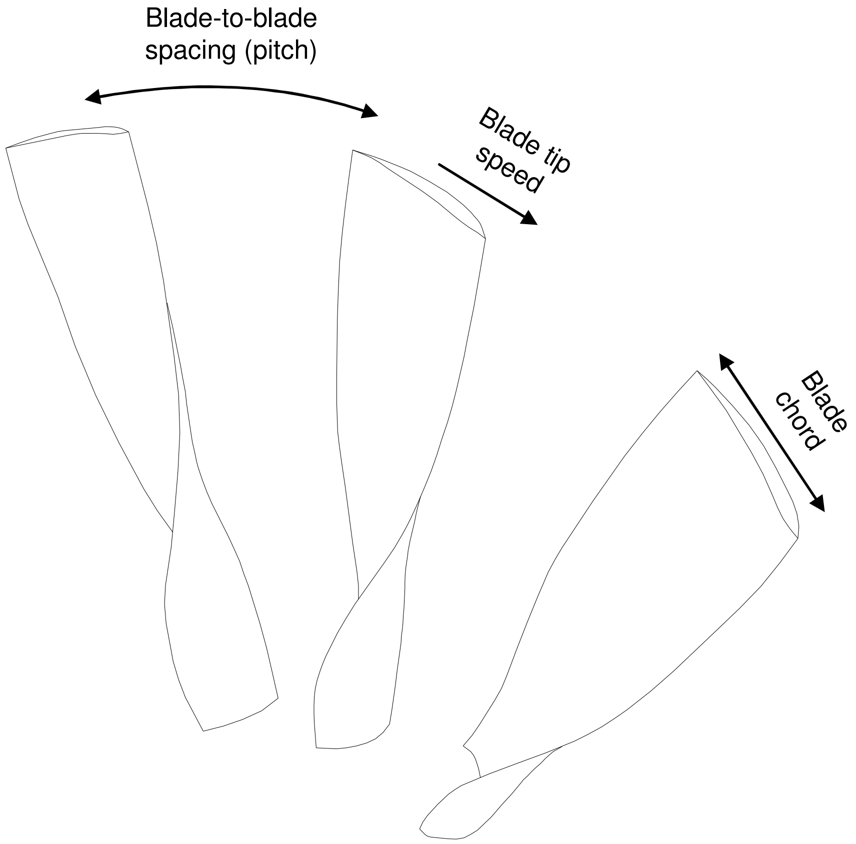

Figure 3 Turbine blade cascade parameter definition.

A series of basic design requirements were established that infer that fish mortality may be reduced substantially by:

1. Minimising the magnitude and maximising time of pressure transients.
2. Maintaining low speed flow through the turbine.
3. Reducing blade speed.
4. Maximising blade-to-blade and row-to-row spacing.
5. Maximising blade chord (distance from blade leading to trailing edge).
6. Reducing hub and tip clearance.

Operating a highly porous structure over a low net head inherently reduces the magnitude of pressure transients and maintaining a low flow speed through the turbine increases the time over which pressure transients occur while also reducing relative blade speed. An absolute design point tip speed ratio (blade speed to axial flow speed) of 3.2 is used throughout the design to minimise blade impact mortality. This results in a tip speed below the 12.2 m/s (40 ft/s) defined for negligible mortality in INL studies.

Reduced hub and tip clearances result from detailed features in the turbine production design and are equally applicable to any turbine configuration deployed on the Severn. Turbines designed to eliminate surface roughness and minimise hub and tip clearances are known as ‘minimum gap runners’ and the requirement does not substantially influence the concept design.

The study has considered two bar alignments at Cardiff-Weston and Minehead-Aberthaw. The tidal range, cross-sectional profile, and available power from the estuary at the two locations is substantially different.

The Cardiff-Weston alignment is shallower and unable to accommodate turbine diameters exceeding 14 metres and 9 metres for approximately 50% of the channel with minimal dredging work. The shallower cross-section creates challenges for heavy shipping navigation as deeper water is ideally retained for navigation channels. In order to maximise turbine swept area two turbine diameters are required to fill the estuary cross-section.

The Minehead-Aberthaw alignment is deeper and impounds a larger basin area. The deeper cross-section area permits turbines of up to diameter 20 metres, however a set of three discrete turbine diameters are required to achieve a large flow area with minimum dredging.

The very-low head tidal bar at either Cardiff-Weston or Minehead-Aberthaw alignments represents the largest single power station in the United Kingdom. Current requirements for frequency stability forbid single connections to the grid exceeding 1320 MW. A tidal bar scheme at Cardiff-Weston or Minehead-Aberthaw would have a peak power output of 5,800 MW or 16,000 MW respectively requiring multiple grid connection points. These grid connections must be at 400 kV and synchronised to grid frequency at 50 Hz.

Analysis of the fundamental economics of the tidal bar demonstrate that the very-low head bar becomes uneconomic relative to alternative options once normalised installed turbine capital cost exceeds £2.0 m / MW. High efficiency and availability are also required to maintain an economic levelised cost of electricity. The capital cost of the turbine is amortised over the production life inherently establishing the minimum required mechanical life under corrosion and cyclic pressure loading.

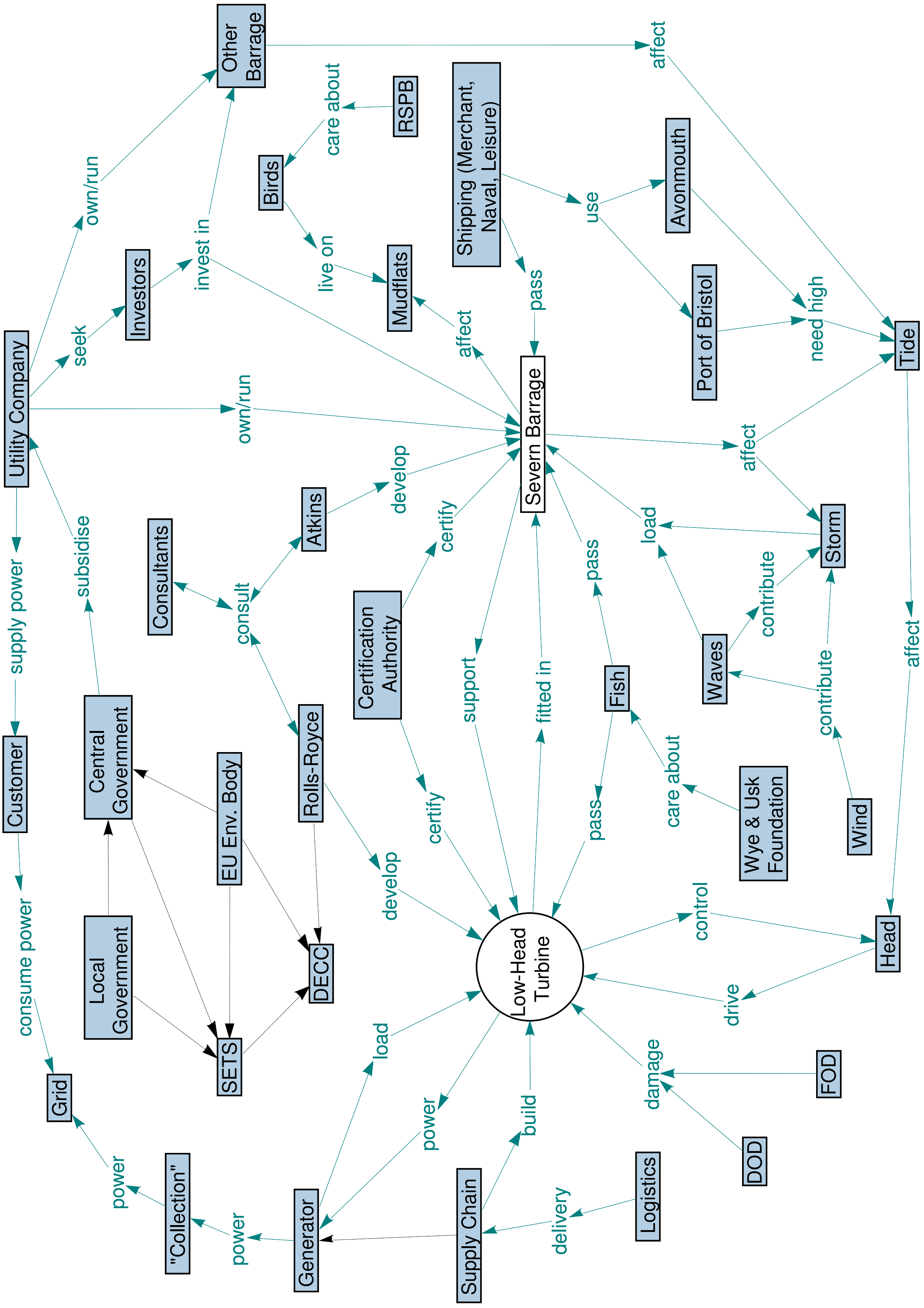

Figure 4 Severn tidal barrage context diagram showing interactions between representative stakeholders, the bar and the turbine.

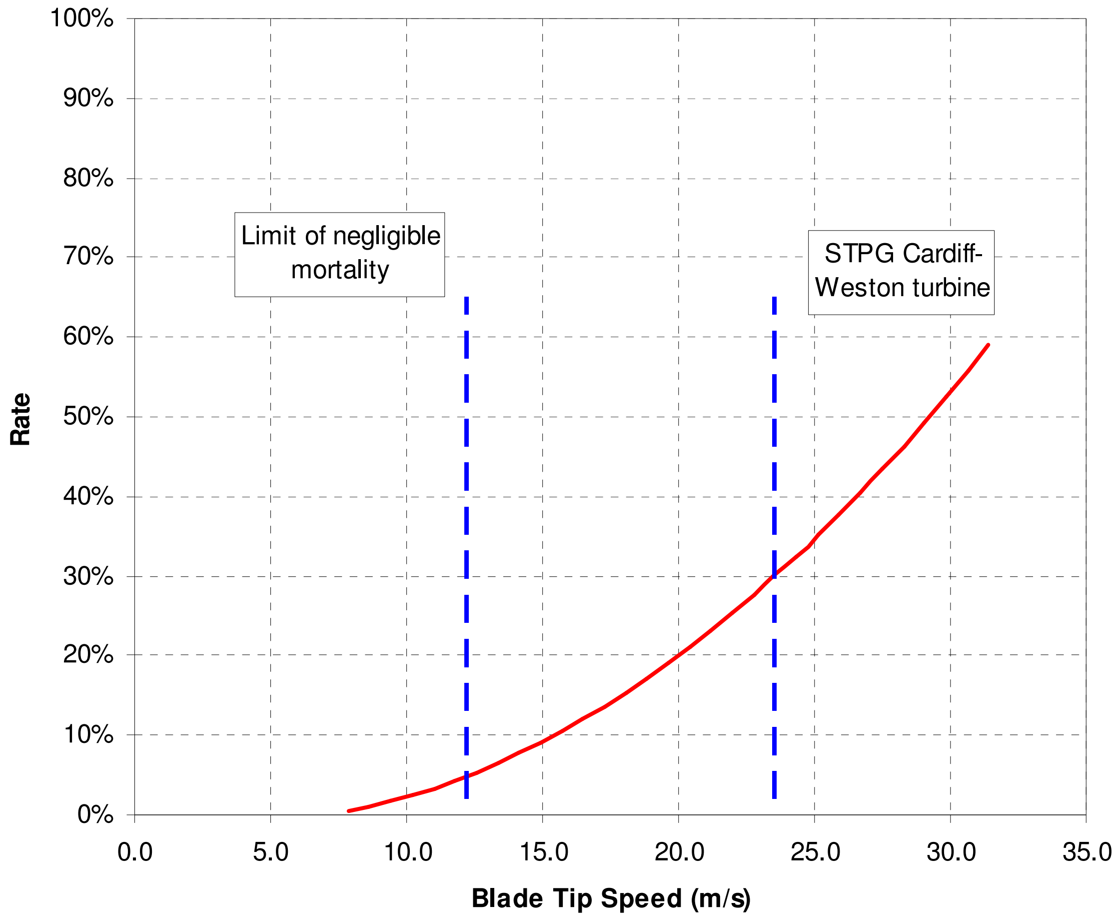

Figure 5 Assumed fish mortality performance of turbines extrapolated from INL studies. The left hand dashed line indicates the limit of negligible mortality defiend in INL studies and the right hand dashed line the operating point of a bulb-turbine proposed in STPG studies.

The significant number of turbines within a tidal bar and entry-into-service date to achieve Government renewable commitments establishes production volume and availability requirements for developing a turbine assembly facility and sub-component load onto the supply chain. Related technical risk requirements are also addressed to ensure timely availability of the required technology.

A list of functional requirements is presented in Annex D.

2.2 Design Concepts

2.2.1 Blue Turbine Configuration

The first design (Figure 6) evaluated is an axial flow machine consisting of two contra-rotating blade rows. Both blade rows are variable pitch to enable fixed speed operation over a wide head-flow operating range and each blade row is pitched through 180 degrees to face the prevalent flow direction. This turbine design is referred to as the blue concept throughout the remainder of the report.

Each rotor is connected to an independent drive train and the complete turbine assembled from two separable rotor units. Pitch bearings support the blade and transfer the torque and axial load into the rotor hub and shaft. Thrust bearings support the shaft and transfer axial load into the turbine structure. Mechanical shaft power is converted to electrical power through a step-up transmission and synchronous generator mounted in the turbine hub nacelle.

The turbine hub is supported upstream and downstream of the rotors by profiled struts canted away from the rotor. Access to the drive train machinery is provided through the strut internals. The struts also support the turbine casing to maintain tip clearance and minimise over tip leakage, and provide locating features for turbine installation.

Rolls-Royce prefers the contra-rotating turbine configuration as in-service reliability and flexibility is considered to be superior with no detriment to fish survivability.

2.2.2 Red Turbine Configuration

The second design (Figure 7) evaluated is an axial flow machine consisting of an upstream stator blade cascade and downstream rotor blade row. Both stator cascade and blade row are fixed pitch and the turbine operates at variable speed over the required head-flow operating range. The turbine cassette is rotated to face the prevalent flow direction. This turbine design is referred to as the red concept in the remainder of the report.

The blade root supports the blade and transfer the torque and axial load into the rotor hub and shaft. Thrust bearings support the shaft and transfer axial load into the turbine structure. Mechanical shaft power is converted to electrical power through a step-up transmission and permanent magnet generator mounted in the turbine hub nacelle. Power electronics are required for conversion from variable output to grid frequency.

The turbine hub nacelle is supported upstream of the rotor by the stator cascade and downstream of the rotor by a profiled strut. Access to the drive train machinery is provided through the strut internals. The struts also support the turbine casing to maintain tip clearance and minimise over tip leakage, and provide locating features for turbine installation.

The continued development of the red turbine is suspended because:

- The red turbine requires a variable speed drive train to access the same operating range as the blue turbine. This may be achieved using either a hydraulic transmission or variable frequency converters, however both have lower efficiency than a standard gear box arrangement. The former technology is currently immature and the latter relatively expensive.

- The support and rotation structure required for bi-directional operation is physically large, costly and may be difficult to integrate with the barrage. It is also though that such a structure may reduce the achievable turbine packing density. Further, there are limited examples of similar systems in operation.

- The higher blade count and solidity of the red turbine are likely to increase turbine cost and are considered detrimental to fish survival.

- The higher blade root twist makes mechanically supporting the blade axial loads more difficult and may require a solid blade construction.

2.3 Concept Identification, Evaluation and Selection

Identifying suitable generating concepts is a highly creative exercise. A number of sessions with engineering expertise from Rolls-Royce and Atkins were held to identify machine options for the tidal bar. A total of 21 different feasible configurations were identified including vertical and horizontal axis impulse and reaction machines in various configurations.

Options were evaluated against the functional requirements and the number of options reduced to four. Preliminary one-dimensional analysis of the four remaining options was completed to yield an understanding of critical characteristics in uni-directional operation (mechanical loading, efficiency) and then an assessment of these characteristics in bi-directional conditions completed. The results of this assessment were used to select the two configurations progressed to detailed design.

The sections following describe following criteria were used in identifying suitable turbine configurations.

2.3.1 Operating Conditions

Energy extraction from a tidal basin is a function of the head and volumetric flow rate through the barrage. Studies in zero-dimensional estuary models (described in §2.9) have demonstrated that a reasonable trade between loss of intertidal habitat and efficient energy

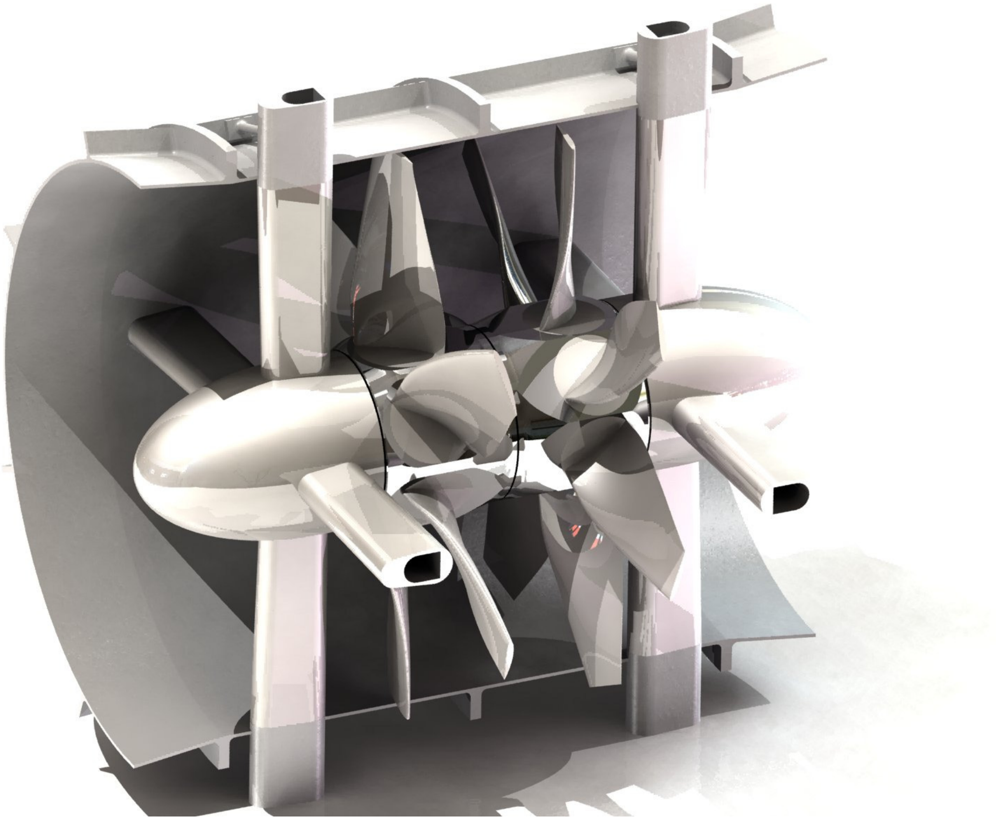

Figure 6 Blue turbine configuration developed under SETS.

Figure 7 Red turbine configuration developed under SETS.

extraction is achieved at a 3 metre net head at spring high tide and an ideal capture area occupying as much of the estuary sectional area as possible.

These operating conditions are such that nominally small losses have a significant detrimental effect on total recoverable energy from the flow. Sources of these losses include contraction, expansion and turning of the flow, duct skin friction, swirl and hydrofoil drag.

2.3.2 Duct Configuration

Acceleration of the flow through a nozzle is a nominally preferred method for reducing the size of turbo-machinery at the cost of installing a downstream diffuser or draft tube.

Efficient dynamic head recovery (and hence the maximisation of available energy extraction) in a diffuser requires that a maximum included angle of 7 degrees be maintained to prevent wall separation and loss of dynamic head. The resultant diffuser length for an economic reduction in turbo-machinery size is significant and effectively doubled for a dual generation tidal.

Nevertheless it can be shown that for a Cardiff-Weston alignment a diffuser of entrance diameter 7.5 metres and exit diameter 5 metres can be effectively installed to provide an increase in the axial velocity through the turbine by a factor of 3 and a net reduction in the required turbine diameter of 2.5 metres for a barrage of approximately 50 metres breadth.

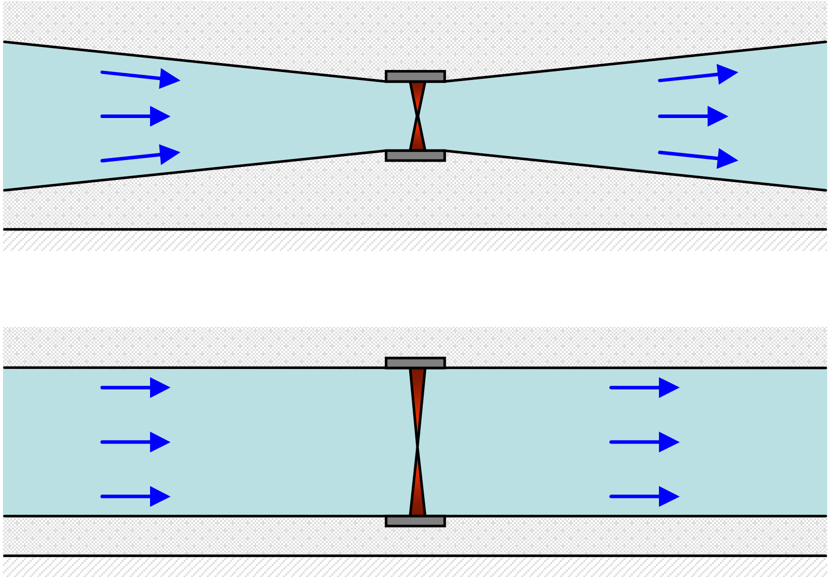

Figure 8 Schematic comparison between tidal bar solutions with upstream and downstream diffusers (upper) and straight walled ducts (lower).

2.3.3 Axial vs. Radial Flow Turbomachinery

Both turbine configurations developed to the outline design stage are axial flow turbines because of the requirement to maximise turbine swept area and minimise mixing and duct losses.

The non-dimensional and semi-dimensional operating parameters however suggest that radial flow devices are suited for use in the very-low head barrage. Maximum flow area through a radial turbine is a linear function of the turbine radius thus, precluding the use of a diffuser, a significant diameter impeller would be required to achieve the necessary flow area.

Flow area through an axial flow machine is close to the turbine rotor area (excluding the hub area) and scales with the square of the duct radius. Low blade speed and axial velocity require significant turning of the flow to effectively extract energy resulting in very high solidity (low blade spacing to chord ratio) cascades.

This situation is directly analogous to the use of axial flow machinery in large civil aircraft engine turbomachinery where a machine with a low frontal area with respect to the air flow rate is required in order to minimise weight and drag.

2.3.4 Principal Axis Alignment

Both turbine configurations developed to the outline design stage are horizontal axis because of the requirement to maximise turbine swept area and minimise mixing and duct losses.

Vertical axis machinery requires flow turning ducts at entrance and exit to the turbine occupying significant volume in the caisson. It offers the advantage of a direct shaft line connection to gearbox and electrical generating equipment mounted above the waterline.

Horizontal axis machines are not subject to the same requirement and may simply be installed within the flow duct. The ability to place generation equipment above the waterline is not excluded as a bevel gear arrangement may be used to switch the direction of the shaft line, however such an arrangement is inefficient and costly at low speed operation.

2.3.5 Bi-Directional Generation

The project identified three methods by which a turbine may be made to generate in opposing flow directions – rotation of the complete turbine assembly, rotating blade rows, or symmetrical geometry turbines.

Rotation of the turbine assembly will produce the most efficient device as blade row function remains constant in both flow orientations. The disadvantages include cost of the frame rotation system, mechanical difficultly (due to the significant load carried by the bearing structure and infrequent and slow rotation) and unreliability in service.

Reversing blade rows requires a solidity (blade spacing to chord) of less than one at each radial station to mechanically permit rotation of the cascade through 180 degrees. Rotation of the blade reverses the functionality of each row thus it is not possible to optimise the blade form to maximise efficiency in both directions and compromise blade forms must be used.

Symmetrical turbines generate identical stage loadings and velocity triangles in both ebb and flood flow direction requiring a blade with zero camber or static angle of attack. Relatively poor efficiency results due to the increase in hydrofoil drag in both cases. Introducing self-pitching mechanisms and additional contra-rotating turbine geometry improve hydrodynamic performance.

2.3.6 Minimising Fish Mortality

Blade impact mortality rate is a function of length and net speed of the fish, and blade speed and spacing. When explored further the latter suggests that the probability of a fish passing through the turbine encountering a rotor blade and suffering the impact damage is related linearly and quadratically to the blade speed respectively.

An absolute design point tip speed ratio of 3.2 is used throughout the design to minimise blade impact mortality resulting in a tip speed below the 12.2 m/s (40 ft/s) defined for negligible mortality in INL studies. The probability of blade impact is related to the number of blades and the number of blade rows is inconsequential.

2.4 *Turbine and Duct Hydrodynamic Modelling*

This work package has evaluated the performance and loading of the turbine, and exit losses from the turbine duct into the estuary. The hydrodynamic design and analysis of the turbine has employed progressively higher fidelity computational models to efficiently evaluate the design space and generate appropriate solutions.

Zero-dimensional isolated aerofoil theory models were used to evaluate the idealised performance of turbine concepts across the operating envelope on the basis of defined lift-to-drag ratios at a defined rotor speed and fixed pitch. Four turbine concepts were evaluated using zero-dimensional methods with performance maps generated to enable down selection.

An idealised performance map for an axial turbine is shown in Figure 9. The performance maps show contours of operating efficiency and assume a fixed lift-to-drag ratio for each rotor, ideal blade shape, and that each blade is ideally pitched at the specified axial through flow speed, head, and blade speed condition.

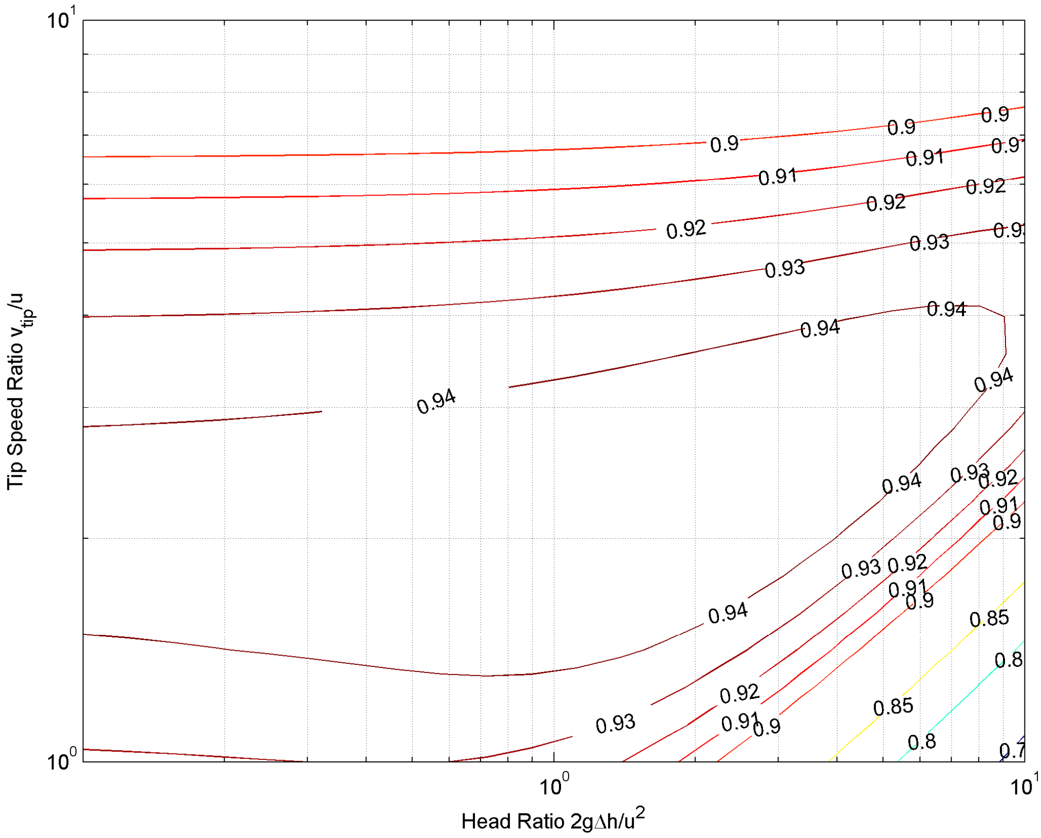

Figure 9 Idealised performance map generated using isolated aerofoil methods for an axial turbine operating in a uni-directional mode.

Two-dimensional potential models were used to determine efficiency, head-power curves, steady state blade loading, row solidity, blade count, hub blockage, and geometric profile. Potential methods calculate the separation of flow from the blade as flow conditions change and enable the required pitch range to be defined. Two-dimensional transient coupled computational fluid dynamic modelling was used to understand the progression of wakes from the blade row or supporting structures to neighbouring rows.

Three-dimensional volume of fluid computational models have been used to provide an understanding of expansion and mixing losses of flow exiting the barrage to validate assumptions on head loss and therefore net head available to the turbine. Investigative studies were completed to establish the effect of introducing square-to-round transition ducting and upstream and downstream diffusers on the rotor performance and geometry.

Validation of computational models has been completed where possible and appropriate under SETS programme time scales. This has taken the form of comparative studies using well understood operating parameters (for example back-to-back code comparisons with existing in-service Rolls-Royce aero-engine turbine blades) or by complementary methods.

Two turbine designs were evaluated to define operating characteristics, rotor blade profiles and blade counts at the operating tip speed and head ratio. Several blade design iterations were required to overcome the challenges associated with very-low head operation and large steady state and transient loads.

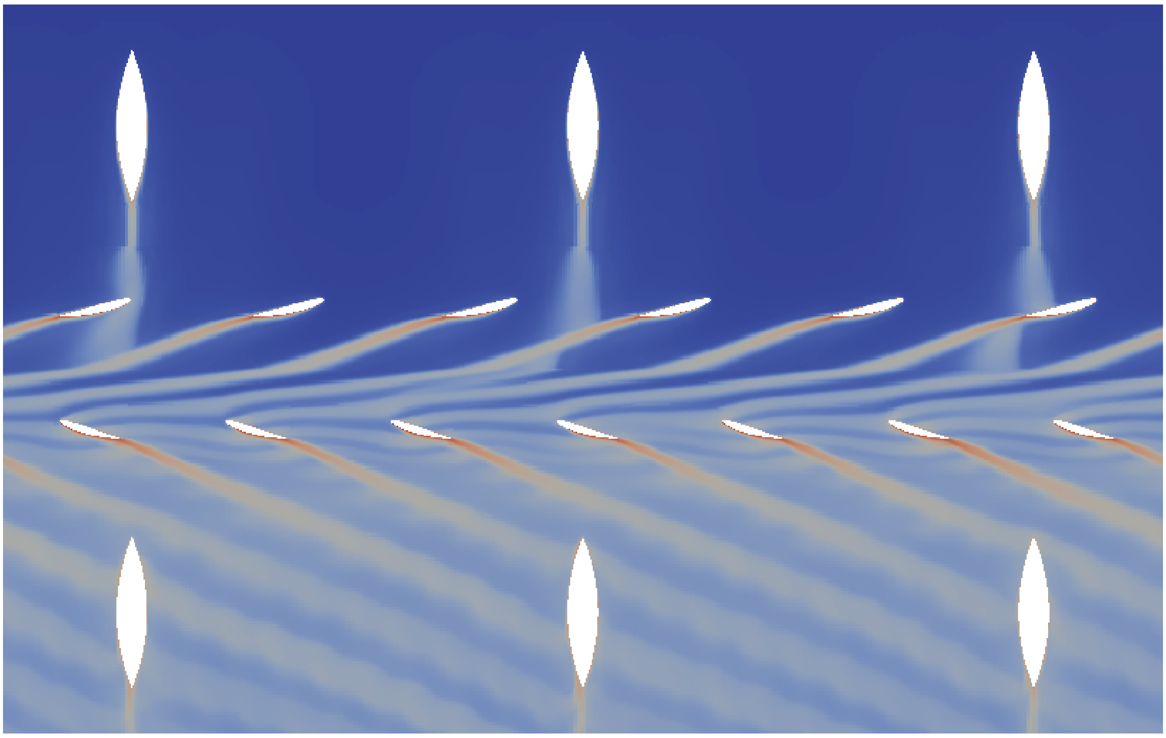

Figure 10 Two-dimensional coupled transient computational fluid model of wake progression between rotor cascades and support turbine structures.

Performance estimates completed under SETS funding indicate that both turbine concepts are capable of exceeding 90% hydraulic efficiency across the majority of the operating envelope. Over speed characteristics have been determined for both rotor designs to enable control system response to loss-of-grid connectivity cases to be determined.

Both blue and red designs achieve a significant turning of flow to efficiently extract power and blade row global pitch is set such that the combination of contra-rotation or stator-rotor rows result in zero exit swirl at the design point. The red option has only one rotating component thus the design has a significantly higher solidity and larger number of blades on both the rotor and stator than the blue option.

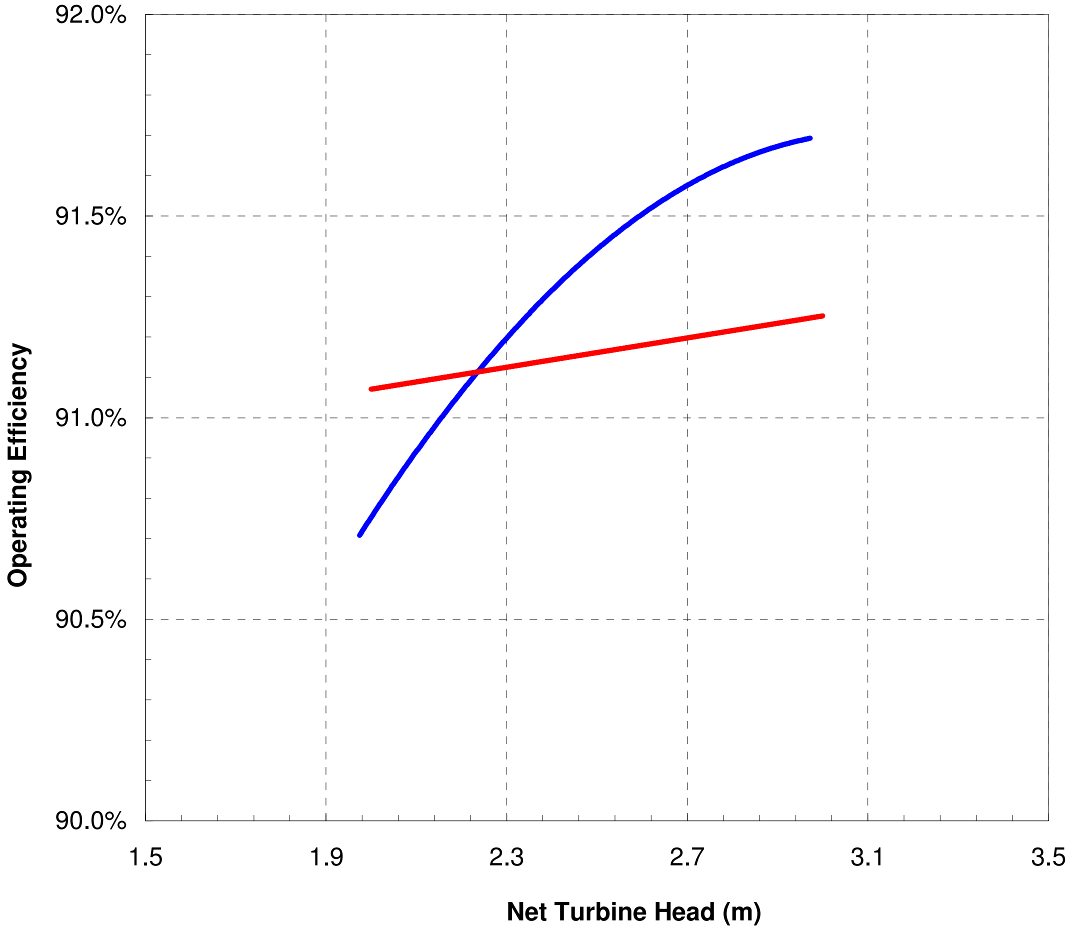

Figure 11 Operating hydraulic efficiency of contra-rotating (blue) and Kaplan turbine (red).

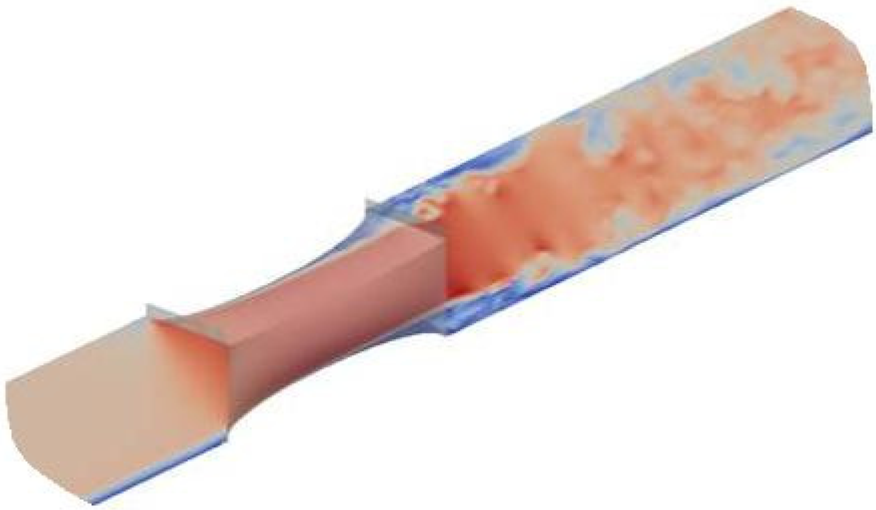

Figure 12 Volume of fluid computational fluid dynamic modelling of inlet, through duct and exit loss estimates for a 'square-to-round' transition duct without turbine installed. Note separation of flow from walls during the diffusion process.

Zero-dimensional non-linear basin modelling of the barrage at Cardiff-Weston suggests significant additional energy may be available from the barrage by pumping at slack water and that the loss of intertidal habitat may be further reduced. The blue configuration has significant flexibility and with minimal additional control system functionality will operate effectively as a pump.

2.5 Structural and Mechanical Shaft Line Design

This work package has designed and analysed the turbine structure, power train, and actuators. The turbine structure includes the hub, casing and support spars transferring the load from the rotor and shaft line to the caisson structure. Shaft line equipment includes the rotor blades, pitch mechanism, bearings, transmission and electrical generator.

The turbine casing function is to maintain adequate roundness and tip clearance for the rotor blades to prevent over tip leakage and minimise tip losses, smooth the transition of flow from the caisson duct into the turbine, prevent leakage of flow around the turbine, and contain debris from a damaged rotor. The casing structure must support the axial and radial load from the water pressure head. The design is primarily driven by the former flow requirements and axial loading as the low rotor speeds eliminate sources of high energy debris. Materials are selected to provide the minimum overall economic case weight and resistance to corrosion. Additional corrosion protection methods have also been investigated to ensure adequate turbine life.

The struts transfer axial and torque loading from the hub into the caisson and provide an access route for maintenance work where feasible. The number, cross-sectional profile, and construction of the struts have employed both computational fluid dynamics and finite element analysis to optimise material content and minimise the resulting wake on the downstream rotor.

The rotor blade has a complex profile defined by the hydrodynamic modelling but must also be capable of supporting the principal static mechanical loadings that include the axial load from the reduction in static pressure across the cascade, tangential loading by the lift force generated by the aerofoil, and centrifugal load from rotation of the blade mass. Complex transient loadings resulting from structural support and blade wakes define the high-cycle fatigue life of the blade.

Three-dimensional blade finite element models have been developed from the hydrodynamic blade profiles. These models were used to determine the location and magnitude of the principal stresses experienced by the blade as a solid structure. Progressive refinement of the blade internal structure has been completed to reduce the material required in the manufacturing of the blade and guide the selection of appropriate manufacturing technology.

Larger blade lengths require a structure similar to an aircraft wing or wind turbine in which a metallic box spar structure supports a composite skin. Smaller blade lengths may make use of manufacturing techniques employed for aero-engine turbofan blades or more recent developments in composite blade technology for open-rotor engines.

The blue turbine concept makes use of variable pitch blades with a wide pitch range requirement. Several technologies have been evaluated that include both hydraulic and electrically driven solutions and the solution selected on the basis of lowest risk and cost. Blade root fittings have been designed and analysed using finite element models to minimise material content and cost while providing adequate structural support and fatigue life.

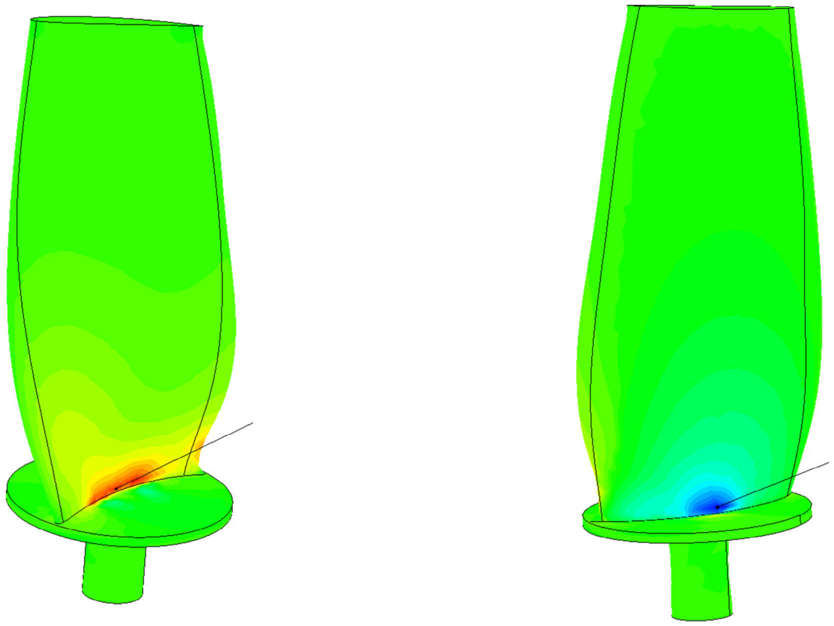

Figure 13 Solid blade finite element analysis showing magnitudes of principal stresses for a solid blade geometry.

Axial and circumferential load on the rotor are supported and transferred to the static structure by rolling element bearings within the hub. Bearings are selected on the basis of design life from the established requirements and understanding the static and transient hydrodynamic forcing of the rotor and circumferential forces under design and over speed conditions. The surrounding structure and seals have been developed to provide adequate lubrication of the bearings and prevent the escape of lubricant into the estuary water. The bearings selected are large but commercial off-the-shelf items.

The low design tip speed, large rotor diameter and high power output of the turbine result in a significant torque on the rotor output shaft. Conventional permanent magnet, induction and synchronous electrical machines operate in a 750 - 3000 rpm shaft speed range and require a significant step-up in shaft speed from the rotor to operate. Electrical machine technology issues are discussed further in the appropriate section. Increasing electrical generator input speed reduces generator installation volume but increases transmission gear ratio.

Step-up transmission options have been considered that include conventional parallel and epicyclic gearboxes and novel hydrostatic, hydrodynamic and magnetic transmissions. Each option has been evaluated on the basis of technology maturity, reliability, service experience, transmission efficiency, installation volume, and cost.

Shaft line and structural requirements for withstanding critical failure modes in conjunction with control system action have been identified and a design developed with suitable integrity.

The design process has been inherently aware of the large number of units that must be produced and the design approach has deliberately minimise the requirement for novel technology in the shaft line design. New technology introduces several additional risks from a supply chain perspective in that:

- Production designs are not available and may delay design of the system.

- Manufacturing capabilities are limited to small scale demonstrations and substantial ramp-up rate may be required.
- Frequently there may only be one supplier increasing the probability of common mode failure.

The design process has minimised both technical and economic risk in the proposed concepts hence technologies with limited service or high-volume production experience have been excluded. As service and production experience accumulates technologies which show economic merit may be incorporated however the proposed concept is not technically or economically dependant upon novel transmission technologies.

Various shaft line arrangements were studied to optimise the packaging and installation of transmission and electrical generators, and provide access for maintenance and repair. Trade studies on transmission ratio and transmission and electrical generator volume have been completed to define the proposed solution. Equipment installation location has been studied including an integrated hub shaft-line and on-barrage generation.

The effect of scaling on the turbine drive train and structure has been considered to develop an understanding of the variation in loading characteristics with turbine diameter. Factors such as blade construction, transmission and generator size, supply chain availability, and maintenance have been considered.

The use of a rotating turbine casing is required for the red option and systems and equipment for performing cassette rotation defined including identification of component suppliers. The internal cassette structural requirements to support rotation have been calculated and an adequate framework designed.

2.6 Control and Instrumentation System

The critical requirements and functionality of the barrage control system have been evaluated to enable the capability, technology and risk associated with the system to be defined. Assessments have been made of the turbine and barrage under the normal operating cycle and in response to critical failure mechanisms.

Control system actions (including blade pitch and speed control, maintenance brake engagement and sluice gate deployment) have been evaluated for effectiveness and response time and a component specification established against the time constant of key events. Instrumentation specification (parameters, range and tolerance) have been developed to support assessment of system risk.

2.7 Electrical Conversion and Grid Connection

Substantial electrical machines are required to convert shaft power delivered by the rotor or gearbox into electrical power. These electrical machines may be directly synchronised to the National Grid for fixed speed machines or require power conversion and conditioning electronics in the case of variable speed machines.

The use of permanent magnet direct-drive electrical machines has been considered and traded comparatively against the use of a step-up transmission and permanent magnet, induction and synchronous generator arrangement at various operating speeds. This trade has been completed on the basis of current electrical machine capability and installation space within the hub or on the barrage. Applications of novel electrical machines such as the Rolls-Royce rim driven tunnel thruster have also been investigated.

An appropriate grid connection system has been defined that meets current requirements for frequency stability with no single grid connection exceeding 1320 MW. The architecture has been defined from the National Grid connection at 400 kV through to interconnecting the turbines deployed on the barrage generating at 11 kV. Estimates of numbers of transformers, switchyards, and circuit breakers, as well as the length of cabling have been produced to assist in estimating the cost of on-barrage electrical equipment. Where appropriate power conditioning and conversion electronics have been defined and costs detailed.

2.8 Alignment and Civil Works

The alignment of the B3 Cardiff Weston barrage is shown in the Figure 19. Also shown is an alternative alignment for a bi-directional barrage. Pushing the barrage alignment further out increases the cross section area by about 50% for an increase in length of just 20%. This enables many more turbines to be fitted across the estuary, thus increasing the total flow potential.

For the purpose of this study the construction methodology and installation sequence would be the same as proposed in the IOAR and Energy paper 57. The caissons would be constructed in a dry dock and then floated and towed to the site by tugs. The slightly lower draft requirements may have some advantages but for the purposes of the construction cost estimate the same unit rates and programme period have been used.

2.9 Energy Yield Modelling

A so called “flat estuary model” or zero dimensional model has been used to calculate energy output. This model calculates the flow through turbines and sluices based on the head difference between the outside tidal level and the inside basin level. The basin level is adjusted at each time step by calculating the incremental change is level as the total flow in or out divided by the basin area.

A ‘flat estuary’ or 0-degree estuary model derives flows numerically by the principle of mass conservation between the upstream basin and the downstream estuary. Tidal levels seaward of a barrage are assumed to be unchanged, and turbine and sluice flows are determined by the head difference up- and downstream of the barrage at short time steps over a tidal cycle or cycles.

The Atkins flat estuary model uses a backward difference scheme. The basin level is adjusted for each time step based on the calculated turbine and sluice flows from the previous time step. Provided that the time step is small, the error is acceptable. The results are reported on the basis of a 10% reduction in seaward tidal levels, however cases considering no loss of seaward tidal level (consistent with the IOAR) and 20% seaward tidal level reductions.

2.10 Cost and Commercial Modelling

Primary cost models of turbine concepts were developed to provide a comparative estimate of solutions. Preliminary bottom-up cost models for a range of cases were produced to understand the key drivers (efficiency and capital cost) on the effective cost of the turbines.

Assuming the total cost of the device is constant, a 1% increase in device efficiency yields a 1.3% decrease in the peak power normalised unit cost. Assuming civil works as a fixed price with negligible opportunity cost a 1% increase in turbine efficiency is worth 3% in overall turbine cost. This relationship is apparent because the turbines only represent a proportion of the total installation cost and infers that device efficiency should be maximised to yield economic output.

Refinements in the concept design have permitted equipment suppliers to provide more robust costs for key components as specifications became more detailed. The initial primary cost models were revisited and sub-system costs accounted. Sub-systems accounts defined included:

1. Rotor and stator blades.
2. Blade fixing and pitch mechanism.
3. Transmission.
4. Electrical generator.
5. Power conditioning.
6. Hub, bearings and shafts.
7. Structures and casings.
8. Control and instrumentation.
9. Assembly, testing and commissioning.

Total installation and unit cost for the turbine has been accumulated and normalised against the turbine power output for evaluating scheme costs. A capital contingency of 15% is incorporated but no special contingency for supply chain risk incorporated or considered to be required. The expected cost normalised installed cost of the turbine is £0.85m / MW.

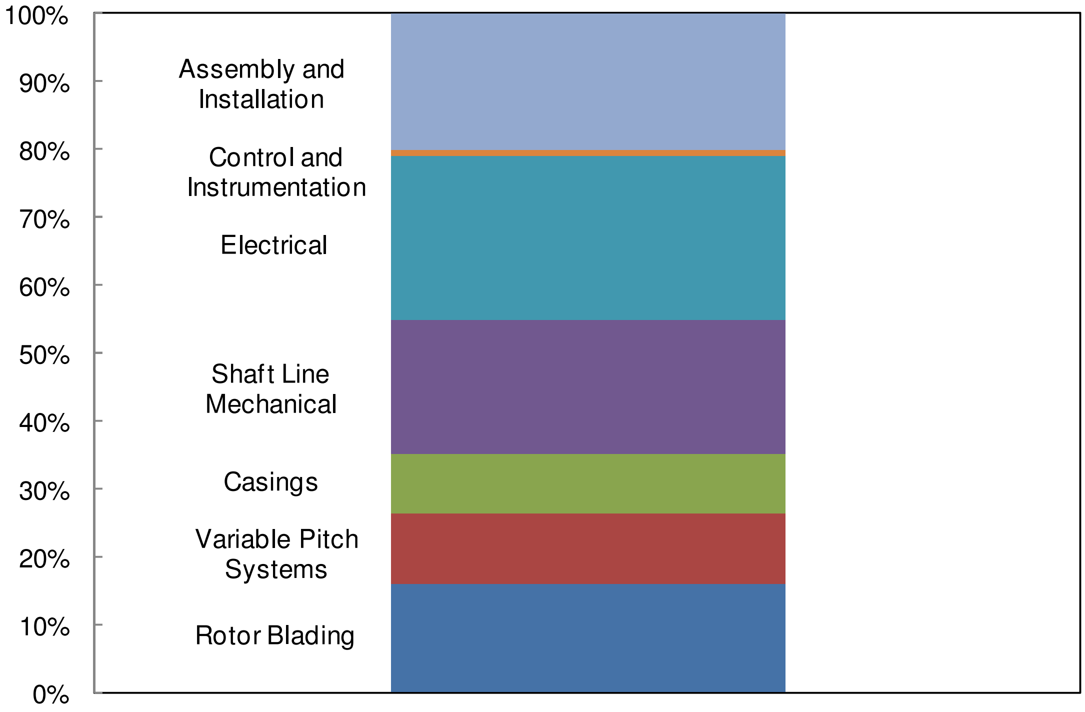

Figure 14 Breakdown of accounts for normalised turbine capital cost.

A commercial model and route to deployment have been established show the total project cost throughout its life. This commercial model takes provision of the requirement to conduct product development and establish a manufacturing facility. The following cost of electricity assessment is consistent with that completed in the Interim Options Analysis Report (IOAR) [4] for fair-basis comparison. No optimism bias[1] is included in published data however some discussion of where potential conservatism is present is provided.

The levelised cost of electricity model assumes 4 years of development and construction planning, and 7 years of turbine and civil construction. During development the civil structural surveys, planning and designs are completed, a turbine production facility is established, and the production design finalised.

In the subsequent construction period, the barrage civil elements are constructed, electrical grid reinforcement completed and the turbines manufactured and installed in the barrage. Compensatory habitat is also established and the cost incurred during the construction period. A compensatory ratio of 2:1 is assumed at a cost of £65,000 / hectare.

The cost of the construction is assumed to be spread evenly across the construction period and derived from the primary cost models discussed earlier. Barrage handover occurs at the end of construction period and revenue generation is assumed to start immediately.

A series of annualised cash flows are paid to operate, maintain and replace the turbines at a rate of 1.75% of the total barrage capital cost excluding habitat allowances. Further cash out flows are made for major services and overhauls of the turbine mechanical and electrical equipment assumed to be 70% of the total mechanical and electrical equipment at first installation.

The cost of electricity has been evaluated with major maintenance intervals at both 20 and 40 years. The complete operational life of the barrage structure is assumed to be 120 years and cash flows discounted at 8% consistent with the IOAR. A comparison between the very-low head dual generation tidal bar and the options considered in the IOAR is given in Figure 17. The annuities are discounted such that the project NPV is calculated from notice-to-proceed.

Figure 17 includes the assessment of offshore wind under IOAR fair-basis cost of energy assumptions using data disclosed by the DECC [5] notably an installed capital cost of £3.2 m / MW with planning and construction completed in 2 years, an operations and maintenance cash flow of £0.395 m and an installation life of 20 years.

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[1] Optimism bias includes economic benefits such as mass production, efficiency benefits such as step-change advanced technology benefits, etc.

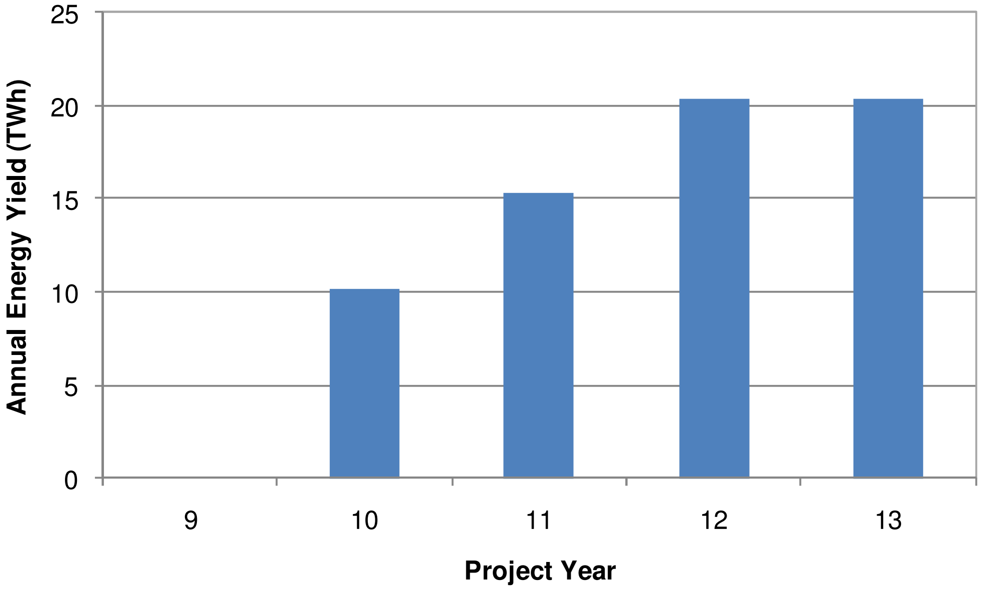

Figure 15 Generator capacity ramp-up during from first power operation to full power operation.

An alternative set of cost of electricity model assumptions specified in the SETS study utilises the same construction, operation and maintenance cash profiles however an 8% discount rate is applied during the accounting amortisation period (35 years from start of generation) and 3% discount rate to subsequent cash flows.

Electrical generation is assumed to start at half capacity during project year 10 and ramps-up to full power generation in year 12. This ramp-up profile is shown in Figure 15. Electrical energy output is reduced by 20% during maintenance periods as turbines are decommissioned and replaced. This reduced power profile is shown for a maintenance window in Figure 16.

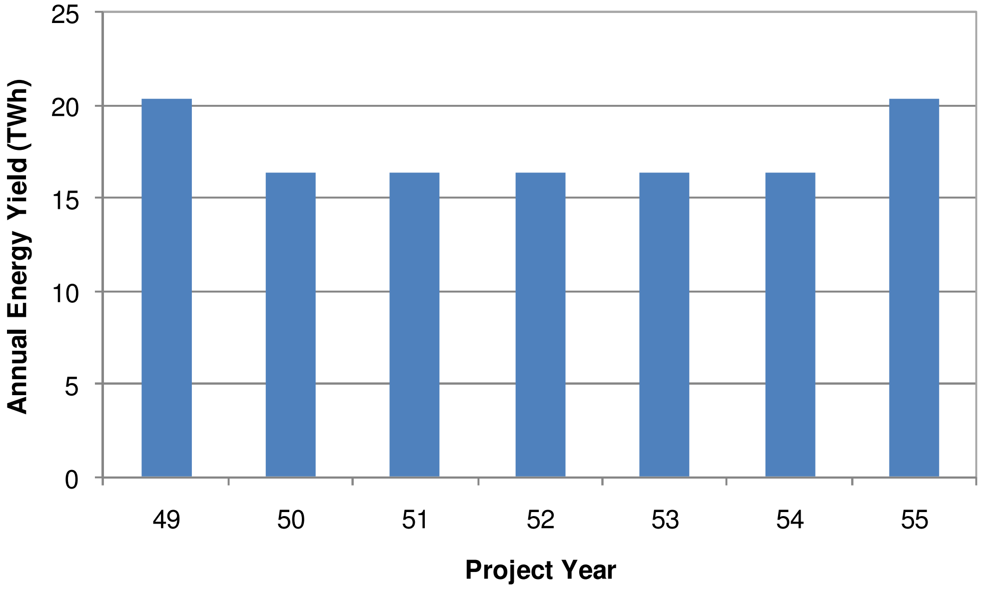

Figure 16 Reduction in barrage energy output during maintenance periods.

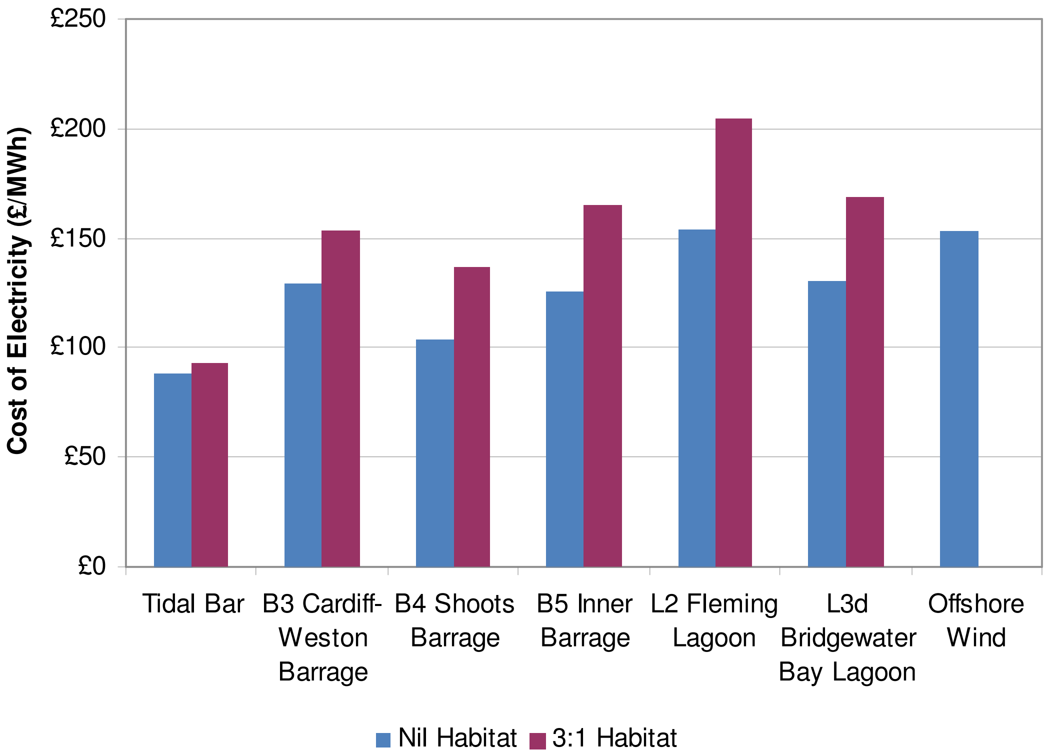

Figure 17 Comparison between the very-low head dual generation tidal bar, alternatives short listed in the IOAR, and offshore wind under IOAR assumptions.

Elements of differentiating capability are not included in the levelised cost of electricity analysis. The model does not account for cash flow opportunities from operating the turbine on free stream flow prior to completion of construction these are expected to be small relative to the total barrage output but will help establish operating experience with the turbine before full power generation. An estimate of the tidal bar yield operating on in free stream generation is shown in Figure 18.

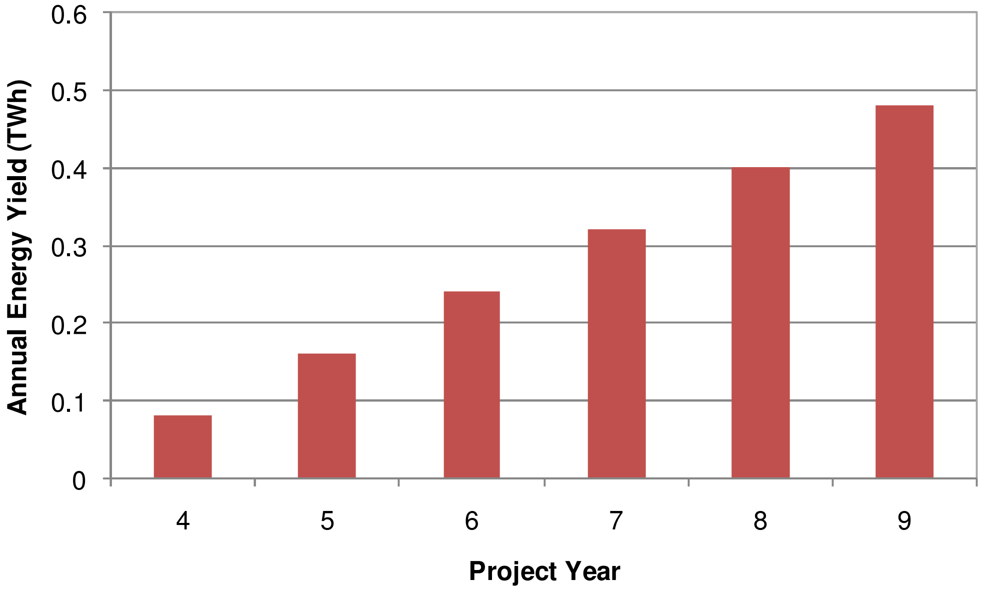

Figure 18 Estimated free stream generation output profile during construction.

2.11 Manufacturing, Logistics and Supply Chain

The supply of electrical and mechanical sub-system equipment for a very-low head barrage is substantial. The supply chain capability and delivery rate in the required design range has been evaluated to understand the effect barrage and turbine construction would have on supply chain economics, notably for the following critical elements:

- Turbine casing shroud.
- Turbine blades.
- Electrical switchboard, transformer and generator sets.
- Transmission sets.

High-level analysis has shown that the supply chain of electrical switchboards, transformers and generators, transmissions, casings and other machined components is broad and substantial and that the impact of barrage construction will be minimal. Elements of this supply chain currently address various markets including but not limited to onshore and offshore wind. Approximately 1000 new wind turbines were manufactured in 2008 and the sector experienced annual growth of the order of 30%. Many of the components (such as transmissions and electrical generators) are also supplied to many other sectors.

The supply of metallic spar and composite skin blades is currently small with few small scale manufacturers providing blades into the tidal stream market. Development activity in this supply chain will be required to yield the required number of blades for a tidal barrage however new manufacturing techniques are reducing lead times and improving production rates.

The significant size of the turbines will require assembly close to the barrage and sub-components will need to be supplied to this facility. The sub-components are small enough to be shipped to the facility by road, rail or sea providing flexibility in siting the assembly line.

2.12 Installation, Removal and Maintenance

The development of the tidal bar structure and turbine has studied opportunities to optimise the installation, removal and maintenance by adopting an integrated approach to the design of the turbine and bar. A fleet based remove-replace-repair strategy has been considered as an alternative to traditional line repair for high-head facilities and in-situ assembly approach to turbine installation.

The design has evaluated features turbine and barrage features that enable rapid installation and removal using overhead gantry cranes. Mean time between failure analysis has been conducted to establish likely maintenance intervals and to develop assumptions on the number of additional turbines required for a fleet management strategy. Maintenance access for line-replaceable units has been considered and incorporated into the design where possible.

The effect of various maintenance strategies has been evaluated on availability, capital and maintenance costs. The turbine is expected to have an operating life of 40 years.

SECTION 3

RESULTS

3 RESULTS

Rolls-Royce and Atkins have completed the outline design of a very-low head dual generation scheme for development in the Severn estuary. Two barrage alignments were evaluated to provide estimates of available turbine swept area, siting of ship transit passages, net energy yield, loss of intertidal habitat, capital cost and cost of electricity from the schemes.

Rolls-Royce has produced two separate turbine design concepts to address the very-low head operating conditions and bi-directional generation requirement. The first is an axial flow fixed speed machine with two contra-rotating blade rows that rotate to face the on-coming tide. The second is an axial flow variable speed machine with rotor and stator blade rows and produces bi-directional power by rotation of the turbine assembly.

Both configurations produced are designed to reduce the mortality rate of fish passing through the bar. Axial flow and rotor blade speed are kept well below current operating low head turbines, blade-to-blade spacing and blade chord maximised, and substantial clearances maintained between subsequent blade cascades. These characteristics should minimise the damage to fish on the basis of the four principal mortality mechanisms defined and are expected to yield an order-of-magnitude decrease in mortality rate.

Analytical and computational modelling of the two designs indicates that > 80% efficiency may be achieved from both across the majority of the operating envelope.

Dual-generation tidal bar designs were produced for Minehead-Aberthaw and Cardiff-Weston and integrated with the turbine concepts to enable defensible capital and cost of electricity estimates.

These fair-basis estimates suggest that a dual generation scheme can be effectively produced at lower cost than the ebb-only Cardiff-Weston scheme proposed by the Severn Tidal Power Group (both inclusive and exclusive of grid reinforcement and compensatory habitat allowance). The cost of electricity for both dual generation schemes is shown to be less than the ebb-only Cardiff-Weston scheme and the inner most Shoots barrage considered the most economic option in the IOAR.

An estimate of the change in tidal range, energy yield, and maximum rate power output was established using zero-dimensional non-linear basin modelling. The maximum rated power for a dual generation scheme is reduced relative to the ebb-only Cardiff-Weston scheme proposed by the Severn Tidal Power Group however the total energy output is higher. The loss of intertidal habitat is substantially reduced.

Both alignments are illustrated in Figure 19 and Figure 20.

The consortium has progressed development of a very-low head dual generation scheme but has identified that the following risks associated with the turbine and tidal bar require further treatment beyond the SETS programme:

1. Confirmation and acceptance testing of turbine passage fish rates.
2. Physical validation and acceptance testing of turbine hydrodynamic performance (including pumping) and control strategy.
3. Government and financial commitment to development programme.
4. Turbine blade supply chain development and availability.

5. Design, manufacture and validation of a production turbine.

A summary of the key results in provided in Table 3.

Scheme and alignment	Tidal bar at Cardiff-Weston	Tidal bar at Minehead-Aberthaw
Rated power output	5800 MW	10,000 MW
Annual energy output	20.8 TWh	30.4 TWh
Construction cost	£16,856 m	£26,267 m
Cost of electricity (IOAR basis)	£93.5 / MWh	£106.9 / MWh
Cost of electricity (SETS basis)	£52.4 / MWh	£60.6 / MWh
Carbon offset	9.3 mt CO_2 / yr	17.2 mt CO_2 / yr
Environmental impact	• Significant reduction in power generation carbon emissions. • Significant reduction in intertidal habitat loss relative to Cardiff-Weston STPG ebb-only scheme. • Reduction in through turbine fish mortality.	• Significant reduction in power generation carbon emissions. • Significant reduction in intertidal habitat loss relative to Cardiff-Weston STPG ebb-only scheme. • Reduction in through turbine fish mortality.

Table 3 Summary of results for dual generation Cardiff-Weston and Minehead-Aberthaw schemes.

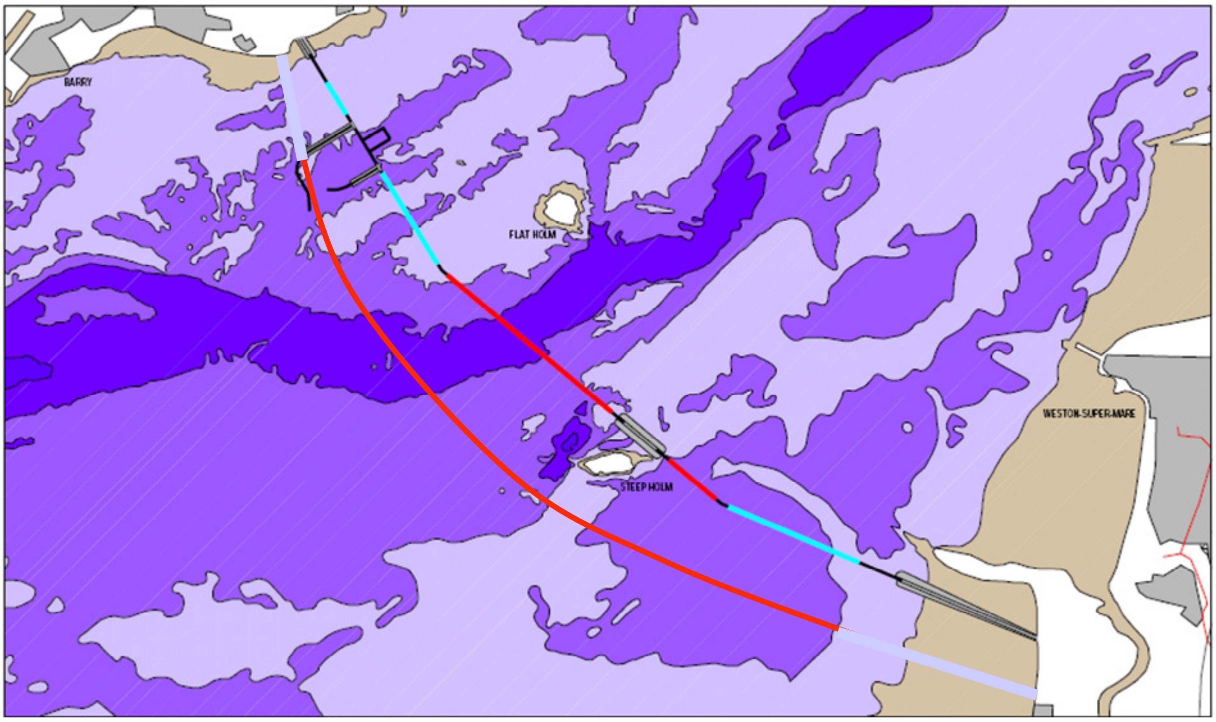

Figure 19 Revised Cardiff-Weston alignment used in the design of the very-low head dual generation tidal bar (reproduced from Interim Options Analysis Report).

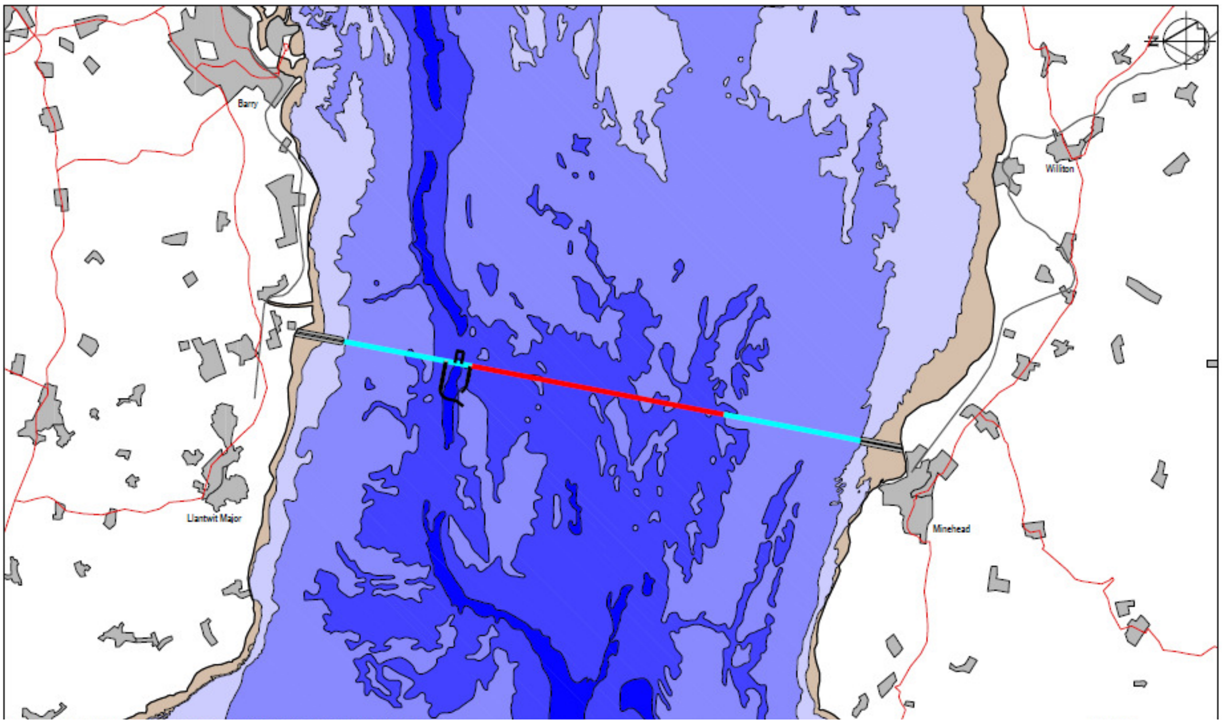

Figure 20 Minehead-Aberthaw alignment used in the design of the very-low head dual generation tidal bar (reproduced from Interim Options Analysis Report).

SECTION 4

CONCLUSIONS

4 CONCLUSIONS

The work programme has produced two essentially viable turbine designs and civil structures for Cardiff-Weston and Minehead-Aberthaw. Rolls-Royce and Atkins consider that:

1. A tidal bar may be installed in a Cardiff-Weston alignment at an expected capital cost of £16,174 m excluding habitat loss and £16,856 m inclusive of habitat loss.
2. A tidal bar may produce a peak power output in a Cardiff-Weston alignment of 5,800 MW with a total annual energy yield of 20.8 TWh at a cost of £93.5 / MWh.
3. A tidal bar in a Cardiff-Weston alignment may result in a loss of intertidal habitat of 5,200 hectares. High and low water pumping may be used to reduce this loss further.
4. A tidal bar may be installed in a Minehead-Aberthaw alignment at an expected capital cost of £25,383 m excluding habitat loss and £26,267 m inclusive of habitat loss.
5. A tidal bar may produce a peak power output in a Minehead-Aberthaw alignment of 10,000 MW with a total annual energy yield of 30.4 TWh at a cost of £106.9 / MWh.
6. A tidal bar in a Minehead-Aberthaw alignment may result in a loss of intertidal habitat of 6,000 hectares.
7. A tidal bar requires lower capital investment than the Severn Tidal Power Group (STPG) ebb-only barrage at Cardiff-Weston.
8. A tidal bar substantially reduces the loss of intertidal habitat relative to the STPG ebb-only barrage.
9. A tidal bar provides greater energy yield than the STPG ebb-only barrage.
10. A tidal bar provides competitive or better economics than an ebb-only barrage, tidal stream or offshore wind generation.
11. A tidal bar could reasonably be in service by 2020 - 2030 subject to planning consent and commercial commitments.
12. A tidal bar should be less disruptive to shipping than an ebb-only barrage due to the retention of existing navigation channels, shorter lock transitions, and higher structure permeability during construction. A ship lock structure will still be required.
13. A tidal bar is more likely to retain the natural flow patterns of the estuary, however higher fidelity modelling will be required to confirm this conclusion.
14. A tidal bar would require reduced grid reinforcement for a given energy yield due to the lower peak capacity and longer generating window.
15. A tidal bar in the Severn estuary may be complementary to a North-West estuary scheme with substantial commonality in the turbine technology.
16. A very-low head bi-directional turbine with high reversible efficiency is technically feasible and no new technology or engineering methodology is required.

17. A very-low head bi-directional turbine can eliminate the requirement for a downstream diffuser.

18. A majority of the components for a very-low head bi-directional turbine are within the current supply chain scope and production of the required number of turbines is reasonable feasible.

19. Turbine passage fish mortality rates can theoretically be significantly improved over existing bulb turbines and a feasible design developed on the derived operating conditions.

20. The turbine concepts may be scaled to diameters between 5 metres and 15 metres. Larger and smaller diameters may be feasible however detailed analysis beyond this range was not completed.

21. The affordability of a tidal bar may be improved by operating the incomplete structure as a tidal stream device. Further validation work will be required to assess the energy yield and economics of this operating mode.

SECTION 5

REFERENCES

5 REFERENCES

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[3] Coutant C. C., Whitney R. R. "Fish Behaviour in Relation to Passage Through Hydropower Turbines: A Review", Transactions of the American Fisheries Society, 2000.

[4] "Analysis of Options for Tidal Power Development in the Severn Estuary - Interim Options Analysis Report", Parsons Brinckerhoff for the Department of Energy and Climate Change, December 2008.

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ANNEX A

SCHEME DESCRIPTION

ANNEX A SCHEME DESCRIPTION

The programme has studied the design of a tidal bar operating in dual (i.e. ebb and flood) generation scheme at Cardiff-Weston and Minehead-Aberthaw alignments.

The Cardiff-Weston alignment follows a revised profile to accommodate the required turbine swept area. The Minehead-Aberthaw alignment follows the profile reported in the Interim Options Analysis Report (IOAR).

The tidal bar operating conditions and turbine configurations for Cardiff-Weston and Minehead-Aberthaw alignments are disclosed in Table 4 and Table 5 respectively. The tidal cycle seaward and inland of the barrage at Cardiff-Weston is shown for a spring tide in Figure 21.

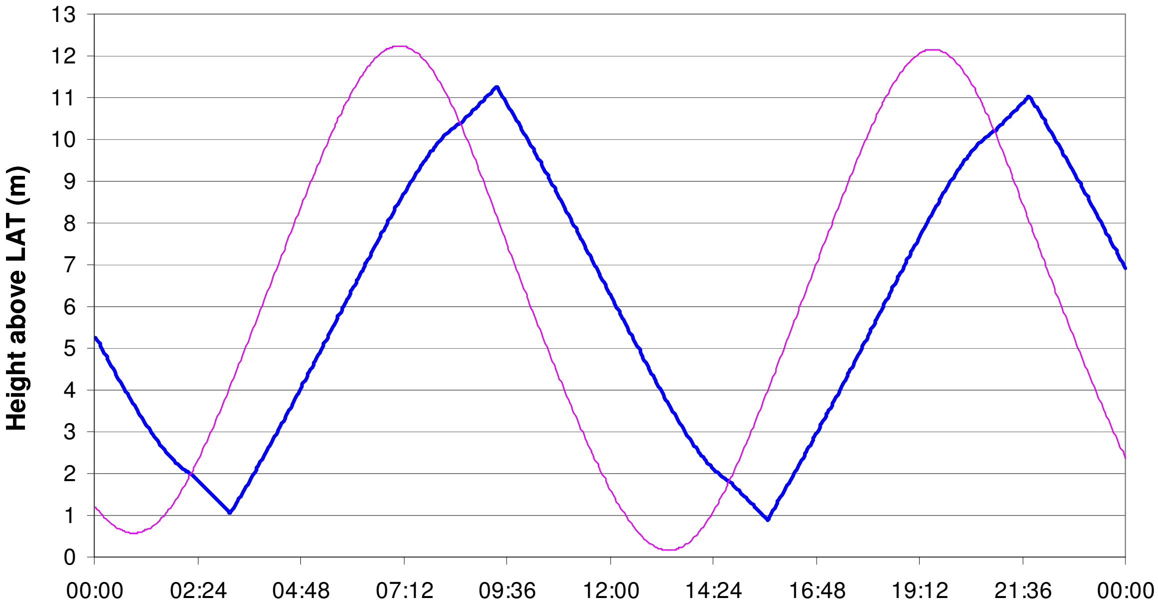

Figure 21 Seaward and inland basin levels during a spring tide with a pumped dual generation scheme at Cardiff-Weston.

Two turbine concepts were developed to the outline design stage.

The first design evaluated is an axial flow machine consisting of two contra-rotating blade rows. Both blade rows are variable pitch to enable fixed speed operation over a wide head-flow operating range and each blade row is pitched through 180 degrees to face the prevalent flow direction. This turbine design is referred to as the blue concept in the remainder of the report.

Each rotor is connected to an independent drive train and the complete turbine assembled from two separable rotor units. Pitch bearings support the blade and transfer the torque and axial load into the rotor hub and shaft. Thrust bearings support the shaft and transfer axial load into the turbine structure. Mechanical shaft power is converted to electrical power through a step-up transmission and synchronous generator mounted in the turbine hub nacelle.

The turbine hub is supported by upstream and downstream of the rotors by profiled struts canted away from the rotor. Access to the drive train machinery is provided through the strut internals. The struts also support the turbine casing to maintain tip clearance and minimise over tip leakage, and provide locating features for turbine installation.

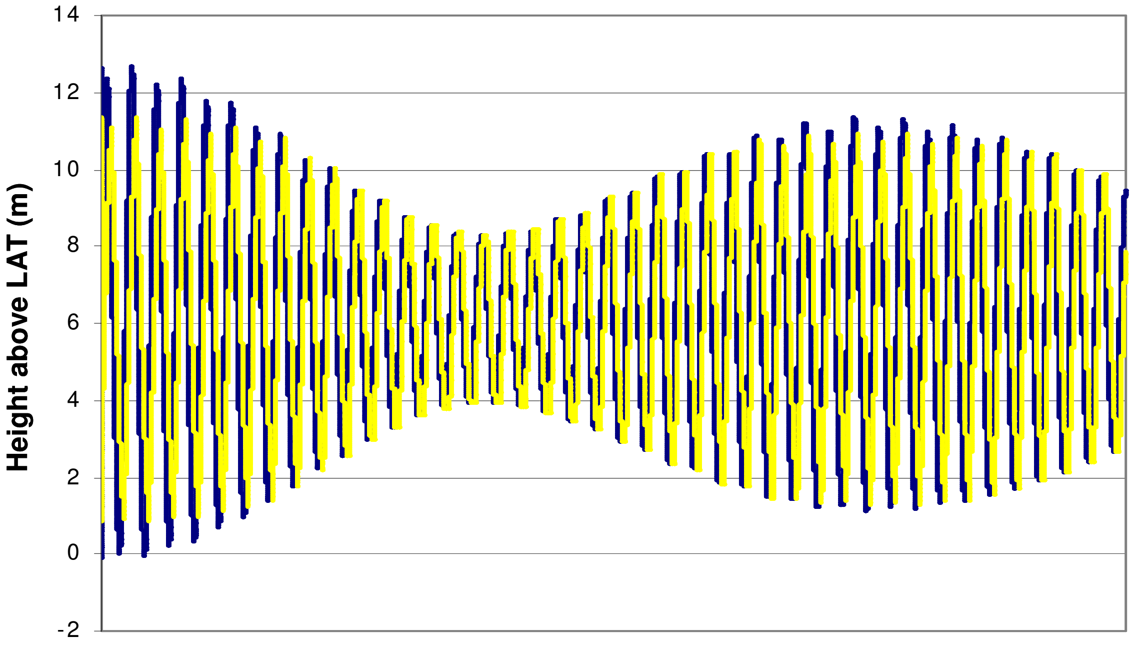

Figure 22 Tidal range showing original seaward basin level (blue) and inland tidal basin level with a pumped scheme and a 20% loss of seaward basin level (yellow).

The second design evaluated is an axial flow machine consisting of an upstream stator blade cascade and downstream rotor blade row. Both stator cascade and blade row are fixed pitch and the turbine operates at variable speed over the required head-flow operating range. The turbine cassette is rotated to face the prevalent flow direction. This turbine design is referred to as the red concept in the remainder of the report.

The blade root supports the blade and transfer the torque and axial load into the rotor hub and shaft. Thrust bearings support the shaft and transfer axial load into the turbine structure. Mechanical shaft power is converted to electrical power through a step-up transmission and permanent magnet generator mounted in the turbine hub nacelle. Frequency conversion power electronics are used to convert variable generating output to grid frequency.

The turbine hub nacelle is supported upstream of the rotor by the stator cascade and downstream of the rotor by a profiled strut. Access to the drive train machinery is provided through the strut internals. The struts also support the turbine casing to maintain tip clearance and minimise over tip leakage, and provide locating features for turbine installation.

Grid connection for both schemes is made through an architecture principally reliant on conventional technology.

The caissons proposed for the B3 Cardiff Weston barrage would be 73.9m wide. A benefit of the new turbine design is that a draft tube would not be required. Moreover, the smaller head would mean a smaller horizontal force on the caissons, and consequently it would be possible to reduce the width of the caissons to about 50m.

The bottom level of the caisson is a function of the turbine diameter and the required submergence depth to prevent cavitation at the root of the runner blades. Again, the new turbine design has an advantage in that it requires less submergence because it operates at a lower head and slower speed. This means that the 9m contra-rotating turbine caisson would have a foundation level of about -17m OD compared with a level of -28.7m OD for a 9m bulb turbine. Since deeper water is available in the middle of the channel, 14m dia contra-rotating turbines are also used and these would have a foundation level of -22m OD.

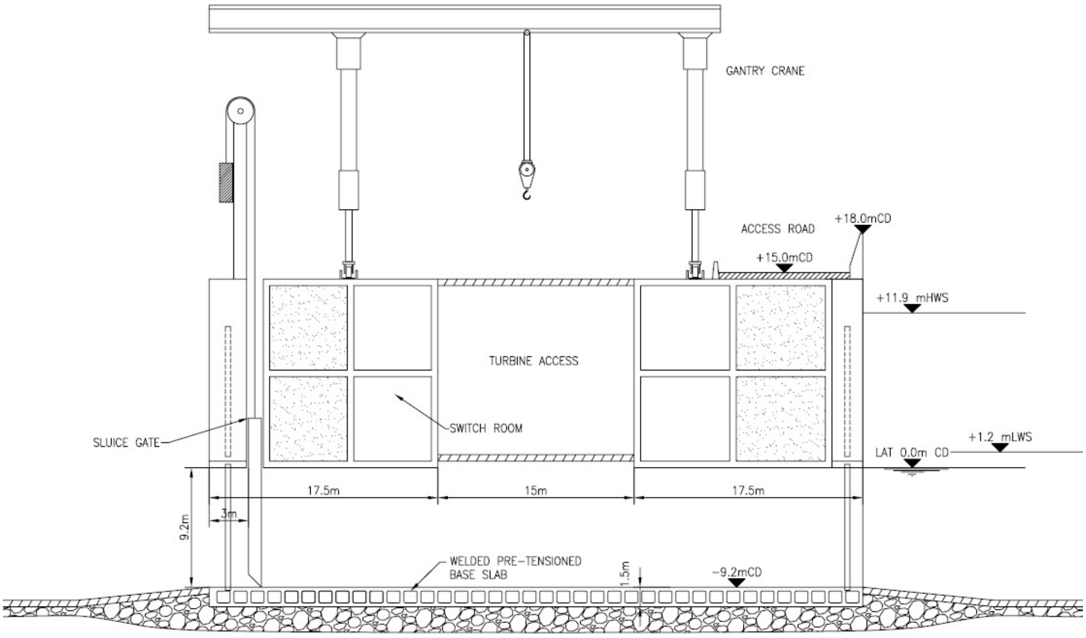

Figure 23 Caisson design proposed for the Cardiff-Weston dual generation alignment.

	Cardiff-Weston	Minehead-Aberthaw
Spring Differential Head	3 m	4 m
Neap Differential Head	2 m	3 m
Δ High Water Mean Neap	0 m	0 m
Δ Low Water Mean Neap	0 m	0 m
Δ High Water Peak Spring	-1.4 m	-1.2 m
Δ Low Water Peak Spring	+1.4 m	+1.2 m
Tidal cycle delay	135 minutes	135 minutes
Habitat Loss (hectares)	5,200 hectares	6,000 hectares

Table 4 Bar operating conditions for Cardiff-Weston and Minehead-Aberthaw alignments.

The top level of the caissons would be similar to the B3 barrage design as it would be based on the same extreme water levels estimates, sea level rise assessment, and design wave heights. Our calculations suggest that a wave wall would be useful in reducing overtopping volumes during storm events.

The total caisson volume for a bi-directional barrage would be some 25% less than for the B3 barrage scheme for the reasons discussed above. Figure 23 shows the proposed caisson design:

The width of the caisson has been reduced to about 50m now that there is no requirement for a draft tube. The caissons would be constructed of reinforced concrete. The turbine passage is straight and of square cross section. A hatch is provided above the caisson and a gantry crane of about 500 tonnes would be able to lift out the turbine in two pieces.

A vertical counter-weighted sluice gate is provided to close the turbine off and to “stand” at high and low water. The gantry crane would install stop logs across the ends of the turbine passage for maintenance. An access road is provided across the top of the caissons. The reduced with of caisson would not provide the opportunity to locate a public highway across the barrage.

	Cardiff-Weston	Minehead-Aberthaw
Total Number of Turbines	1065	1152
Maximum Turbine Diameter	14 m	14 m
Total Barrage Rated Power	5,800 MW	10,000 MW

Table 5 Installed turbine parameters for Cardiff-Weston and Minehead-Aberthaw alignments.

Technical Risk

The programme has actively pursued an economic turbine with minimum design risk however risk associated with product and supply chain development remain. A comprehensive risk register is presented in Annex C. This approach to risk management in the design has established that the following key risks require further treatment:

1. Validation and acceptance testing of turbine passage fish rate.
2. Physical validation and acceptance testing of turbine hydrodynamic performance (including pumping) and control strategy.
3. Government and financial commitment to development programme.
4. Turbine blade supply chain development and availability.
5. Design, manufacture and validation of a production turbine.

The fundamental design of the turbine has been completed using progressively higher fidelity design codes up to analysis with 2D computational fluid dynamics and consistent results have been produced using the various analysis techniques. These analysis codes are validated against known Rolls-Royce aero-engine blade designs to provide confidence in the results.

Further work beyond the SETS programme should consider 3D steady computational flow analysis to investigate blade forms for flow separations, complete more detailed design optimisation and confirm rotor efficiency. Scale model testing at representative Reynold's numbers is recommended to further confirm performance.

The hydrodynamic models assume a conservative tip clearance to model over tip leakage and establish tip losses. The tip clearance is dependant on the manufacturing conformance to process of diameter and roundness of the casing and length of the blade. The diameter of the casing is larger than the 9 metre bulb turbines proposed for a Cardiff-Weston ebb-only barrage, however blade length is similar due to the larger hub blockage. Insert materials may be used to reduce tip clearances and a low risk is considered to exist against the turbine due to overtip leakage.

Fish mortality rates for turbine passage have been evaluated on the most complete and reputable data available, however it is recognised that mortality rate statistics may be confounded by factors such as geometric dissimilarity between the turbines considered in the present study and those used in United States Department of Energy studies, as well as differences between fish species in the estuaries and rivers.

The reliance on mostly mature technology reduces the risk of capital cost excursions in the production of the turbines. Cost data has been derived both from supplier quotations and experience with the Rolls-Royce tidal stream turbine providing reasonable confidence in the reported result.

The process of developing and demonstrating a production turbine design is outlined in Annex B. Rolls-Royce has experience in the development and demonstration programmes in similar environments again through its subsidiary Tidal Generation Limited and the programme costs and timescales are viewed as reasonable and representative. Rolls-Royce has robust product development and through life management process used in the development of a broad spectrum of products that would be deployed in any future turbine development.

The scheme described retains the key residual risks described above that must be addressed after the SETS programme however the project consortium considers that both the turbine design and barrage structure are technically feasible.

Cost and Amount of Energy

The energy yield and cost of electricity for Cardiff-Weston and Minehead-Aberthaw alignments are disclosed in Table 6. A full cash flow analysis is detailed in Annex F and sensitivity to key parameters tested. A habitat allowance of 2:1 replacement ratio is included where indicated. The economic life of the turbine is 40 years and the barrage 120 years.

Both Cardiff-Weston and Minehead-Aberthaw dual generation alignments demonstrate better economics than the STPG ebb-only scheme when habitats allowance is excluded. Inclusion of a habitats allowance has a modest effect on dual-generation schemes but significantly increases the cost of ebb-only operations. It can therefore be concluded that very-low head dual-generation are more economic than ebb-only generation.

	Cardiff-Weston	Minehead-Aberthaw
Net energy yield	20.8 TWh	30.4 TWh
Cost of electricity – excluding habitat allowance (IOAR basis)	£92.7 / MWh	£104.0 / MWh
Cost of electricity – including habitat allowance (IOAR basis)	£93.5 / MWh	£106.9 / MWh
Cost of electricity – excluding habitat allowance (SETS basis)	£51.0 / MWh	£59.3 / MWh
Cost of electricity – including habitat allowance (SETS basis)	£52.4 / MWh	£60.6 / MWh

Table 6 Net energy yield and cost of electricity results for tidal bar alignments at Cardiff-Weston and Minehead-Aberthaw.

Upper and lower bound cost cases were both calculated on the basis of no loss of seaward tidal range and 20% loss of seaward tidal range. Compensatory habitat and energy yield data has been adjusted to account for the reduction in seaward tidal range. The reported data is the figure using a 20% loss of seaward tidal range under a pumped scheme.

		Lower Bound[2]	Upper Bound
Cardiff-Weston	Energy yield	23.8 TWh	16.3 TWh
	Cost of electricity – including habitat allowance (IOAR basis)	£78.7 / MWh	£122.4 / MWh
Minehead-Aberthaw	Energy yield	50.4 TWh	29.7 TWh
	Cost of electricity – including habitat allowance (IOAR basis)	£74.5 / MWh	£129.3 / MWh

Table 7 Upper and lower bound cost of energy cases from zero and 20% loss of seaward tidal range.

Impact on Energy Market and Security of Supply

Connection to the grid is proposed through 16 500 MW 400 kV transformers installed in two separate sub-stations. Interconnection between transformers and turbines is used throughout the barrage network to provide a level of redundancy. Sub-stations are positioned at both ends of the barrage in the concept design however it is not unreasonable for both sub-stations to be positioned at either end of the barrage depending on grid connection availability and requirements.

The tidal bar has the advantage of a lower peak capacity than the equivalent Cardiff-Weston ebb-only barrage with similar annual energy output. The result is a higher capacity factor for the turbine equipment and a more consistent power export to the grid. The overall lower peak barrage capacity will therefore require significantly less grid reinforcement than an equivalent ebb-only barrage. Each generating unit within the barrage has a net smaller output relative to total barrage yield hence the electrical grid will not see significant output fluctuations in the event of a turbine failure.

The capability of the turbines to operate as pumps to further limit intertidal habitat loss and increase net energy yield allows the barrage to import excess power from the grid and act as a temporary energy storage system to reduce instabilities from intermittent supplies. A recent study at the University of Liverpool and Proudman Oceanographic Laboratories suggest that the longer generating window of dual model schemes would enable co-ordination of North-West and Severn tidal schemes to provide a more stable grid input.

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[2] Lower bound estimates are comparable with figures reported in the IOAR.

Affordability and Value for Money

The capital investment required for tidal bar is substantial. Estimates of installed capital cost completed during the present study suggest a value of (excluding compensation for loss of intertidal habitat) of £16,174 m and £25,383 m for Cardiff-Weston and Minehead-Aberthaw alignments respectively.

The Cardiff-Weston tidal bar costs are less than those associated with the equivalent ebb-only barrage. An additional premium of £682 m and £884 m must be applied to each scheme respectively to account for habitat replacement under a 2:1 replacement ratio. The normalised installed capital cost of the tidal bar is expected to be £3.0 m / MW.

Installed capital cost of the proposed bi-directional turbine is expected to be in the range £0.85 m / MW and is comparable to the £0.676 m / MW expected for a bulb turbine. This differential in unit capital cost is offset partially by the lower peak rating and higher utilisation of the very-low head scheme for the same net energy yield. Further savings are expected due to the simplified install and removal process from the use of single module turbines and the use of the concrete structure as an installation base.

Commercial financing of such a capital intensive project is relative unknown in the UK and worldwide and Government backed debt may be required. UK nuclear new build faces equal challenge as a capital intensive energy generator and may provide guidance on appropriate commercial models.

Unlike an ebb-only barrage using bulb turbines with relatively small flow area the large swept area defined in the current study may permit the bar turbines to operate as tidal stream devices when the barrage is partially complete. This may assist either in reducing build risk by generating early cash flows or by enabling staged build of the barrage. Energy yield will be reduced significantly during free stream generation

The equivalent energy yield from an offshore wind farm would require an approximate installed capacity of 8,300 MW and installed cost of £26,500 m.

Environmental Impact

The programme has evaluated the impact of the bar and turbine design on the intertidal mudflats and both migratory and non-migratory fish species inhabiting the Severn estuary. The tidal bar inherently reduces the loss of intertidal by reducing the delay in the tidal cycle. The bar turbine operates on a mean peak spring differential head of up to 3 and 4 metres respectively at the Cardiff-Weston and Minehead-Aberthaw alignments evaluated.

Estimated intertidal loss at each location is 5,200 hectares and 6,000 hectares respectively. At both alignments the loss of intertidal habitat is substantially less than the Severn Tidal Power Group Cardiff-Weston proposal. An opportunity to mitigate further intertidal habitat has been identified in employing slack water pumping. Both turbine options offer the potential to operate in pumping mode however the blue turbine is expected to operate more effectively than the red turbine.

Migratory fish are required to pass twice through the turbine according to their migratory pattern relative to the single pass through a turbine and single pass through the sluices in an ebb-only barrage. Non-migratory fish may pass the turbines multiple times during a year. The high turbine swept area requires sluice gates to be integrated with the turbine passage effectively eliminating alternative passage other than the turbine, however the highly porous structure is also less likely to present a barrier to migratory fish.

Both turbine designs maintain periphery velocities substantially below the 12.2 m/s recommended for minimising fish mortality in Idaho National Laboratory studies funded by the United States Department of Energy. The operating mode of the blue turbine concept substantially reduces the solidity of each rotor blade row. Specific design features such as the ‘minimum gap runner’ may be readily integrated during product development.

United States Department of Energy evidence suggests that current best-of-class bulb turbines achieve mortality rates of greater than 15% however the species of fish inhabiting a particular environment will have a significant effect on this figure. Prediction of a per passage fish mortality probability is complex and difficult without experimental data on actual rotor geometry however the analysis completed during the programme suggests that mortality rates should be at an order of magnitude better than bulb-turbines and statistically insignificant relative to other environmental pressures. A risk of failing to achieve low mortality rates has been recognised and early validation exercises included in the development plan.

It is noted that construction of any substantial structure across the estuary will alter the marine ecology in an unpredictable way in the region of the bar. Features such as protruding rock piers may be constructed to encourage colonisation of the bar without interfering with the turbine equipment and maintaining the biodiversity of the estuary. The modest delay in the tidal cycle for a very-low head bar is more likely to encourage colonisation of the piers than the substantial delays for an ebb-only barrage.

Regional Level Economic and Social Impacts

All estuary constructions present an obstruction to navigation channels in the estuary and require vessels to pass through ship locks during transit. Typical transit times for each of the three locks in the Panama Canal are around one hour to raise a vessel through a 26 metres gradation and require support crew and vessels during the operation. The very-low head barrage equivalent maximum gradation is approximately 3 metres during spring tides and less during the remainder of the tidal cycle.

The adoption of a minimum dredging approach, a discrete selection of turbine diameters, and a modular installation enables substantial coverage of the barrage to achieve the necessary permeability without encroaching on the deepest estuary sections and allowing existing navigation channels to be maintained on both Cardiff-Weston and Minehead-Aberthaw alignments. Modelling of the estuary water levels upstream of the barrage suggests that a reduction of 1 metre on high water and an increase of 1 metre on low water is to be expected during peak tides.

The presence of a partially constructed barrage will affect water flows through the estuary which will cause difficulty for vessels navigating the estuary. A tidal bar is less likely to cause difficulty for vessel due to the high porosity of the structure which will have substantially less impact on the natural flows.

Production of the required number of very-low head turbines will require a significant manufacturing and assembly facility supported by a significant supply chain. The single module approach adopted for turbine installation and major overhaul requires complete assembly of the turbine before delivery to the bar. Each turbine would be far too large to transport fully assembled by road and therefore the final assembly facility is likely to be in proximity to the barrage providing long term local employment.

Sub-components (such as transmissions, electrical generators and blades) may be readily shipped by road, rail or sea allowing access to a local, national and international supply chain. Local supply chain capability exists for a number of components and may be readily exploited during construction. A moderate increase in traffic may be expected during major manufacturing periods and isolated local transport connections may require reinforcement however the area is generally well serviced.

ANNEX B

DEVELOPMENT ROUTE MAP

ANNEX B DEVELOPMENT ROUTE MAP

The consortium has progressed development of a very-low head dual generation barrage but has identified that the following risks associated with the turbine and barrage require further treatment beyond the SETS programme:

1. Physical confirmation and acceptance testing of turbine passage fish mortality.
2. Physical confirmation and acceptance testing of turbine hydrodynamic performance (including pumping) and control strategy.
3. Government and financial commitment to development programme.
4. Turbine blade materials, supply chain development and availability.
5. Design, manufacture and validation of a production turbine.

The proposed development programme is shown in Figure 24 and a description of the work programmes provided. The programme does not consider the impact of Government planning or procurement processes, nor bids for research funding and is principally focused on the development of the turbine. The estimated cost of the development programme is £50 m.

A small scale hydrodynamic test is intended to confirm the basic turbine hydrodynamics (including pump performance), control strategy and flow patterns of the selected concept. The tests are to be conducted in a tank environment modified to incorporate structure to develop the required static head on the machine. A scale model of the turbine will be designed and constructed, and the control system strategy refined and built into the model. A series of tests will be conducted with this model to confirm the hydrodynamic performance of the turbine, the control system strategy and address the fish mortality assumptions. This test programme can be expected to take up to a year to complete and to be relatively low cost.

A demonstrator unit is considered necessary to prove the machine mechanical design prior to full scale production. It is not deemed necessary to test at any intermediate scale, and that a full-scale unit design be completed on the basis of lessons learned from tidal stream developments.

The significant size of the demonstrator unit required for a very-low head tidal barrage unit will necessitate a unique test facility to accumulate operating cycles. This facility is considered to be best constructed in the environment in which the turbine will operate therefore it is intended that a lagoon facility is constructed in the estuary with berths for one or two turbines.

The process of constructing the lagoon facility and designing and preparing the demonstrator unit is expected to take up to 4 years. At least one year of operating experience would be required to prove and refine the turbine design to a production standard due to the significant size of the production run.

The total turbine development programme can reasonably be expected to be completed in 5 years and the complete production run of turbines completed for barrage handover by 2020 - 2030. The anticipated high-level programme is illustrated in the Gant chart in Figure 24 and the milestones recorded in Table 8.

During this time a substantial amount of development time is available for optimising the scheme design.

Achieving this handover data is subject to programme and financial commitments as the turbine development programme will need to be completed before planning consent for the barrage is obtained, and results from selected work package will need to be prior to selection of the final scheme configuration.

Time	Milestone	Process / Work Package	Assumptions
T	Funding support available and awarded.	Campaign for funding support for scaled tank demonstration.	Availability of Government funding support for Severn estuary resource exploitation.
T + 1.5	Validated control strategy and performance data.	Design, construct and test scale turbine model.	Tank test facility availability.
T + 4	Test lagoon planning consent available.	Plan and design lagoon test facility.	Suitable lagoon test site availability.
T + 4	Demonstrator design passed to manufacture.	Detailed design and analysis of demonstrator turbine.	Availability of Government funding support for Severn estuary resource exploitation.
T + 5	Demonstrator turbine construction complete and passed-off to test.	Manufacture, assemble and commission demonstrator turbine.	Availability of Government funding support for Severn estuary resource exploitation.
T + 5	Lagoon test facility construction complete.	Build and commission lagoon test facility.	Availability of Government funding support for Severn estuary resource exploitation.
T + 8	Assembly facility planning consent available.	Plan and design assembly facility.	Formal commitment to barrage construction.

Time	Milestone	Process / Work Package	Assumptions
T + 7	Demonstrator design validated.	Lagoon turbine operational testing.	Formal commitment to barrage construction.
T + 9.5	Production design passed to manufacture.	Detailed design and analysis of production turbine.	Formal commitment to barrage construction.
T + 11	First production turbine construction complete and passed-off to installation.	Build, staff and commission assembly facility. Develop supply chain capability.	Formal commitment to barrage construction.
T + 17	Full power operation.	Construct barrage and install turbines.	Barrage planning consent available by T + 9.

Table 8 Key milestones in the development and production of a very-low head dual-generation barrage.

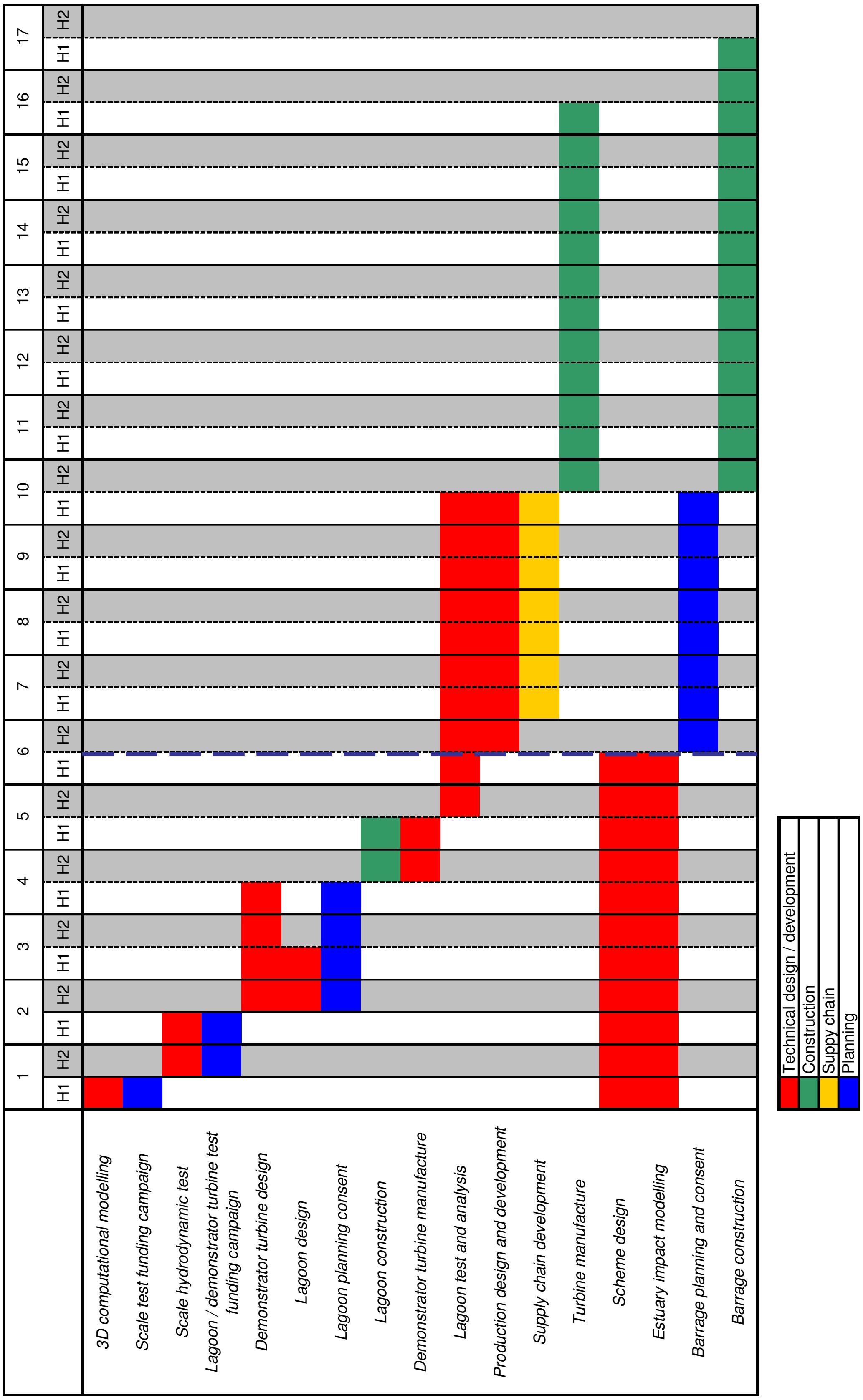

Figure 24 Turbine development and construction programme Gant chart laid out against anticipated civil programme.

ANNEX C

RISK REGISTER

ANNEX C RISK REGISTER

The following tables detail the result of the risk assessment and treatment completed under the SETS programme. This assessment has identified that the following risks associated with the turbine and barrage require further treatment beyond the SETS programme:

1. Physical validation and acceptance testing of turbine passage fish mortality.
2. Physical validation and acceptance testing of turbine hydrodynamic performance (including pumping) and control strategy.
3. Government and financial commitment to development programme.
4. Turbine blade supply chain development and availability.
5. Design, manufacture and validation of a production turbine.

The assessment is relative to the Severn Tidal Power Group (STPG) Cardiff-Weston ebb-only scheme and is therefore not an absolute listing of all programme risks. The criteria listed in Table 9 are applied to probability and impact of risks both pre- and post-SETS.

Class	Description
🟩 *Low (L)*	Probability or impact of risk less than STPG Cardiff-Weston scheme.
🟨 *Medium (M)*	Probability or impact of risk comparable to STPG Cardiff-Weston scheme.
🟥 *High (H)*	Probability or impact of risk greater than STPG Cardiff-Weston scheme.

Table 9 Risk probability and impact classifications applied to very-low head dual generation scheme.

Ref #	Description of event If…	Description of impact Then…	Probability	Impact	Treatment	Probability	Impact	Post-SETS Status
1	Energy yield from dual generation scheme is substantially less than ebb-only schemes.	Dual generation scheme may not be economic.	M	H	Zero-dimensional non-linear modelling of dual generation scheme.	L	H	Energy yield comparable to ebb-only Cardiff - Weston barrage at substantially reduced operating differential head.
2	Differential head required for dual generation turbine is not low enough to substantially reduce intertidal habitat loss.	Dual generation scheme may be less economic than an ebb-only scheme and construction of barrage may be prohibited by EU environmental legislation.	M	H	Outline design of turbine at very-low operating differential head and high volume flow rate to maximise energy capture.	L	H	Demonstration that very-low head turbine is technically feasible.
3	Dual generation scheme capital cost is substantially higher than ebb-only schemes.	Dual generation scheme may not be economic.	H	H	Bottom-up cost modelling of barrage and turbine. Sensitivity analysis on key costs.	L	H	Demonstration that a very-low head dual generation barrage can be produced at comparable cost to an ebb-only Cardiff - Weston scheme.
4	Loss of intertidal habitat is unacceptably high.	European Union environmental legislation may prohibit construction of the Severn Barrage.	H	H	Zero-dimensional non-linear modelling of dual generation scheme.	L	H	Environmental and legislative risk substantially less than Cardiff-Weston ebb-only scheme.
5	The turbine inflicts unacceptable damage on migratory marine species populations.	European Union environmental legislation may prohibit construction of the Severn Barrage.	H	H	Review of Idaho National Laboratory Advanced Hydropower studies into turbine fish mortality mechanisms.	M	H	Environmental risk comparable or less than ebb-only Cardiff-Weston barrage. Further validation work required to confirm expected mortality rates.

Ref #	Description of event If…	Description of impact Then…	Probability	Impact	Treatment	Probability	Impact	Post-SETS Status
6	European government legislation may prohibit subsidies for turbine development or barrage build.	Utilities may not be able to afford barrage without subsidy and turbine manufacturer may not accept development risk.	M	H	Reduce capital investment required for barrage construction.	M	M	Demonstration that a very-low head dual generation barrage can be produced at comparable cost to an ebb-only Cardiff - Weston scheme.
7	Sea-level rises over the life of the barrage.	Structural integrity of barrage will not be sufficient to withstand increased loading.	H	H	Barrage structure designed to withstand predicted hundred year sea level rise.	L	L	Technology risk comparable or less than ebb-only Cardiff - Weston barrage.
8	Barrage becomes the largest consumer of permenant rare-earth magnetic material.	Short term demand may notably escalate commodity pricing.	M	M	Review of current and predicated permenant magnet consumption.	L	L	Supply chain risk comparable or less than ebb-only Cardiff - Weston barrage.
9	A design fault develops in the turbine product during high-volume production.	Production may be halted while the design fault is corrected and installed turbine units may need to be prematurely overhauled.	M	H	Reliance on conventional technology where possible with multiple component suppliers.	L	L	Technology risk comparable or less than ebb-only Cardiff - Weston barrage.
10	Supply chain can not handle delivery rate.	Total construction period will be extended which will escalate financing charges.	M	H	Reliance on conventional technology where possible with multiple component suppliers.	L	L	Supply chain risk comparable or less than ebb-only Cardiff - Weston barrage.

Ref #	Description of event If…	Description of impact Then…	Probability	Impact	Treatment	Probability	Impact	Post-SETS Status
11	Composite blade supply chain can not handle production volumes.	Barrage handover will be delayed.	H	H	Review of current composite blade manufacturers and manufacturing technology.	H	H	Supply chain risk slightly greater than ebb-only Cardiff - Weston barrage. Supplier development activity will be required to meet barrage requirements.
12	Supply chain capability can not be developed to deliver barrage in required timescale.	Development and testing of device prototypes may be delayed.	M	H	Reliance on conventional technology where possible with multiple component suppliers.	L	L	Technology risk comparable or less than ebb-only Cardiff - Weston barrage.
13	Axial thrust bearings are too large to be machined with current supply chain capability.	Specialist capability will need to be developed which may escalate cost and extend development time.	M	H	Review of current bearing technology capability and review trade-offs for remaining within existing technology limits.	L	L	Technical risk comparable or less than ebb-only Cardiff-Weston barrage.
14	Electrical grid capacity in South West is not sufficient to support peak barrage output.	South West electrical grid will need to be upgraded.	M	H	Lower peak output and longer generating window decrease grid upgrade requirements relative to ebb-only Cardiff-Weston scheme.	L	L	Economic risk less than ebb-only Cardiff-Weston barrage.
15	Another organisation controls Intellectual Property critical to yielding an effective barrage solution.	Purchase cost of intellectual property may be significant and escalate barrage cost.	M	M	Review of existing Intellectual Property in design space.	L	L	Economic risk comparable or less than ebb-only Cardiff - Weston barrage.

Ref #	Description of event If…	Description of impact Then…	Probability	Impact	Treatment	Probability	Impact	Post-SETS Status
16	Required torque and power output for direct drive electrical machines is not available within development timescales.	Variable speed gearbox technology will be required which may increase cost and reduce reliability for fixed pitch devices.	M	M	Installation of step-up transmission to reduce torque in electrical machine.	L	L	Technology risk comparable or less than ebb-only Cardiff - Weston barrage.
17	High efficiency bi-directional turbine is not technically feasible.	Uni-directional turbines will be required and energy yield from barrage will be reduced.	M	M	Conceptual design of a turbine for operation in dual generation mode at high efficiency.	L	M	Technology risk slightly greater than ebb-only Cardiff - Weston barrage. Three-dimensional steady computational fluid dynamic blade design and modelling, and scale testing will be required to validate design.
18	Radial stream lines mix out between cascades.	Hydrodynamic efficiency of the turbine will be reduced.	M	H	Blade design methods evaluated by internal expert panel and considered feasible. Higher fidelity analysis beyond scope of SETS programme.	L	L	Technology risk slightly greater than ebb-only Cardiff - Weston barrage. Three-dimensional steady computational fluid dynamic blade design and modelling, and scale testing will be required to validate design.

ANNEX D

FUNCTIONAL REQUIREMENT REGISTER

ANNEX D FUNCTIONAL REQUIREMENT REGISTER

Ref #	Class	Requirement	Rationale
1	Functional	The turbine shall minimise the damage to native marine life populations.	The Severn estuary supports 6 - 7 species of migratory fish whose migratory route will be impeded. The high flow area required by a low-head barrage may not permit the provision of large bypass passages for fish to pass through without encountering a turbine rotor.
2	Functional	The turbine shall generate power in both ebb and flood flow conditions.	The barrage flow area in both directions must approach 80% of the total estuary area to maximise the total power output of the barrage by minimising kinetic energy losses from flow velocity through the turbine.
3	Functional	The barrage shall permit the passage of shipping.	The Severn estuary is an active port (managed by the Port of Bristol Authority). The barrage will obstruct the passage of shipping along the estuary therefore provision must be made to allow passage of ships through the barrage. This should include provision for the future expansion of the port through proposed deep sea docking facilities.
4	Functional	The barrage shall be produced and installed at a cost of less than £2.0m/MW.	The barrage represents a significant capital investment. Ensuring a low capital cost results is essential in making the barrage affordable over it's lifetime.
5	Functional	The turbine shall achieve an overall water-to-wire efficiency of > 75%.	Initial economic assessment of the barrage assumes that approximately £13440 million of the total barrage 'overnight capital' is fixed civil works. Increasing turbine efficiency increases the power output over which this capital is distributed and improves the barrage economics.
6	Functional	The turbine shall achieve 95% availability.	Initial economic assessment of the barrage assumes that approximately £13440 million of the total barrage 'overnight capital' is fixed civil works. Increasing turbine availability increases the energy output over which this capital is distributed and improves the barrage economics.
7	Functional	The turbine shall be available for a 2050 entry-into-service.	The barrage makes a substantial contribution towards Government carbon reduction targets of 80% by 2050.
8	Functional	The manufacture of the barrage shall not release more carbon dioxide than it saves in generation.	Major source of carbon dioxide production is the caisson structure. Offsetting carbon dioxide production is achieved by maximising turbine efficiency.
9	Functional	The barrage shall be resistant to storm surge conditions.	Standard practice (as per BS6349) to design maritime structures to withstand 100 year storm surge condtions.

10	Functional	The turbine shall operate continously between 2 year service periods.	Reducing maintenance intervals improves efficiency and reliability but increases maintenance costs. 2 years is a relatively standard period for marine power system servicing and given the high siltation and biofouling potential in the Severn estuary is considered a reasonable service interval.
11	Functional	The turbine shall operate for a design life of 40 years.	The total cost of turbine is amortised over the design life shorter design life significantly increases cost.
12	Functional	The turbine shall generate on a nominal static head of between 1.5 and 3 metres passing flow at a speed between 1.4 and 2.8 m/s.	Optimal operating conditions for a low-head turbine between highest and lowest astromonical tide in the Severn estuary in both ebb and flood flow direction.
13	Functional	The turbine structure shall be resistant to wear from silt and debris suspended in the river without degrading below design performance through design life.	The Severn carries particulate matter (up to 0.2 mm at 500 ppm) in suspension that represents a particular threat to hydrofoil surfaces.
14	Functional	The turbine shall not discharge environmentally harmful substances into the estuary.	Discharge of substances such as lubricating oil are likely to be viewed unfavourably by the Environmental Agency and may incur fines.
15	Functional	The turbine shall be protected from over speed.	Turbine overspeed may be driven by grid disconnect, shaft or gearbox failure, failed pitching, or by an excessive head on the turbine. Overspeed may cause disk burst, blade release or damage to the electrical generating set.
16	Functional	The barrage and turbine shall be tolerant to system faults.	System faults may cause damage to the turbine.
17	Functional	The barrage shall produce electricity at a cost of 12 p / kWh.	The limit on barrage cost of electricity is relative to the equivalent cost of the Cardiff-Weston ebb-only barrage including the additional compensatory habitat from operating at a higher head discounted over an economic life of 35 years at an 8% discount rate.
18	Functional	The spacing between blade cascades shall not be less than 150 cm.	Seven migratory species inhabit the River Severn - the European Eel, River and Sea Lamprey, Atlantic Salmon, Allis Shad, Twaite Shad, and Sea Trout. Of these seven species the Atlantic Salmon is the largest at 150 cm which sets the minimum spacing to prevent a fish from being trapped between cascades.
19	Functional	The turbine mechanical structure shall support a maximum design loading of 2.9 tonnes / m^2.	Defined by Bernoulli equation head drop across the turbine for power extraction.
20	Functional	The turbine shall be capable of withstanding neutrally buoyant foreign objects without releasing machine components.	It is highly unlikely that non-neutrally buoyant objects will be ingested into the turbine due to the relatively slow estuary flow speeds.

ANNEX E

FISH PASSAGE MODELLING

ANNEX E FISH PASSAGE MODELLING

A simple fish friendly turbine assumes the fish to be neutrally buoyant in that the fish may be represented as a control volume of water passing through the turbine. The fish will swirl with the flow through the turbine and fluid shear forces will align the fish with the local principal flow direction. A fish will see a blade row (whether rotor or stator) as an approaching obstruction on a constant bearing.

As the fish moves through the blade row and that static pressure reduces, the fish will experience the perception of surfacing. The simple fish will pass unharmed through the turbine at any rotor speed provided that the fish is much smaller than the blade spacing and row-to-row spacing. This suggests that a simple fish friendly turbine has the following design features:

- Operational head and velocity are not restricted.
- The number of rotor and stator blade rows are irrelevant.
- Blade spacing is significantly larger than the largest fish that must safely pass through the turbine.
- Foreign object traps will be detrimental to fish survival.

Studies into fish behaviour by Coutant [3] infer that fish should not be assumed to be neutrally buoyant during their passage through the turbine because of the effect of complex pressure fields on swim bladders and resulting compensatory behaviour. Fish rely on their lateral line system to sense obstacles and change orientation however this sensory response system may be compromised in the rapid passage times and complex pressure regimes of turbine systems.

Further work under the Advanced Hydropower Turbine System research programme at the Idaho National Laboratory (INL) [2] funded by the United States Department of Energy has established the primary fish mortality mechanisms within turbines are:

- Direct blade impact.
- Exposure to rapid pressure transients.
- Exposure to localised high-velocity jet streams.
- Entrapment within hub and tip gaps.

Blade impact is the simplest mortality mechanism to understand and simply describes the damage of fish by encounter with a rotor blade or by the fish becoming trapped between blade rows. The second case is easily addressed by providing sufficient axial spacing between cascades to prevent the largest fish from becoming trapped. The former case requires more detailed consideration.

A shoal of fish of length l equally distributed at all radial and circumferential stations approaches a blade row with N blades of linear blade velocity u at a net velocity v has a probability P of encountering a blade given by

$$P = \frac{l \cdot N \cdot u}{2\pi \cdot v}$$

Clearly the encounter probability is dependant on the length of fish, net velocity through the turbine, rotor speed, blade spacing and blade length. The probability of impact may be lowered by reducing the speed and number of turbine blades or by increasing the axial flow speed through the turbine. Mortality resultant from blade impact is a function of kinetic energy dissipated as a result of the collision and is itself a function of the blade speed squared. The product of the impact and mortality probability functions yields the expected mortality rate due to blade impact.

Operating a highly porous structure over a low net head inherently reduces the magnitude of pressure transients and maintaining the low flow speed of the barrage through the turbine increases the time over which pressure transients occur while also reducing relative blade speed.

Fish becoming caught in sections between the rotor blade tip and the casing or the rotor blade root and hub result from detailed features in the turbine production design and are equally applicable to any turbine configuration deployed on the Severn. Turbines designed to eliminate surface roughness and minimise hub and tip clearances are known as ‘minimum gap runners’ and are shown to reduce fish mortality rate.

A series of basic design requirements were established that infer that fish passage may be improved substantially by:

1. Minimising the magnitude and maximising time of pressure transients.
2. Maintaining low speed flow through the turbine.
3. Reducing blade speed.
4. Maximising blade-to-blade and cascade-to-cascade spacing.
5. Maximising blade chord.
6. Reducing hub and tip clearance.

ANNEX F

CASH FLOW ANALYSIS

ANNEX F CASH FLOW ANALYSIS

The following annex discloses cash flows and energy yields in tabular form developed using a methodology consistent with the Interim Options Analysis Report [4] for the following barrage schemes

- Cardiff-Weston alignment with 40 year major turbine mechanical and electrical overhaul.

- Minehead-Aberthaw alignment with 40 year major turbine mechanical and electrical overhaul.

In addition the following schemes were developed using the discounting methodology specified in the SETS programme:

- Cardiff-Weston alignment with 40 year major turbine mechanical and electrical overhaul.

- Minehead-Aberthaw alignment with 40 year major turbine mechanical and electrical overhaul.

The Interim Options Analysis Report B3 scheme with zero habitat compensation has also been reproduced using the model and is disclosed to demonstrate consistency in IOAR methodology.

Cardiff-Weston very-low head dual generation barrage scheme at 40 year turbine life (IOAR basis)

Discount rate	8%
Levelised cost of electricity (£ / MWh)	£93.43

Project year	Yield (TWh)	Future value				Present value			
		Pre-construction	Construction	Operations and maintenance	Generator income	Pre-construction	Construction	Operations and maintenance	Generator income
0	0	£52,250,000	£0	£0	£0	£52,250,000	£0	£0	£0
1	0	£52,250,000	£0	£0	£0	£48,379,630	£0	£0	£0
2	0	£52,250,000	£0	£0	£0	£44,795,953	£0	£0	£0
3	0	£52,250,000	£0	£0	£0	£41,477,735	£0	£0	£0
4	0	£0	£2,322,910,714	£0	£0	£0	£1,707,408,720	£0	£0
5	0	£0	£2,322,910,714	£0	£0	£0	£1,580,934,000	£0	£0
6	0	£0	£2,322,910,714	£0	£0	£0	£1,463,827,778	£0	£0
7	0	£0	£2,322,910,714	£0	£0	£0	£1,355,396,091	£0	£0
8	0	£0	£2,322,910,714	£0	£0	£0	£1,254,996,380	£0	£0
9	0	£0	£2,322,910,714	£0	£0	£0	£1,162,033,685	£0	£0
10	10.4	£0	£2,322,910,714	£157,261,327	£971,632,761	£0	£1,075,957,116	£72,842,423	£450,053,968
11	15.6	£0	£0	£264,000,000	£1,457,449,141	£0	£0	£113,225,075	£625,074,955
12	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£104,838,032	£771,697,475
13	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£97,072,252	£714,534,699
14	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£89,881,715	£661,606,203
15	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£83,223,810	£612,598,336
16	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£77,059,083	£567,220,682
17	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£71,351,003	£525,204,335
18	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£66,065,744	£486,300,310
19	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£61,171,985	£450,278,065
20	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£56,640,727	£416,924,134
21	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£52,445,117	£386,040,865
22	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£48,560,294	£357,445,245
23	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£44,963,235	£330,967,820
24	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£41,632,625	£306,451,685
25	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£38,548,727	£283,751,560
26	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£35,693,266	£262,732,926
27	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£33,049,320	£243,271,228
28	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£30,601,222	£225,251,137
29	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£28,334,465	£208,565,867
30	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£26,235,616	£193,116,544
31	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£24,292,237	£178,811,615
32	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£22,492,812	£165,566,310
33	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£20,826,678	£153,302,139
34	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£19,283,961	£141,946,425
35	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£17,855,519	£131,431,875
36	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£16,532,888	£121,696,180
37	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£15,308,230	£112,681,649
38	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£14,174,287	£104,334,860
39	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£13,124,340	£96,606,352
40	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£12,152,166	£89,450,326

41	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£11,252,006	£82,824,376
42	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£10,418,524	£76,689,237
43	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£9,646,781	£71,008,552
44	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£8,932,205	£65,748,660
45	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£8,270,560	£60,878,389
46	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£7,657,926	£56,368,878
47	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£7,090,672	£52,193,406
48	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£6,565,437	£48,327,228
49	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£6,079,109	£44,747,433
50	16.64	£0	£0	£953,000,000	£1,554,612,417	£0	£0	£20,319,131	£33,146,247
51	16.64	£0	£0	£953,000,000	£1,554,612,417	£0	£0	£18,814,010	£30,690,969
52	16.64	£0	£0	£953,000,000	£1,554,612,417	£0	£0	£17,420,380	£28,417,564
53	16.64	£0	£0	£953,000,000	£1,554,612,417	£0	£0	£16,129,981	£26,312,559
54	16.64	£0	£0	£953,000,000	£1,554,612,417	£0	£0	£14,935,168	£24,363,481
55	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£3,830,870	£28,198,473
56	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£3,547,102	£26,109,697
57	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£3,284,353	£24,175,646
58	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£3,041,068	£22,384,857
59	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£2,815,804	£20,726,720
60	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£2,607,226	£19,191,407
61	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£2,414,098	£17,769,821
62	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£2,235,276	£16,453,538
63	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£2,069,700	£15,234,758
64	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£1,916,389	£14,106,257
65	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£1,774,434	£13,061,349
66	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£1,642,994	£12,093,842
67	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£1,521,291	£11,198,002
68	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£1,408,603	£10,368,520
69	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£1,304,262	£9,600,482
70	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£1,207,650	£8,889,335
71	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£1,118,194	£8,230,866
72	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£1,035,365	£7,621,172
73	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£958,671	£7,056,641
74	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£887,659	£6,533,926
75	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£821,906	£6,049,932
76	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£761,024	£5,601,789
77	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£704,652	£5,186,841
78	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£652,456	£4,802,631
79	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£604,126	£4,446,881
80	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£559,376	£4,117,482
81	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£517,940	£3,812,483
82	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£479,574	£3,530,077
83	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£444,050	£3,268,590
84	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£411,158	£3,026,472
85	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£380,702	£2,802,289
86	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£352,501	£2,594,712
87	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£326,390	£2,402,511
88	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£302,213	£2,224,547
89	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£279,827	£2,059,766
90	20.8	£0	£0	£953,000,000	£1,943,265,522	£0	£0	£935,309	£1,907,191

91	16.64	£0	£0	£953,000,000	£1,554,612,417	£0	£0	£866,026	£1,412,734
92	16.64	£0	£0	£953,000,000	£1,554,612,417	£0	£0	£801,876	£1,308,087
93	16.64	£0	£0	£953,000,000	£1,554,612,417	£0	£0	£742,478	£1,211,192
94	16.64	£0	£0	£953,000,000	£1,554,612,417	£0	£0	£687,480	£1,121,474
95	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£176,339	£1,298,002
96	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£163,276	£1,201,854
97	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£151,182	£1,112,828
98	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£139,983	£1,030,396
99	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£129,614	£954,070
100	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£120,013	£883,398
101	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£111,123	£817,961
102	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£102,892	£757,372
103	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£95,270	£701,270
104	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£88,213	£649,324
105	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£81,679	£601,226
106	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£75,629	£556,691
107	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£70,026	£515,454
108	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£64,839	£477,273
109	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£60,036	£441,919
110	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£55,589	£409,184
111	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£51,472	£378,874
112	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£47,659	£350,810
113	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£44,129	£324,824
114	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£40,860	£300,763
115	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£37,833	£278,484
116	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£35,031	£257,856
117	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£32,436	£238,755
118	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£30,033	£221,070
119	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£27,808	£204,694
120	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£25,749	£189,532
121	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£23,841	£175,492
122	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£22,075	£162,493
123	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£20,440	£150,456
124	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£18,926	£139,311
125	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£17,524	£128,992
126	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£16,226	£119,437
127	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£15,024	£110,590
128	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£13,911	£102,398
129	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£12,881	£94,813
130	20.8	£0	£0	£264,000,000	£1,943,265,522	£0	£0	£11,927	£87,790
Total	2463.76	£209,000,000	£16,260,374,998	£38,727,261,327	£230,179,801,044	£186,903,318	£9,600,553,771	£1,667,494,303	£11,454,951,391
		Net future value			£174,983,164,719	Net present value			£0

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Minehead-Aberthaw very-low head dual generation barrage scheme at 40 year turbine life (IOAR basis)

Discount rate	8%
Levelised cost of electricity (£ / MWh)	£106.95

Project year	Yield (TWh)	Future value				Present value			
		Pre-construction	Construction	Operations and maintenance	Generator income	Pre-construction	Construction	Operations and maintenance	Generator income
0	0	£104,500,000	£0	£0	£0	£104,500,000	£0	£0	£0
1	0	£104,500,000	£0	£0	£0	£96,759,259	£0	£0	£0
2	0	£104,500,000	£0	£0	£0	£89,591,907	£0	£0	£0
3	0	£104,500,000	£0	£0	£0	£82,955,469	£0	£0	£0
4	0	£0	£3,752,428,571	£0	£0	£0	£2,758,147,020	£0	£0
5	0	£0	£3,752,428,571	£0	£0	£0	£2,553,839,833	£0	£0
6	0	£0	£3,752,428,571	£0	£0	£0	£2,364,666,512	£0	£0
7	0	£0	£3,752,428,571	£0	£0	£0	£2,189,506,030	£0	£0
8	0	£0	£3,752,428,571	£0	£0	£0	£2,027,320,398	£0	£0
9	0	£0	£3,752,428,571	£0	£0	£0	£1,877,148,517	£0	£0
10	15.2	£0	£3,752,428,571	£262,500,000	£1,625,673,274	£0	£1,738,100,479	£121,588,291	£753,001,274
11	22.8	£0	£0	£525,000,000	£2,438,509,911	£0	£0	£225,163,501	£1,045,835,103
12	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£208,484,723	£1,291,154,448
13	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£193,041,410	£1,195,513,378
14	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£178,742,047	£1,106,956,832
15	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£165,501,895	£1,024,960,029
16	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£153,242,495	£949,037,064
17	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£141,891,200	£878,738,022
18	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£131,380,740	£813,646,317
19	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£121,648,834	£753,376,219
20	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£112,637,809	£697,570,574
21	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£104,294,267	£645,898,679
22	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£96,568,766	£598,054,333
23	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£89,415,524	£553,754,012
24	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£82,792,152	£512,735,196
25	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£76,659,400	£474,754,811
26	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£70,980,926	£439,587,788
27	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£65,723,080	£407,025,730
28	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£60,854,703	£376,875,676
29	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£56,346,948	£348,958,959
30	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£52,173,100	£323,110,147
31	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£48,308,426	£299,176,062
32	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£44,730,024	£277,014,872
33	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£41,416,689	£256,495,252
34	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£38,348,786	£237,495,604
35	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£35,508,135	£219,903,337
36	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£32,877,903	£203,614,201
37	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£30,442,503	£188,531,667
38	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£28,187,502	£174,566,359
39	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£26,099,539	£161,635,517
40	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£24,166,240	£149,662,516

41	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£22,376,148	£138,576,404
42	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£20,718,656	£128,311,485
43	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£19,183,940	£118,806,931
44	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£17,762,908	£110,006,417
45	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£16,447,137	£101,857,794
46	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£15,228,830	£94,312,772
47	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£14,100,769	£87,326,641
48	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£13,056,268	£80,858,001
49	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£12,089,137	£74,868,519
50	24.32	£0	£0	£1,788,500,000	£2,601,077,238	£0	£0	£38,133,017	£55,458,162
51	24.32	£0	£0	£1,788,500,000	£2,601,077,238	£0	£0	£35,308,349	£51,350,150
52	24.32	£0	£0	£1,788,500,000	£2,601,077,238	£0	£0	£32,692,916	£47,546,435
53	24.32	£0	£0	£1,788,500,000	£2,601,077,238	£0	£0	£30,271,219	£44,024,477
54	24.32	£0	£0	£1,788,500,000	£2,601,077,238	£0	£0	£28,028,906	£40,763,405
55	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£7,618,207	£47,179,867
56	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£7,053,895	£43,685,062
57	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£6,531,384	£40,449,131
58	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£6,047,578	£37,452,899
59	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£5,599,609	£34,678,611
60	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£5,184,823	£32,109,825
61	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£4,800,762	£29,731,319
62	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£4,445,150	£27,528,999
63	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£4,115,880	£25,489,814
64	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£3,811,000	£23,601,680
65	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£3,528,704	£21,853,407
66	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£3,267,318	£20,234,636
67	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£3,025,295	£18,735,774
68	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£2,801,199	£17,347,939
69	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£2,593,703	£16,062,907
70	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£2,401,576	£14,873,062
71	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£2,223,682	£13,771,353
72	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£2,058,965	£12,751,253
73	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£1,906,449	£11,806,716
74	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£1,765,230	£10,932,144
75	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£1,634,473	£10,122,356
76	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£1,513,401	£9,372,552
77	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£1,401,297	£8,678,289
78	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£1,297,497	£8,035,452
79	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£1,201,386	£7,440,234
80	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£1,112,395	£6,889,105
81	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£1,029,995	£6,378,801
82	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£953,699	£5,906,297
83	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£883,055	£5,468,794
84	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£817,643	£5,063,698
85	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£757,077	£4,688,609
86	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£700,997	£4,341,305
87	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£649,072	£4,019,727
88	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£600,992	£3,721,969
89	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£556,474	£3,446,268
90	24.32	£0	£0	£1,788,500,000	£2,601,077,238	£0	£0	£1,755,298	£2,552,791

91	24.32	£0	£0	£1,788,500,000	£2,601,077,238	£0	£0	£1,625,276	£2,363,695
92	24.32	£0	£0	£1,788,500,000	£2,601,077,238	£0	£0	£1,504,885	£2,188,607
93	24.32	£0	£0	£1,788,500,000	£2,601,077,238	£0	£0	£1,393,412	£2,026,488
94	24.32	£0	£0	£1,788,500,000	£2,601,077,238	£0	£0	£1,290,197	£1,876,378
95	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£350,673	£2,171,733
96	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£324,697	£2,010,864
97	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£300,646	£1,861,911
98	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£278,376	£1,723,992
99	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£257,755	£1,596,289
100	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£238,662	£1,478,045
101	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£220,984	£1,368,560
102	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£204,614	£1,267,186
103	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£189,458	£1,173,320
104	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£175,424	£1,086,407
105	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£162,430	£1,005,933
106	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£150,398	£931,419
107	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£139,257	£862,425
108	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£128,942	£798,542
109	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£119,391	£739,391
110	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£110,547	£684,621
111	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£102,358	£633,908
112	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£94,776	£586,952
113	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£87,756	£543,474
114	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£81,255	£503,217
115	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£75,236	£465,941
116	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£69,663	£431,427
117	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£64,503	£399,470
118	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£59,725	£369,879
119	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£55,301	£342,481
120	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£51,205	£317,112
121	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£47,412	£293,622
122	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£43,900	£271,872
123	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£40,648	£251,734
124	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£37,637	£233,087
125	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£34,849	£215,821
126	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£32,268	£199,834
127	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£29,877	£185,032
128	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£27,664	£171,326
129	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£25,615	£158,635
130	30.4	£0	£0	£525,000,000	£3,251,346,548	£0	£0	£23,718	£146,884
Total	3594.8	£418,000,000	£26,266,999,997	£75,897,500,000	£384,471,729,297	£373,806,635	£15,508,728,790	£3,282,512,305	£19,165,047,730
		Net future value			£281,889,229,300	Net present value			£0

Cardiff-Weston very-low head dual generation barrage scheme at 40 year turbine life (SETS basis)

Discount rate	8%
Levelised cost of electricity (£ / MWh)	£52.43

Project year	Yield (TWh)	Future value				Present value			
		Pre-construction	Construction	Operations and maintenance	Generator income	Pre-construction	Construction	Operations and maintenance	Generator income
0	0	£52,250,000	£0	£0	£0	£52,250,000	£0	£0	£0
1	0	£52,250,000	£0	£0	£0	£48,379,630	£0	£0	£0
2	0	£52,250,000	£0	£0	£0	£44,795,953	£0	£0	£0
3	0	£52,250,000	£0	£0	£0	£41,477,735	£0	£0	£0
4	0	£0	£2,408,000,000	£0	£0	£0	£1,769,951,886	£0	£0
5	0	£0	£2,408,000,000	£0	£0	£0	£1,638,844,338	£0	£0
6	0	£0	£2,408,000,000	£0	£0	£0	£1,517,448,462	£0	£0
7	0	£0	£2,408,000,000	£0	£0	£0	£1,405,044,872	£0	£0
8	0	£0	£2,408,000,000	£0	£0	£0	£1,300,967,474	£0	£0
9	0	£0	£2,408,000,000	£0	£0	£0	£1,204,599,513	£0	£0
10	10.4	£0	£2,408,000,000	£157,261,327	£545,245,552	£0	£1,115,369,919	£72,842,423	£252,554,189
11	15.6	£0	£0	£264,000,000	£817,868,328	£0	£0	£113,225,075	£350,769,707
12	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£104,838,032	£433,049,021
13	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£97,072,252	£400,971,316
14	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£89,881,715	£371,269,737
15	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£83,223,810	£343,768,275
16	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£77,059,083	£318,303,958
17	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£71,351,003	£294,725,887
18	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£66,065,744	£272,894,340
19	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£61,171,985	£252,679,944
20	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£56,640,727	£233,962,911
21	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£52,445,117	£216,632,325
22	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£48,560,294	£200,585,486
23	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£44,963,235	£185,727,302
24	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£41,632,625	£171,969,724
25	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£38,548,727	£159,231,226
26	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£35,693,266	£147,436,321
27	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£33,049,320	£136,515,112
28	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£30,601,222	£126,402,881
29	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£28,334,465	£117,039,705
30	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£26,235,616	£108,370,097
31	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£24,292,237	£100,342,682
32	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£22,492,812	£92,909,891
33	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£20,826,678	£86,027,677
34	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£19,283,961	£79,655,256
35	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£17,855,519	£73,754,867
36	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£16,532,888	£68,291,544
37	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£15,308,230	£63,232,911
38	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£14,174,287	£58,548,991
39	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£13,124,340	£54,212,029
40	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£12,152,166	£50,196,323

41	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£11,252,006	£46,478,077
42	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£10,418,524	£43,035,257
43	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£9,646,781	£39,847,460
44	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£8,932,205	£36,895,796
45	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£69,811,797	£288,367,967
46	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£67,778,443	£279,968,900
47	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£65,804,314	£271,814,466
48	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£63,887,683	£263,897,539
49	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£62,026,877	£256,211,203
50	16.64	£0	£0	£953,000,000	£872,392,883	£0	£0	£217,386,047	£198,998,993
51	16.64	£0	£0	£953,000,000	£872,392,883	£0	£0	£211,054,415	£193,202,906
52	16.64	£0	£0	£953,000,000	£872,392,883	£0	£0	£204,907,199	£187,575,637
53	16.64	£0	£0	£953,000,000	£872,392,883	£0	£0	£198,939,028	£182,112,269
54	16.64	£0	£0	£953,000,000	£872,392,883	£0	£0	£193,144,687	£176,808,028
55	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£51,946,533	£214,572,849
56	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£50,433,527	£208,323,155
57	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£48,964,590	£202,255,490
58	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£47,538,436	£196,364,553
59	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£46,153,822	£190,645,197
60	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£44,809,536	£185,092,425
61	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£43,504,404	£179,701,383
62	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£42,237,285	£174,467,362
63	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£41,007,073	£169,385,789
64	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£39,812,692	£164,452,222
65	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£38,653,099	£159,662,351
66	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£37,527,281	£155,011,992
67	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£36,434,253	£150,497,079
68	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£35,373,061	£146,113,669
69	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£34,342,778	£141,857,931
70	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£33,342,503	£137,726,147
71	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£32,371,362	£133,714,706
72	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£31,428,507	£129,820,103
73	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£30,513,113	£126,038,935
74	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£29,624,382	£122,367,898
75	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£28,761,536	£118,803,784
76	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£27,923,821	£115,343,480
77	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£27,110,506	£111,983,961
78	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£26,320,880	£108,722,292
79	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£25,554,252	£105,555,623
80	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£24,809,954	£102,481,188
81	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£24,087,334	£99,496,299
82	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£23,385,761	£96,598,348
83	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£22,704,622	£93,784,804
84	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£22,043,322	£91,053,208
85	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£21,401,284	£88,401,173
86	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£20,777,945	£85,826,381
87	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£20,172,763	£83,326,584
88	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£19,585,206	£80,899,596
89	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£19,014,763	£78,543,297
90	17.36	£0	£0	£953,000,000	£910,140,652	£0	£0	£66,641,180	£63,644,120

91	16.64	£0	£0	£953,000,000	£872,392,883	£0	£0	£64,700,175	£59,227,672
92	16.64	£0	£0	£953,000,000	£872,392,883	£0	£0	£62,815,703	£57,502,595
93	16.64	£0	£0	£953,000,000	£872,392,883	£0	£0	£60,986,120	£55,827,762
94	16.64	£0	£0	£953,000,000	£872,392,883	£0	£0	£59,209,825	£54,201,710
95	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£15,924,565	£65,778,775
96	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£15,460,743	£63,862,888
97	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£15,010,430	£62,002,804
98	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£14,573,233	£60,196,897
99	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£14,148,770	£58,443,589
100	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£13,736,670	£56,741,349
101	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£13,336,573	£55,088,688
102	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£12,948,129	£53,484,163
103	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£12,570,999	£51,926,372
104	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£12,204,853	£50,413,954
105	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£11,849,372	£48,945,586
106	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£11,504,245	£47,519,986
107	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£11,169,170	£46,135,909
108	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£10,843,854	£44,792,145
109	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£10,528,014	£43,487,519
110	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£10,221,372	£42,220,892
111	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£9,923,662	£40,991,158
112	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£9,634,624	£39,797,241
113	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£9,354,004	£38,638,098
114	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£9,081,557	£37,512,716
115	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£8,817,046	£36,420,113
116	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£8,560,238	£35,359,333
117	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£8,310,911	£34,329,449
118	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£8,068,846	£33,329,562
119	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£7,833,831	£32,358,798
120	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£7,605,661	£31,416,309
121	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£7,384,137	£30,501,271
122	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£7,169,065	£29,612,885
123	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£6,960,257	£28,750,373
124	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£6,757,531	£27,912,984
125	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£6,560,710	£27,099,984
126	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£6,369,621	£26,310,664
127	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£6,184,098	£25,544,334
128	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£6,003,979	£24,800,325
129	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£5,829,106	£24,077,985
130	20.8	£0	£0	£264,000,000	£1,090,491,103	£0	£0	£5,659,326	£23,376,684
Total	2460.32	£209,000,000	£16,856,000,000	£38,727,261,327	£128,988,320,739	£186,903,318	£9,952,226,463	£4,666,593,248	£14,805,723,029
		Net future value			£73,196,059,412	Net present value			£0

Minehead-Aberthaw very-low head dual generation barrage scheme at 40 year turbine life (SETS basis)

Discount rate	8%
Levelised cost of electricity (£ / MWh)	£60.56

Project year	**Yield (TWh)**	**Future value**				**Present value**			
		Pre-construction	**Construction**	**Operations and maintenance**	**Generator income**	**Pre-construction**	**Construction**	**Operations and maintenance**	**Generator income**
0	0	£104,500,000	£0	£0	£0	£104,500,000	£0	£0	£0
1	0	£104,500,000	£0	£0	£0	£96,759,259	£0	£0	£0
2	0	£104,500,000	£0	£0	£0	£89,591,907	£0	£0	£0
3	0	£104,500,000	£0	£0	£0	£82,955,469	£0	£0	£0
4	0	£0	£3,752,428,571	£0	£0	£0	£2,758,147,020	£0	£0
5	0	£0	£3,752,428,571	£0	£0	£0	£2,553,839,833	£0	£0
6	0	£0	£3,752,428,571	£0	£0	£0	£2,364,666,512	£0	£0
7	0	£0	£3,752,428,571	£0	£0	£0	£2,189,506,030	£0	£0
8	0	£0	£3,752,428,571	£0	£0	£0	£2,027,320,398	£0	£0
9	0	£0	£3,752,428,571	£0	£0	£0	£1,877,148,517	£0	£0
10	15.2	£0	£3,752,428,571	£262,500,000	£920,442,822	£0	£1,738,100,479	£121,588,291	£426,343,122
11	22.8	£0	£0	£525,000,000	£1,380,664,234	£0	£0	£225,163,501	£592,143,224
12	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£208,484,723	£731,041,018
13	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£193,041,410	£676,889,831
14	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£178,742,047	£626,749,844
15	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£165,501,895	£580,323,929
16	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£153,242,495	£537,336,972
17	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£141,891,200	£497,534,233
18	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£131,380,740	£460,679,845
19	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£121,648,834	£426,555,412
20	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£112,637,809	£394,958,715
21	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£104,294,267	£365,702,514
22	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£96,568,766	£338,613,439
23	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£89,415,524	£313,530,962
24	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£82,792,152	£290,306,446
25	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£76,659,400	£268,802,265
26	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£70,980,926	£248,890,986
27	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£65,723,080	£230,454,617
28	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£60,854,703	£213,383,904
29	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£56,346,948	£197,577,689
30	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£52,173,100	£182,942,305
31	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£48,308,426	£169,391,023
32	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£44,730,024	£156,843,540
33	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£41,416,689	£145,225,500
34	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£38,348,786	£134,468,055
35	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£35,508,135	£124,507,459
36	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£32,877,903	£115,284,684
37	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£30,442,503	£106,745,078
38	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£28,187,502	£98,838,035
39	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£26,099,539	£91,516,699
40	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£24,166,240	£84,737,684

41	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£22,376,148	£78,460,819
42	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£20,718,656	£72,648,906
43	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£19,183,940	£67,267,506
44	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£17,762,908	£62,284,728
45	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£138,830,277	£486,801,266
46	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£134,786,677	£472,622,589
47	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£130,860,852	£458,856,882
48	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£127,049,370	£445,492,119
49	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£123,348,903	£432,516,620
50	24.32	£0	£0	£1,788,500,000	£1,472,708,516	£0	£0	£407,969,512	£335,935,239
51	24.32	£0	£0	£1,788,500,000	£1,472,708,516	£0	£0	£396,086,905	£326,150,717
52	24.32	£0	£0	£1,788,500,000	£1,472,708,516	£0	£0	£384,550,393	£316,651,182
53	24.32	£0	£0	£1,788,500,000	£1,472,708,516	£0	£0	£373,349,896	£307,428,332
54	24.32	£0	£0	£1,788,500,000	£1,472,708,516	£0	£0	£362,475,628	£298,474,109
55	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£103,302,765	£362,225,860
56	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£100,293,946	£351,675,592
57	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£97,372,763	£341,432,614
58	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£94,536,663	£331,487,975
59	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£91,783,168	£321,832,985
60	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£89,109,872	£312,459,209
61	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£86,514,439	£303,358,455
62	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£83,994,601	£294,522,772
63	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£81,548,156	£285,944,439
64	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£79,172,967	£277,615,960
65	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£76,866,959	£269,530,058
66	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£74,628,115	£261,679,668
67	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£72,454,481	£254,057,930
68	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£70,344,156	£246,658,185
69	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£68,295,297	£239,473,966
70	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£66,306,114	£232,498,996
71	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£64,374,868	£225,727,181
72	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£62,499,872	£219,152,602
73	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£60,679,487	£212,769,517
74	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£58,912,123	£206,572,347
75	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£57,196,236	£200,555,676
76	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£55,530,326	£194,714,249
77	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£53,912,938	£189,042,960
78	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£52,342,658	£183,536,854
79	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£50,818,115	£178,191,121
80	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£49,337,976	£173,001,088
81	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£47,900,947	£167,962,221
82	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£46,505,774	£163,070,118
83	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£45,151,237	£158,320,503
84	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£43,836,152	£153,709,226
85	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£42,559,371	£149,232,258
86	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£41,319,778	£144,885,688
87	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£40,116,289	£140,665,716
88	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£38,947,854	£136,568,657
89	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£37,813,450	£132,590,929
90	24.32	£0	£0	£1,788,500,000	£1,472,708,516	£0	£0	£125,065,845	£102,983,246

91	24.32	£0	£0	£1,788,500,000	£1,472,708,516	£0	£0	£121,423,150	£99,983,734
92	24.32	£0	£0	£1,788,500,000	£1,472,708,516	£0	£0	£117,886,554	£97,071,586
93	24.32	£0	£0	£1,788,500,000	£1,472,708,516	£0	£0	£114,452,965	£94,244,258
94	24.32	£0	£0	£1,788,500,000	£1,472,708,516	£0	£0	£111,119,383	£91,499,280
95	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£31,668,169	£111,042,815
96	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£30,745,795	£107,808,559
97	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£29,850,287	£104,668,503
98	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£28,980,861	£101,619,906
99	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£28,136,758	£98,660,103
100	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£27,317,241	£95,786,508
101	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£26,521,593	£92,996,610
102	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£25,749,120	£90,287,971
103	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£24,999,145	£87,658,224
104	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£24,271,015	£85,105,072
105	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£23,564,092	£82,626,283
106	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£22,877,759	£80,219,692
107	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£22,211,417	£77,883,197
108	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£21,564,482	£75,614,754
109	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£20,936,391	£73,412,382
110	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£20,326,593	£71,274,158
111	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£19,734,556	£69,198,211
112	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£19,159,763	£67,182,729
113	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£18,601,712	£65,225,951
114	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£18,059,914	£63,326,166
115	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£17,533,897	£61,481,715
116	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£17,023,201	£59,690,985
117	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£16,527,380	£57,952,413
118	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£16,046,000	£56,264,478
119	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£15,578,641	£54,625,707
120	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£15,124,894	£53,034,667
121	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£14,684,363	£51,489,968
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123	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£13,841,421	£48,534,233
124	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£13,438,272	£47,120,615
125	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£13,046,866	£45,748,170
126	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£12,666,861	£44,415,699
127	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£12,297,923	£43,122,038
128	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£11,939,731	£41,866,056
129	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£11,591,972	£40,646,656
130	30.4	£0	£0	£525,000,000	£1,840,885,645	£0	£0	£11,254,342	£39,462,773
Total	3594.8	£418,000,000	£26,266,999,997	£75,897,500,000	£217,684,727,519	£373,806,635	£15,508,728,790	£9,106,924,525	£24,989,459,950
		Net future value			£115,102,227,522	Net present value			£0

ANNEX G

ESTUARY MODELLING AND SCHEME DESIGN

ANNEX G ESTUARY MODELLING AND SCHEME DESIGN

DECC SETS
Bi-Directional Very Low Head Turbine Study

Atkins Study Report

March 2010

Notice

This document was produced by *Atkins* and Rolls-Royce plc for the specific purpose of Bi-Directional Very Low Head Turbine Study - Severn Embryonic Technologies Scheme part-funded by the Department for Energy and Climate Change, Welsh Assembly Government, South-West Regional Development Agency, and the Department for Environment, Food and Rural Affairs.

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Contents

Section Page

Appendices

Executive Summary

This report is produced as an Appendix to the main study report[1] and describes the work undertaken predominantly by Atkins in applying the Rolls Royce turbine design to two barrage schemes on the Severn Estuary. These barrage schemes were:

- Cardiff-Weston alignment (IOAR “B3” scheme).
- Minehead-Aberthaw alignment (IOAR “B1” scheme).

The new turbine developed by Rolls Royce has been specifically designed for bi-directional tidal flow conditions. The design characteristic were set out by Atkins at the start of the project based on an optimum operating head of about 3m with a flow rate of about 3m/s. The preferred design developed by Rolls Royce has achieved these characteristics at an efficiency that matches other turbine designs.

The conceptual design for the two barrages is based on low head bi-directional flow. This is achieved by maximising the number of turbines across the estuary with the aim of matching the natural tidal flow. This has a number of advantages as it both maximises power output and reduces the loss of tidal range upstream of the barrage.

One advantage of the turbine design is that it operates at a lower head and lower speed than a conventional hydro turbine. This means that the width and depth of the turbine caissons could be reduced resulting in a 25% saving in the turbine caisson volume.

For a peak spring tide the loss of tidal range upstream of the barrage would be about 12% compared with about 60% for an ebb generation scheme. This is a significant improvement in environmental terms. It would also be expected that the smaller reduction to the natural tidal prism would indicate a reduced geomorphological impact.

The results of this study show that a bi-directional barrage at Cardiff Weston would not only produce more energy than an ebb barrage, it has a lower estimated cost and a significantly reduced environmental impact.

A barrage at Minehead Aberthaw would also be less expensive than an ebb barrage and would produce significantly more energy. The following tables summarise the VLH barrage schemes in comparison with the IOAR ebb schemes:

Scheme	Installed Capacity	Annual Output	Construction Cost	Peak loss of tidal range
Ebb Scheme	8600 MW	17 TWh	20.1bn	60%
VLH Barrage	5783 MW	21 TWh	17.1bn	12%

Table 0.1 – Cardiff Weston Barrage

Scheme	Installed Capacity	Annual Output	Construction Cost	Peak loss of tidal range
Ebb Scheme	14700 MW	24TWh	29.0bn	60%
VLH Barrage	9984 MW	30 TWh	26.3bn	20%

Table 0.2 – Minehead Aberthaw Barrage

1. Introduction

1.1 Background

This report is produced as an Appendix to main study report and describes the work undertaken predominantly by Atkins in applying the Rolls Royce turbine design to two barrage schemes on the Severn Estuary. The scheme locations are shown below:

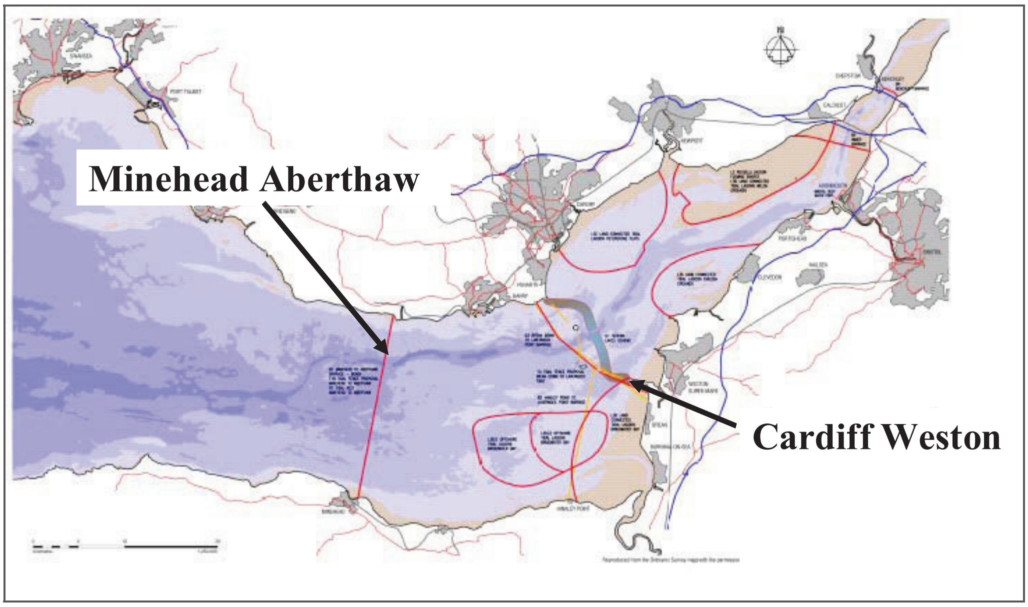

Figure 1.1 – Scheme Location

Atkins scope of services has included the conceptual design of a caisson to house the preferred turbine design and the estimation of the energy output and construction cost.

Section 2 of this report provides a review of the current “state of the art” for the design of tidal barrages and describes the need for a new turbine designed specifically for tidal conditions.

Section 3 describes the design of the barrage schemes for the Cardiff Weston and Minehead Aberthaw alignments, and includes the new caisson design.

The predicted annual energy output of the barrages is presented in Section 4, and Section 5 presents the estimated construction costs.

2. Review of Operational Mode

2.1 Introduction

The proposed new turbine design has been applied to two barrage alignments on the Severn Estuary:

- Cardiff-Weston alignment (IOAR “B3” scheme).
- Minehead-Aberthaw alignment (IOAR “B1” scheme).

The schemes proposed herein are essentially similar to the Interim Options Analysis Report (IOAR)[2] ebb generation options B3 & B1 and have many of the same features including construction using concrete caissons, and the provision of ship locks for navigation.

The main difference is the operation of the turbines on both ebb and flood tides at a lower head than an ebb only generation scheme. The specific requirements and main differences in a bi-directional barrage are described next.

2.2 State of the Art: Tidal Barrage Design

2.2.1 Turbines

Up to the present time, the design of tidal barrages has been based on available technology from the hydroelectric industry. The most widely considered and applicable power unit proposed for tidal barrages has been the bulb turbine. While bulb turbines have been used in many low head hydro-electric applications they were not specifically designed for use in tidal rivers. Consequently, they are only optimised for flow in one direction, which means that full potential of bi-directional tidal flow is not exploited.

The figure below shows the 9m diameter bulb turbine design proposed for a Cardiff Weston barrage in Energy Paper 57[3].

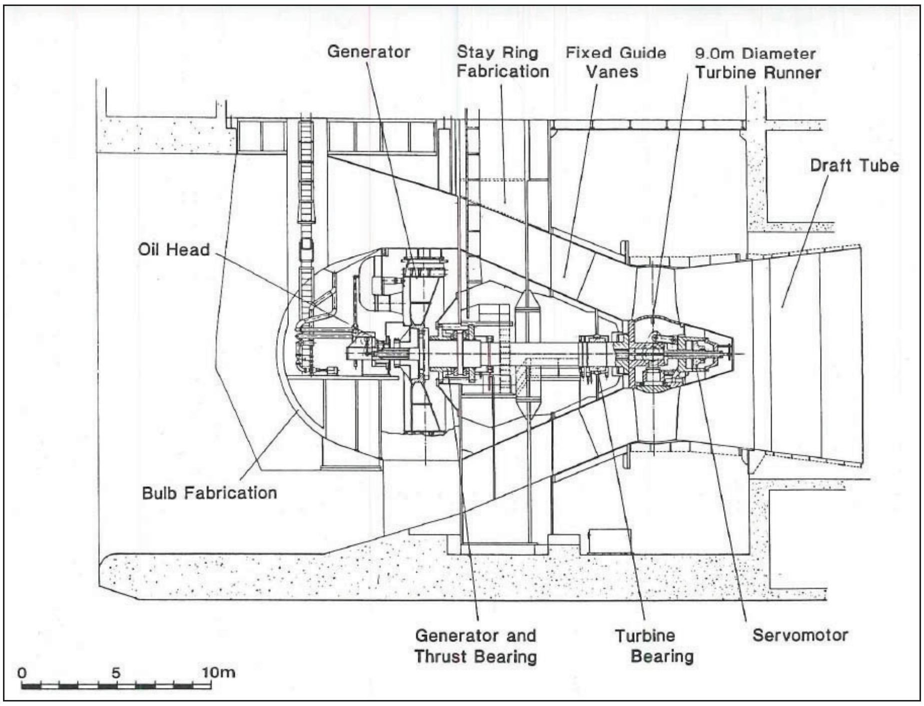

Figure 2.1 – Bulb Turbine (Energy Paper 57)

The entry area to the left is quite large and as water flows into the turbine it is compressed into a much smaller area accelerating to a high speed. The fixed guide vanes put a swirl into the water and the adjustable pitch runner blades are then driven by the water flow achieving a high overall energy conversion. Most bulb turbines are configured for a speed of about 50rpm. As the diameter of the blades increases so does both the flow velocity of the water and the blade tip speed, the latter reaching 20m/s for a 9m diameter turbine. These high speeds dramatically increase the rate of fish mortality, which is a significant disadvantage for tidal schemes across estuaries where there are often migratory fish.

Downstream of the runner blades is a draft tube where flow area is gradually increased to allow for energy recovery from the turbulent flow. There is a significant efficiency penalty if this draft tube is not provided. The figure below shows just how large the draft tube has to be.

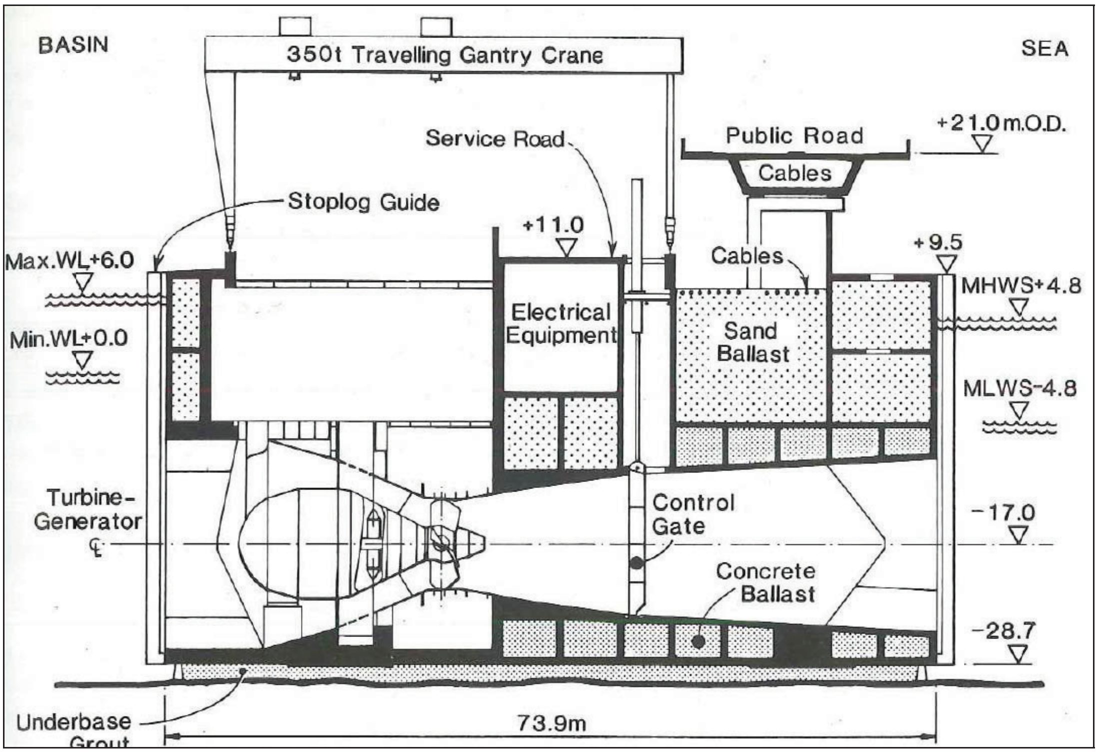

Figure 2.2 – Caisson design for Cardiff Weston Barrage (Energy Paper 57)

In summary, bulb turbines have several significant disadvantages when applied to tidal estuaries:

- Good efficiency in one direction only.
- Long draft tube requires large caisson.
- Higher fish mortality for larger diameters.

2.2.2 Ebb generation

For any barrage scheme the power output and unit cost of electricity can be optimised by changing parameters such as sluice and turbines flows as well as the mode of operation (i.e. ebb, flood or dual generation). The most common approach hitherto is to use one-way ebb generation and to size the turbines and sluices such that the upstream basin has about half the natural tidal range, as the level of high water is essentially unchanged and the level of low water is much increased over a tidal cycle. Figure 2.3 below shows this operational regime:

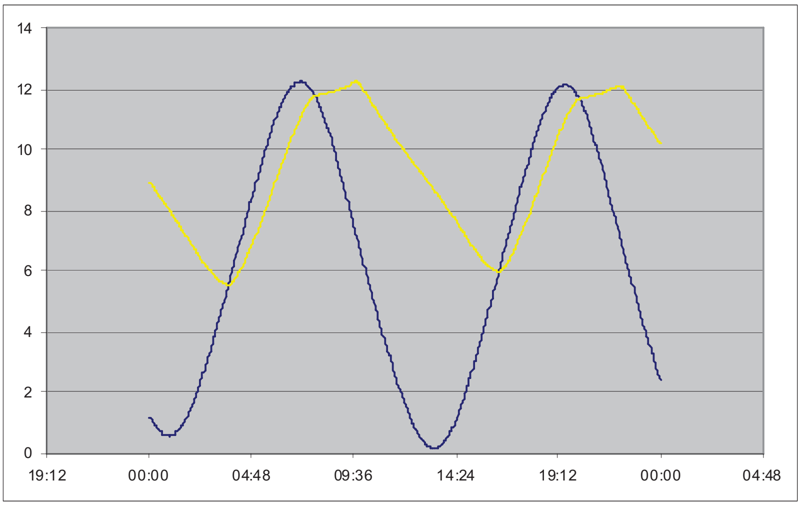

Figure 2.3 - Ebb Generation for Cardiff Weston

The ebb mode of operation would generally produce the lowest unit cost of electricity but would also result in the greatest loss of intertidal area upstream of a barrage: typically 50% to 60% of the tidal range would be lost.

The IOAR B3 barrage at Cardiff Weston comprised the following elements:

- 216 N_o 9m dia bulb turbines of 40MW.
- 144 sluices of area $156m^3$ each.

The bulb turbines need to be submerged to a minimum depth to prevent cavitation and this requires that the turbines are located in the deepest part of the estuary with the sluices being placed in more shallow water.

2.2.3 Ebb & Flood Generation

An alternative to ebb generation is “dual” or ebb and flood generation. This has the potential to produce more electricity as the turbines are used on both ebb and flood tides. The figure below shows a potential dual flow scheme for the B3 barrage using standard bulb turbines. The higher graph is the tidal curve downstream of the barrage, and smaller graph is the tidal level upstream of the barrage.

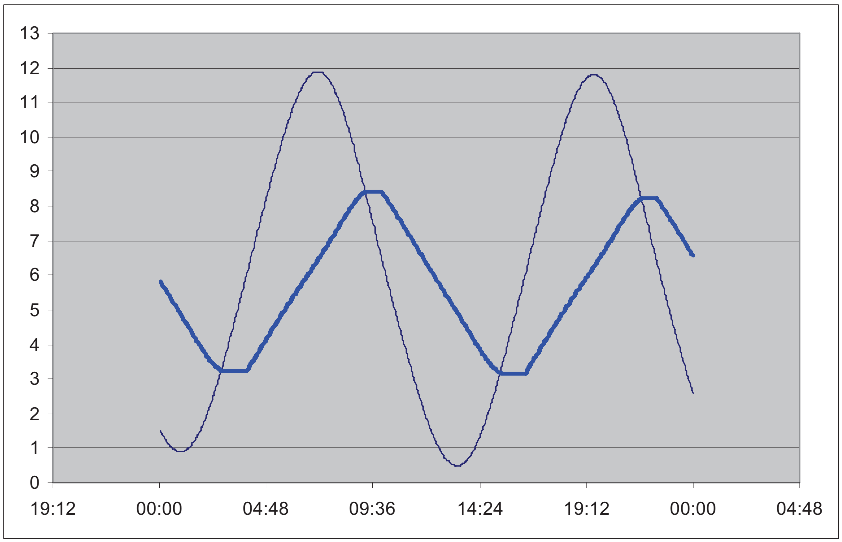

Figure 2.4 - Dual Generation using 2xEbb generation turbines.

For a dual generation scheme the sluices would be replaced with turbines and hence the number of turbines can be double provided that there is available deep water. Unfortunately standard bulb turbines are not very efficient in the reverse mode of operation.

While dual generation can potentially produce more energy, the use of bulb turbines in a reverse direction is inefficient and reduces the actual energy realised. Moreover, the loss of upstream tidal range is still significant.

2.2.4 Joule Study

A recent study by Liverpool University[4] identified a variation on the ebb-flood mode of operation. Referred to as 3x DoEn, it comprises a barrage with three times as many turbines as would be required for an optimised ebb barrage scheme. The figure below shows that model output for this mode of operation for a Cardiff Weston barrage, but using Atkins 0d estuary model.

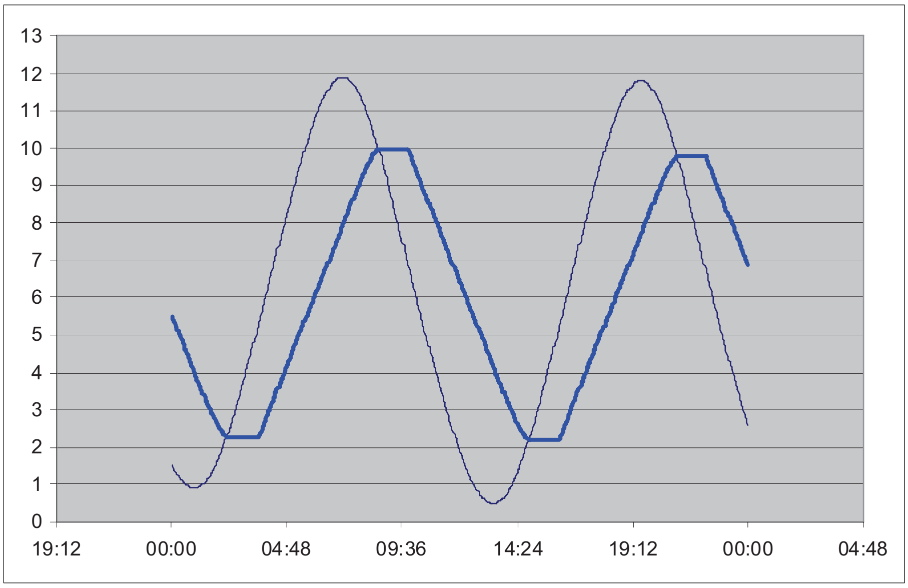

Figure 2.5 – High Flow Dual Generation

The high flow through the turbines means that the tidal curve in the basin tracks the natural tidal level much more closely. In effect the barrage is creating a phase shift in the tidal wave. The overwhelming benefit of this solution is that it minimises the loss of intertidal habitat in the basin, avoiding the need for the extensive habitat compensation required for most ebb generation schemes. Furthermore, because it more closely replicates the natural tidal flows and velocities, a lesser impact on estuarine morphology and sediment movement would be expected. In addition, this operational regime also produces more energy than ebb generation.

Unfortunately, the 3xDoEn mode of operation is difficult to achieve using bulb turbines. For example: to achieve the Joule study results for a Cardiff Weston barrage would require about 600 turbines compared with 216 for an ebb generation scheme. Physically, 600 bulb turbines would not fit across the estuary without a huge amount of dredging to increase the flow area.

While a high flow dual generation mode of operation is desirable in terms of environmental impact and energy output, it is impossible to achieve using bulb turbines in narrow estuary locations.

2.3 Ideal Turbine Characteristics

In defining the operating parameters for a new tidal turbine, it is the high flow dual generation type scheme proposed by the Joule study that provides the ideal. For a tidal barrage, the potential power output is the sum of head across the barrage and the flow through the turbines. Therefore, a higher flow of 2 to 3 times than that of an ebb scheme could be achieved with a head of about 1/3 of an ebb barrage scheme, i.e. about 3m.

The basic turbine flow parameters and head were determined from calculations. These calculations included the estimation of exit or mixing losses. For a low head turbine the exit loss is a proportionally larger percentage of the overall head, and maximising the flow rate through the barrage reduces these losses.

The ideal turbine characteristics were defined as an operational head of about 3m with a corresponding flow rate of about 3m/s.

3. Barrage Design

3.1 Design Parameters

The proposed Rolls Royce contra-rotating turbine has to be incorporated into a bi-directional very low head barrage. This is best achieved by:

- maximising the number of turbines and flow rate to reproduce the natural flow rate of the estuary;
- using a holding head the same as the optimal generating head.

This has been achieved for the Cardiff Weston Alignment on the Severn Estuary by:

- varying the turbine and caisson size to fill the entire estuary cross section with turbines;
- maximising the flow through the turbines by having straight turbine passages;
- and using an alignment that maximises the available cross sectional area.

3.2 Cardiff Weston Barrage

3.2.1 Alignment

The alignment of the B3 Cardiff Weston barrage is shown in the figure below, copied from the IOAR report. Also shown is an alternative alignment for a bi-directional barrage. Pushing the barrage alignment further out increases the cross section area by about 50% for an increase in length of just 20%. This enables many more turbines to be fitted across the estuary, thus increasing the total flow potential.

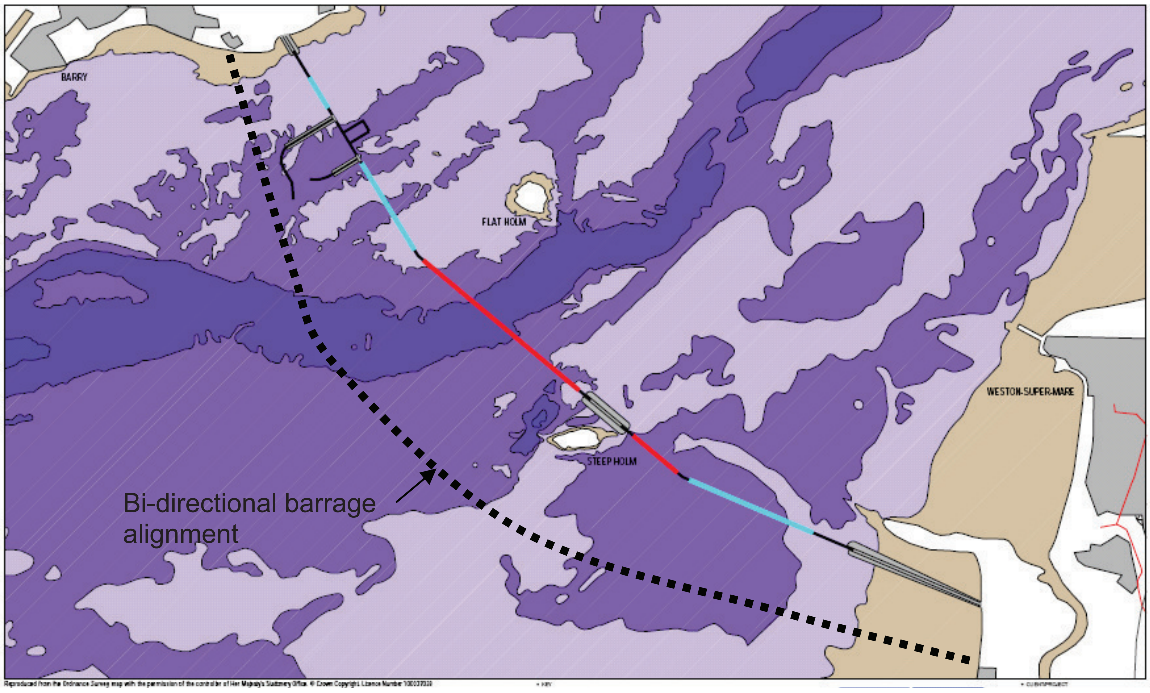

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Figure 3.1 – Barrage Alignment

3.2.2 Number of Turbines

The cross sectional area across the barrage alignment below 0.0mCD was calculated as 158,000m^3. This area would accommodate the following turbines with minimal dredging of the seabed:

- 900 No 9m dia contra-rotating turbines of 4.5 MW rating.
- 165 No 14m dia contra-rating turbines of 10.5 MW rating.
- Total installed capacity = 5783 MW.

3.2.3 Layout

The total length of different elements of the barrage would be:

Embankment	5.2km
Plain caissons	0.8km
9m Caissons	9.9km
14m Caissons	2.6km
Total	18.5km

The embankments and plain caissons would be the same design as the B3 barrage. However, the turbine caissons would be smaller as discussed next.

3.2.4 Turbine Caissons

General Arrangement

The caissons proposed for the B3 Cardiff Weston barrage would be 73.9m wide. A benefit of the new turbine design is that a draft tube would not be required. Moreover, the smaller head would mean a smaller horizontal force on the caissons, and consequently it would be possible to reduce the width of the caissons to about 50m.

The bottom level of the caisson is a function of the turbine diameter and the required submergence depth to prevent cavitation at the root of the runner blades. Again, the new turbine design has an advantage in that it requires less submergence because it operates at a lower head and slower speed. This means that the 9m dia contra-rotating turbine caisson would have a foundation level of about -17mOD compared with a level of -28.7mOD for a 9m bulb turbine. Since deeper water is available in the middle of the channel, 14m dia contra-rotating turbines are also used and these would have a foundation level of -22mOD.

The top level of the caissons would be similar to the B3 barrage design as it would be based on the same extreme water levels estimates, sea level rise assessment, and design wave heights. Our calculations suggest that a wave wall would be useful in reducing overtopping volumes during storm events.

The total caisson volume for a bi-directional barrage would be some 25% less than for the B3 barrage scheme for the reasons discussed above. Figure 3.2 shows the proposed caisson design.

The width of the caisson has been reduced to about 50m now that there is no requirement for a draft tube. The caissons would be constructed of reinforced concrete. The turbine passage is straight and of square cross section. A hatch is provided above the caisson and a gantry crane of about 500 tonnes would be able to lift out the turbine in two pieces.

An access road is provided across the top of the caissons. The reduced width of caisson would not provide the opportunity to locate a public highway across the barrage.

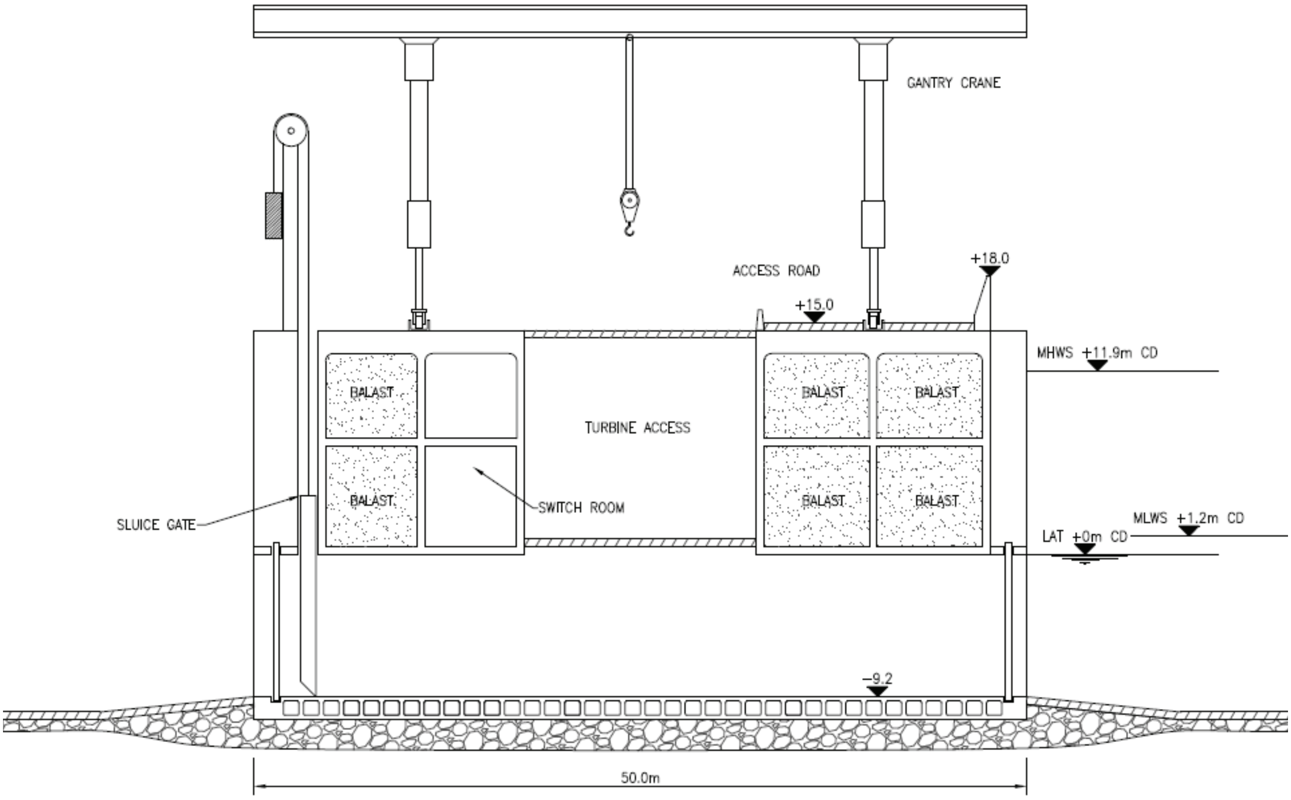

Figure 3.2 – Bi-Directional Caisson Design

Sluice Gates

A vertical counter-weighted sluice gate is provided to close the turbine off and to “stand” at high and low water. This is located on the basin side of the structure to avoid high wave loading and is located as far as possible from the turbine.

Maintenance Access

For the 14m diameter turbines a permanent access would be provided. The smaller turbines would be lifted out using a gantry crane. The turbine shaft would have to be dewatered. Figure 3.2 shows the two stop log positions are the ends of the turbine. Another two could be positioned at each end of the turbine access well. This would allow maximum flexibility and would reduce pump out requirements and issues of flotation.

A gantry crane would be used to install the stop logs and to lift out the turbine.

Initial Sizing and Costing of the Caissons

Initial calculations of section thickness were undertaken for the 9m turbine caisson.

- Bottom slab: 2m thick voided slab
- Side walls: 0.75m thick each,
- Top Slab 1.5m thick
- Other walls 0.5m thick

The caissons would be constructed in a block of three producing a box of dimensions 50m x 31.5m x 26m high.

For each caisson the estimated weight and volumes are as follows:

- Caisson volume = 13,650m^3
- RC concrete volume = 4,200m^3
- Volume of concrete per m^3 of caisson volume = 0.3077m^3/m^3
- Cost per m^3 of caisson = £215/m^3 / 0.3077 = £699/m^3

The above figure of £215/m^3 is taken from the IOAR and is an "all in" price for reinforced concrete. The estimated cost of £699/m^3 of caisson volume compares well with the figure of £707/m^3 used in the IOAR cost estimate for the B3 barrage. Therefore, the same unit cost has been used for a VLH Barrage.

Stability and Floatation

The caisson design has been checked for sliding stability in combination with a head difference across the barrage and wave loading.

The worst case for flotation is when the turbine shaft is dewatered at high tide. The weight of ballast is about 7,000t, and the caisson weight is about 10,000t.

- The uplift force is approx 57,000kN.
- The weight at high water is approx 54,500kN.

Therefore, there is a serious risk of uplift if the turbine shaft is dewatered on a spring tide. This problem was addressed in previous studies by introducing an operating procedure that only allowed one turbine shaft in a set of three to be dewatered at any one time. For the VLH caisson design it would also be possible to reduce the uplift force by using stop logs at the end of the turbine access. Both of these measures would produce an acceptable factor of safety.

3.2.5 Embankments

The embankment design would be the same as for a B3 barrage.

3.2.6 Operational Mode

The proposed mode of operation is to generate in both directions. In addition, it is also possible to pump at high and low water when the turbines would otherwise be idle. This speeds up the filling and emptying of the basin allowing generating to start earlier. It also effectively increases the tidal range allowing a much closer match to the natural state.

Pumping has been shown to increase the energy output and the ebb barrage design developed in Energy Paper 57 and the IOAR B3 barrage includes pumping at high water. However, the real benefit of pumping for a bi-directional barrage is the reduction in the loss of tidal range and the reduced environmental impact.

Figures 3.3 and 3.4 show the barrage operation for spring and neap tides respectively. The figures show the tidal curve downstream of the barrage, both the natural tide and as potentially modified by a barrage, and the upstream basin water level variation. The barrage affects both upstream and downstream water levels. Downstream a small reduction in tidal range would be expected, with a much larger reduction in the upstream basin. However, with a pumping mode of operation, it is possible to more closely replicate the natural tide.

Figure 3.3 also shows the pumping and generating periods over a tidal cycle. For the neap tide shown by figure 3.4 it is possible to pump the water level up and down to match the natural tidal level. For the high spring tide shown by Figure 3.5 the turbine pumping capacity is not sufficient to do this resulting in some reduction in the basin tidal range compared with the natural tide.

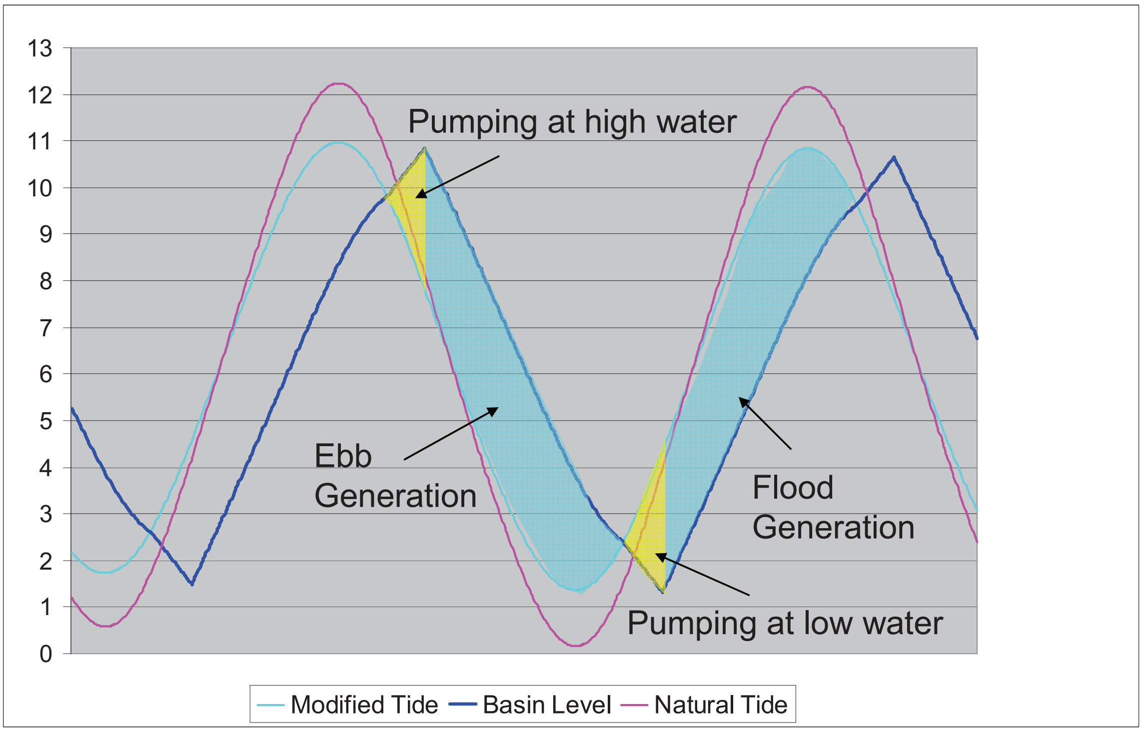

Figure 3.3 – Spring Tide Operation

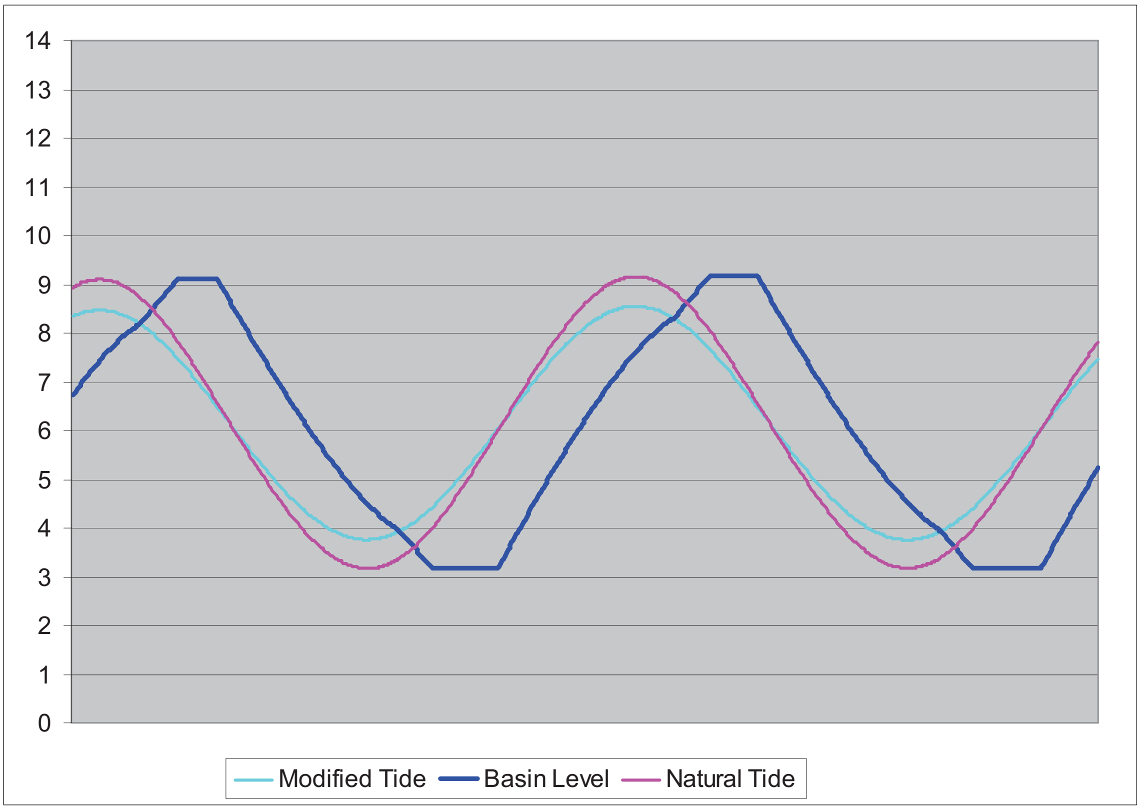

Figure 3.4 – Neap Tide Operation

3.2.7 Construction and Installation

For the purpose of this study the construction methodology and installation sequence would be the same as proposed in the IOAR and Energy paper 57. The caissons would be constructed in a dry dock and then floated and towed to the site by tugs. The slightly lower draft requirements may have some advantages but for the purposes of the construction cost estimate the same unit rates and programme period have been used.

3.2.8 Navigation and Ship Locks

The safe navigation of ships is of immense concern to the Port of Avonmouth as they have plans to build a new deep water container port and to dredge a navigation channel to allow the passage of ultra large container ships (ULCS) of draft 14.5m. A barrage scheme will slow down the passage of ships and make navigation more complicated. It may also increase dredging requirements in any new channel, but may also reduce the capital dredge requirement.

For a VLH bi-directional barrage it is proposed that the ship locks would be located in line with the main navigation channel. This would avoid the need for creating a dredged channel as proposed for the B3 IOAR scheme. While this would simplify navigation, the same harbour and ship lock facilities would be required as for an ebb barrage. However, there may be some construction issues regarding the timing of building the locks and for the present the cost of building the diversion channel has been retained in the cost estimate for the VLH barrage.

3.3 Minehead Aberthaw Barrage

3.3.1 Alignment

The Minehead Aberthaw bi-directional barrage would be on the same alignment as the B1 scheme in the IOAR.

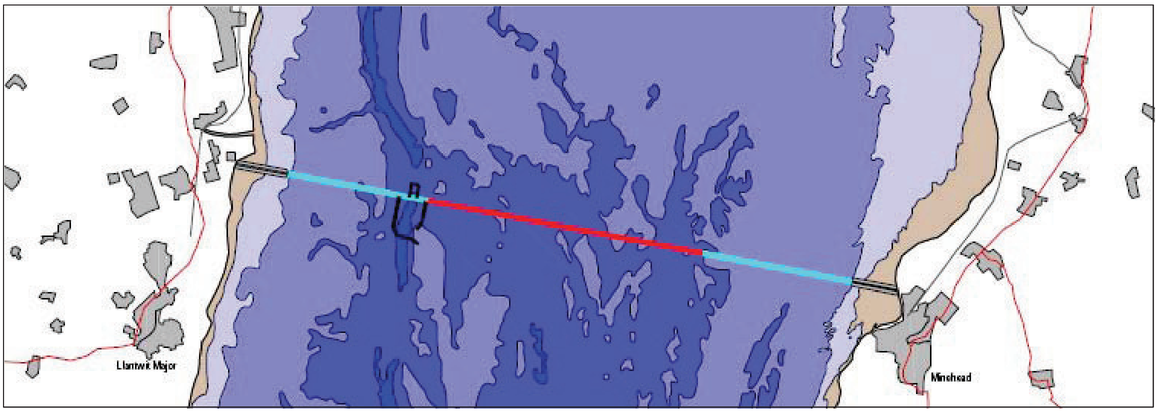

Figure 3.5 – Minehead Aberthaw Barrage B1 Alignment

3.3.2 The IOAR Scheme

The total barrage impoundment area is 1050km^2. The following arrangement was proposed in the IOAR:

- 370 x 40MW 9m dia bulb turbines
- 14800MW installed capacity

The scheme was not taken forward to the shortlist because the overall cost of the scheme was not considered affordable.

3.3.3 Turbines Caissons

The water in this section of the estuary exceeds 30m in some locations. The figure below shows how caissons could be fitted across the estuary to maximise the flow area.

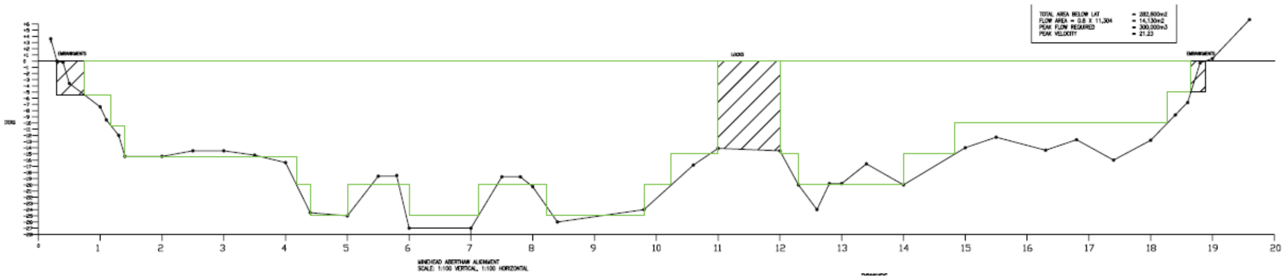

Figure 3.6 – Cross Section

The largest practicable turbine size used in this study is 14m diameter. The turbine caisson foundation level for this size of turbine would be about -16mCD. The gap between this level and the seabed would need to be infilled, either by having larger caissons or by using a rockfill bund.

It would also be possible to use turbines stacked one on the other. The cross sectional area across the barrage alignment below 0.0mCD was calculated as 282,600m^3. Theoretically it would be possible to fit about 2300 9m dia turbines (in 11m square caissons) into this area. However, the technical feasibility of this stacking arrangement would require further investigation and for the purposes of the present study has not been taking further, despite being an intriguing possibility.

Therefore, there are two possible options for a Minehead-Aberthaw barrage:

- Option 1: A single row of turbines with a rock infill foundation.
- Option 2: Stacked turbines.

A construction cost estimate and cost of energy modelling has been undertaken for option 1.

3.3.4 Layout and Turbines

For option 1 the total length of different elements of the barrage would be:

Embankment	2.9km
Plain caissons	1.0km
10m Caissons	3.7km
15m Caissons	12.4km
Total	20.0km

The number of turbines was estimated as 350 N$_o$9m dia and 800 N$_o$ 14m dia. The 0d modelling showed that the head across the barrage varied between 4 and 5m for a spring tide compared with the preferred 3m head. This resulted in the need to increase the rated capacity of the turbines as follows:

- 352 No 9m dia contra-rotating turbines of 4.5 MW rating.
- 800 No 14m dia contra-rating turbines of 10.5 MW rating.
- Total installed capacity approximately 9984 MW.

3.3.5 Caisson Design

The caisson design would be the same as for the Cardiff Weston alignment. In the deeper parts of the estuary the caisson height would be extended down to a depth of -20mCD. Below this depth the caissons would sit on a sand fill and quarry rock bund. The basic design is similar to a composite breakwater. However, the head difference means that this bund would need to be sealed to prevent water flow under the barrage caissons. A sand filled core using large geotextile bags would be sufficient if wide enough. Another possibility is that the bund could be lined with a grout filled mattress or other membrane system.

Construction in the deeper water of this alignment does bring a number of difficulties. While these issues are not insurmountable they do require further study that is outside the scope of this report. For cost estimation purposes it was assumed that the caisson volume extended down to bed level.

4. Energy Modelling

4.1 Introduction

A 'flat estuary'[1] model was used to calculate the power outputs for different modes of generation and to optimise the number of turbines. A linear model[2] was used to derive the tidal range at the barrage and to provide an alternative assessment of the available power.

The power from a tidal barrage is a function of the basin area and the tidal range at the barrage. In additional, if quoting a yearly output, an average year has to be used as the distribution of tides varies over a 19 year cycle.

The estimated energy outputs for the B1 and B3 barrages in the IOAR are based on work done in Energy Paper 57 using a flat estuary model to calculate energy outputs. To provide a basis of comparison with the IOAR, a similar flat estuary model has been used with the same main hydraulic input parameters. In particular, the same average year has been used as has the same basin area. However, the one parameter that is different is the tidal range at the barrage. This is because an ebb barrage and a VLH barrage would have different reflection coefficients resulting in different tidal ranges. The energy paper 57 work used a 1-d tidal model to assess this change. For this study a linear model has been used to provide an estimate of the tidal range for the B1 & B3 VLH barrages.

4.2 Linear Model

A linear model of the Severn estuary has been developed based on an analytical solution of tidal flow. This model is described in a peer reviewed technical paper attached as Appendix A of this report. For this study, this analytical model has been extended to examine a very low head barrage with a holding head of 3m and the ability to pump at high and low water, refer to Appendix B. Because the model is linear the estimated power output is "available" power, before considerations of operating regime, turbine efficiency, availability, and exist losses. Moreover, the physical constraints of the number of turbines are not considered.

The linear modelling as been undertaken for the following locations:

1. Outer Bristol Chanel
2. Mumbles
3. Lynmouth to Porthcawl
4. Minehead to Aberthaw
5. Cardfiff to Weston Super Mare

Figures 4.1 and 4.2 show the power output and the reduction in downstream tidal range respectively. They are plotted against a factor defined as the upstream tidal range divided by the natural tidal range. For example, a factor 1 means that the natural upstream tidal range is matched by the barrage. The graph also plots factors up to 6. While these are not realistic in practical terms, they do demonstrate that power goes on increasing.

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[1] A 'flat estuary' or zero dimensional estuary model derives flows numerically by the principle of mass conservation between the upstream basin and the downstream estuary. Tidal levels seaward of a barrage are assumed to be unchanged, and turbine and sluice flows are determined by the head difference up- and downstream of the barrage at short time steps over a tidal cycle or cycles.

[2] A linear model is an analytical solution of the equations that govern tidal flow.

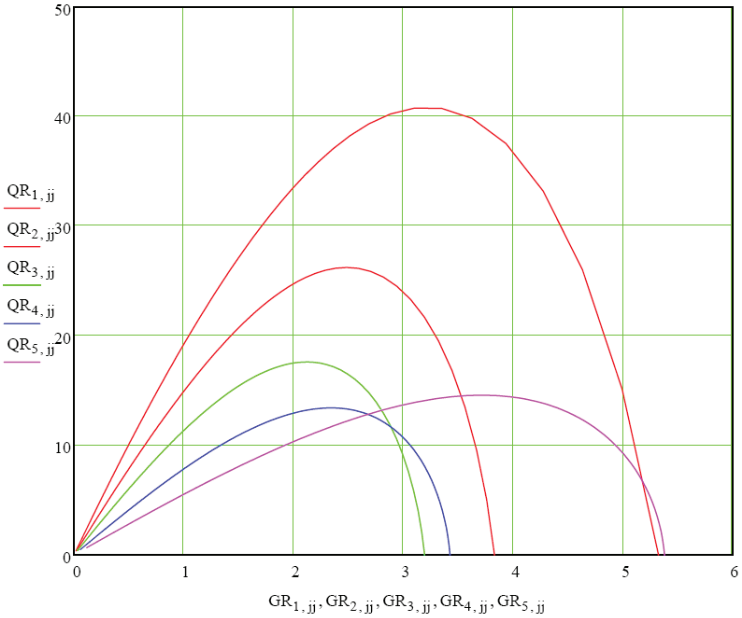

Figure 4.1 – Basin Tidal Range Factor against Versus Power Output

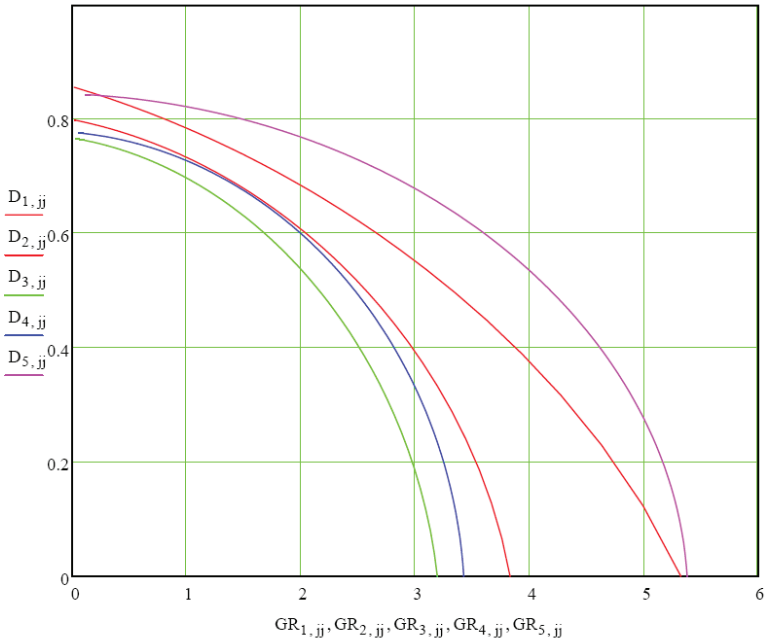

Figure 4.2 – Basin Tidal Range Factor versus Downstream Reduction in Tidal Range

The results also show that as the upstream tidal range factor increases there is a corresponding reduction in the tidal range to seaward. This eventually limits the extractable power. The results from the linear model are summarised in Table 4.1.

	Cardiff Weston	Minehead Aberthaw
Average Power Output for No pumping Mode	3.9 GW	5.2 GW
Average Power Output with pumping	5.2 GW	6.5 GW
Reduction factor in downstream tidal range for pumping mode	0.82	0.73

Table 4.1 – Linear Model Results

For a Cardiff Weston barrage the results show that power increases by about 30% for a pumping mode that matches the natural tidal range. It should be noted that the linear model is based on estuary cross sectional data and therefore includes the dynamic effects of the propagation of the tidal wave up and down the estuary. In this respect, the linear model is like a 1-d numerical model.

The linear model results also show a much larger reduction in the seaward tidal range than for an equivalent ebb barrage. For the purposes of the energy modelling these figures were rounded to 20% and 30% for Cardiff Weston and Minehead Aberthaw respectively. It is interesting to note that the linear model gives a reduction in tidal range of less than 10% for an ebb barrage. This seems to be consistent with the tidal range reductions in Energy Paper 57.

4.3 Flat Estuary Model Description

4.3.1 General

A so called “flat estuary model” or zero dimensional model has been used to calculate energy output. This model calculates the flow through turbines and sluices based on the head difference between the outside tidal level and the inside basin level. The basin level is adjusted at each time step by calculating the incremental change level as the total flow in or out divided by the basin area.

The Atkins flat estuary model uses a backward difference scheme. The basin level is adjusted for each time step based on the calculated turbine and sluice flows from the previous time step. Provided that the time step is small, the error is acceptable.

4.3.2 Turbine and power calculations

The following figures were used in the energy calculations:

Maximum turbine efficiency:	95%
Generator efficiency:	97.5%
Availability	95%
Transformer efficiency	99%

Turbine flow and power were represented by a polynomial approximation in the spreadsheet.

4.3.3 Volume & Area calculations

A cross sectional area was calculated for each tide level and used to calculate the river flow either upstream or downstream of the barrage. The basin water volume was taken as a constant value based on a basin area of 504km^2.

4.3.4 Average year

Annual power calculations were undertaken using predicted tides for 1974. This is because tidal levels vary over a 19-year cycle, and 1974 was an averaged year that had been used in previous studies.

4.3.5 Tidal levels

The 0d modelling has been based on predicted tides in the Severn Estuary. For the Cardiff Weston barrage, tidal predictions for Steep Holm were used, and for Minehead Aberthaw, Minehead was used as shown below:

Main Tidal Harmonics From the Admiralty Tide Tables	Steep Holm	Minehead
M2	3.8	3.5
O2	1.2	1.0

Table 4.2 – Main Tidal Harmonic Constituents

The simplified admiralty method of tidal prediction NP159 was used to derive tidal levels for a time step of 2 minutes.

The main tidal harmonics were then reduced by 20% and 30% for Steep Holm and Minehead respectively to simulate the affect that a barrage would have on the tidal input, refer to section 4.2.

It is noted that a Severn Barrage has been modelled as part of a Joule Centre funded study undertaken by Liverpool University. This study provides an assessment of the changes to the main tidal constituents for the conjunctive operation of a dual generation Severn barrage with a series of tidal barrages in the North East of the UK. These results suggest a 20% (approximately) reduction in the tidal harmonics, which is similar to the linear modelling results presented herein.

4.4 Energy Resource

The available energy resource is a function of the tidal basin area and tidal range. The Table below shows a calculation of the maximum energy (Emax) for the Cardiff Weston and Minehead Aberthaw alignments. The tidal range is the average value and taken as the M2 tidal harmonic.

	Cardiff Weston	Minehead Aberthaw
Basin Area	504km^2	1060km^2
M_2 Tide	3.87m*	3.59m$^+$
Annual Potential Energy (E_{max})	59 TWh	108 TWh

*= Steepholm $^+$= Minehead

Table 4.3 - Potential Energy

Work by Prandle[5] suggests maximum extractable ebb-phase energy will be in the region of 0.27 E_{max}, and 0.37 E_{max} for dual generation. Assuming no modification of the tidal curve, this would give 22 TWh and 40 TWh for Cardiff Weston and Minehead Aberthaw alignments respectively. This assessment is based on the use of bulb turbines and is sensitive to the choice of starting and finishing level. Moreover, it does not include pumping.

4.5 Results for Barrage B3: Cardiff Weston

Tables 4.4 below shows the estimated energy output for a 20% reduction in the tidal range for a pumping and a non pumping scenario.

	No Pumping	With Pumping
Annual Energy Output	16.76 TWh	20.85 TWh
Loss of Tidal Range Seaward	20%	20%
Loss of Tidal Range In Basin (Average)	34%	5%
Loss of Tidal Range at Peak Spring Tide	32%	12%

Table 4.4 – Model Results with 20% reduction in Tidal Curve

Pumping has a significant impact on the tidal range reducing this to a loss of just 5% of the natural range, on average. However, at peak spring tides there is a larger loss of about 12%. This is because the turbines operating as pumps do not have sufficient power to pump the water level up on peak spring tides. Overall, the pumping mode of operation gives a 24% increase in energy.

Table 4.5 below shows that this increase in power is predominantly achieved on low neap tides.

	Neap Tide	Spring Tide
Energy Output – no pumping	14080 MWh	41392 MWh
Energy Output – with pumping	22414 MWh	45934 MWh
Percentage Increase	59%	11%

Table 4.5 – Increase in energy due to pumping

The large increase on neap tides is achieved because pumping allows the operating head across the barrage to be increased to the optimum of 3m. The increase on spring tides is much smaller, which reflects the greater difficulty in pumping up and down from the basin.

4.5.1 Discussion of pumping results

Previous studies using 1d and 2d models undertaken for the Energy paper 57 work found that the increase in energy gained from flood pumping was limited to about 3%. This included a gain of 1.9% on spring tides and just 2.6% on neap tides. No explanation of the physical processes that would limit this energy gain was provided. The modelling work undertaken was for an ebb generation barrage.

The linear model results shown that a VLH barrage has a significantly different impact on the tidal wave propagation than would an ebb barrage. Therefore, these previous results are not applicable for a VLH barrage. Furthermore, the VLH barrage B3 scheme would have 2.5 times as much pumping flow rate as the ebb generation scheme proposed in Energy Paper 57.

The potential gains from pumping will need to be verified by further numerical modelling work using 1d and 2d models.

4.6 Results for Barrage B1: Minehead Aberthaw

The tables below show the estimated energy output for a Minehead Aberthaw Barrage.

	No Pumping	With Pumping
Annual Energy Output	24.07 GWh	30.39 GWh
Loss of Tidal Range Seaward	30%	30%
Loss of Tidal Range In Basin (Average)	45%	18%
Loss of Tidal Range at Mean Spring Tide	40%	20%

Table 4.6 – Model Results with 30% reduction in Tidal Curve

The predicted energy output for a Minehead Aberthaw barrage varies from 24TWh up to 30TWh depending on the use of pumping.

The Bondi committee (Energy paper 46[6]) estimated an annual energy output of 19.7TWh. This figure was updated in the DECC IOAR study to 25.3 TWh by increasing the installed capacity. The above figures are consistent with previous estimates of power at this location.

5. Construction Costs

5.1 Introduction

A construction cost has been estimated for a VLH bi-directional barrage schemes at Minehead Aberthaw (B1) and Cardiff Weston (B3). This has been used to determine a cost of energy that is directly comparable to the "fair-basis" assessment given in the IOAR.

5.2 Construction Cost Model

A spreadsheet costing model was developed based on the financial analysis given in the IOAR. Appropriate modifications to unit costs and quantities were made to reflect the different turbo-machinery and caisson designs for a low head barrage. In all other respects it was assumed that a VLH bi-directional barrage would be planned and constructed in the same manor as a conventional barrage. Estimated construction costs are given below:

Scheme	VLH Bi-Directional Barrage	Ebb Barrage (IOAR)
Option B1: Minehead Aberthaw	£25.4bn	£29.0bn
Option B3: Cardiff Weston	£16.2bn	£18.3bn

Table 5.1 – Construction Cost Excluding Compensatory Habitat

The detailed estimates are included as Appendix D.

For a Cardiff Weston scheme there is a significant cost reduction for a bi-directional barrage, which can be attributed to the savings in the caisson cost and the lower installed capacity of the turbo machinery.

The volume of the caissons is about 25% less than those required for an ebb barrage due to the reduced width as a result of not requiring a draft tube; and the reduced depth resulting from lower submergence requirement.

The turbo-machinery has a higher estimated unit cost at £0.85m/MW compared with £0.676m/MW used in the IOAR for bulb turbines. However, the installed capacity is lower at 5783MW compared with 8640MW for an ebb barrage.

At Minehead Aberthaw the bi-directional barrage is also less expensive than an ebb barrage due to the lower installed capacity.

5.3 Habitat Loss

The reduction in tidal range upstream of a barrage will result in the permanent loss of intertidal habitat due to the reduced height of inundation at high water and reduce low water levels resulting in permanent submergence. The best means of estimating this loss would be by using 2d numerical flow model, but this is not available to the present study. Instead a relationship between intertidal area and tidal height was used to calculate habitat loss. Table 5.2 shows these results:

	Intertidal Habitat	% Loss	Habitat Loss
Cardiff Weston	22,500ha	12% inside and 20% outside	5248ha
Minehead Aberthaw	31,500ha	20% inside and 30% outside	6800ha

Table 5.2 – Habitat Loss

These estimates are probably conservative and are based on the peak tidal range loss and not the average.

5.4 Maintenance & Other Costs

The IOAR gives a value of 1.25% of the construction cost to cover annual maintenance, running costs, consumables, business rates and insurance. A design life of 120 years is taken. Demolition and removal costs are not included in the analysis.

Major maintenance intervals are included every 40 years and are taken as 70% of the supply and commissioning costs of the electro-mechanical machinery.

5.5 Summary

The table below shows the estimated construction costs including the cost of providing compensatory habitat at a 2:1 ratio. These costs are based on the IOAR fair basis approach and as such are suitable for comparison with the other IOAR options.

Scheme	VLH Bi-Directional Barrage
Option B1: Minehead Aberthaw	£26.3bn
Option B3: Cardiff Weston	£17.1bn

Table 5.3 – Construction Cost Including Compensatory Habitat x2

6. References

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[1] Rolls Royce Atkins Severn Embryonic Technologies Scheme Concept Design of a Very Low Head Dual Generation Tidal Scheme for the Severn Estuary. Volume 1 Summary Report. Issue 1 February 2010.

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[5] Prandle D (1984). “Simple theory for designing tidal power schemes”. Advances in water resources, CML Publications, 7, 21-27.

[6] The Severn Barrage Committee (1981), Energy Paper Number 46, “Tidal Power from the Severn Estuary”, HMSO.

Appendix A – Optimum Position for A Tidal Barrage in the Severn Estuary

J. Fluid Mech. (2009), *vol.* 636, *pp.* 497–507. © Cambridge University Press 2009
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The optimum position for a tidal power barrage in the Severn estuary

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G. I. Taylor's approximate analytical solution for the tidal flow in the Severn estuary is extended to find the optimum location for a tidal power barrage, from the power point of view. It appears to be at the lowest point in the estuary, between Ilfracombe and Gower – contrary to earlier computations. The analytical solution shows that barrages radiate tidal waves out to sea, which highlights the important role of the far-field boundary condition in absorbing them. This appears to have been neglected in numerical models, which may explain the difference from the earlier results.

1. Introduction

Tidal power barrages in the Severn estuary were studied intensively 30 years ago, by a UK government committee chaired by Bondi (see Bondi *et al.* 1981). It was concluded from computer models that the optimum position for a barrage from the power point of view was approximately halfway down the estuary at Minehead. If the barrage was moved further downstream, no more power was obtained, because it was found that the barrage increasingly attenuated the incoming tides. Although tidal power barrages for the Severn have been studied on several more recent occasions, it appears that no more recent computer modelling has been undertaken on this point (see Burrows *et al.*, in press).

The problem can be investigated using G. I. Taylor's simple analytical model of the tidal flow in the Severn estuary (Taylor 1921). This has the advantage of revealing the fundamental features of the problem more clearly than a computer model.

Taylor's model is described in Lamb's account of the 'canal theory of the tides' (Lamb 1932, pp. 267–278), of which it is a special case. The canal theory considers tidal flow as a longitudinal gravity wave in a channel. Following Lamb's notation, if the width of the channel is $b(x)$ and its depth is $h(x)$, both varying with position x along the channel, then the equation for the surface elevation $\eta(x,t)$ at time t is (Lamb 1932, p. 274)

$$\frac{\partial^2\eta}{\partial t^2} = \frac{g}{b}\frac{\partial}{\partial x}\left(hb\frac{\partial\eta}{\partial x}\right), \tag{1}$$

where g is the acceleration due to gravity. In an estuary, high tide is assumed to occur at the same time, $t=0$, everywhere, since the extent of the estuary, when measured in degrees of longitude, is small compared with the tidal cycle of approximately 180°. A

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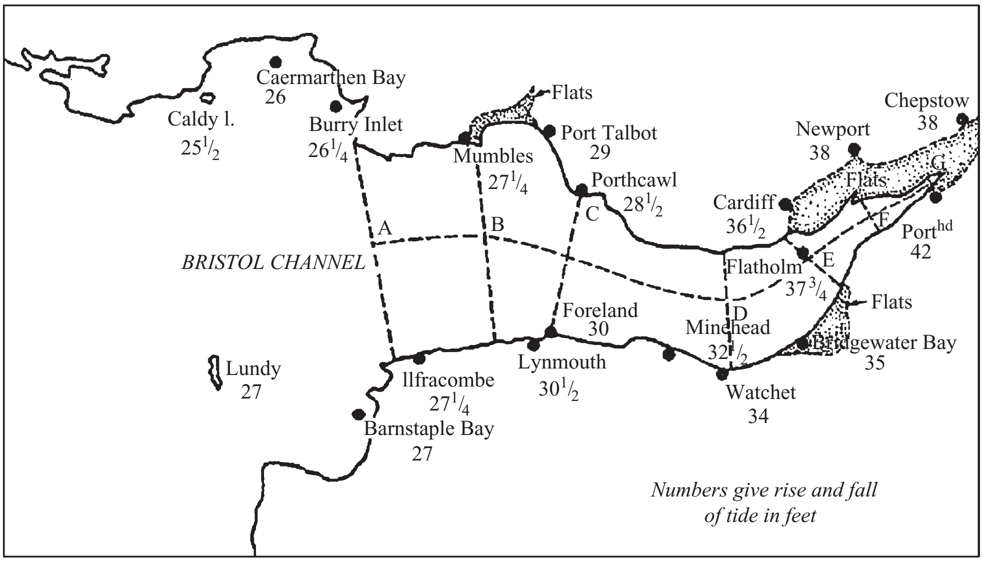

FIGURE 1. Taylor's model of the Bristol Channel. All the data in the table have been updated, from the latest admiralty charts. Breadths, depths and areas are at the mean sea level. The area upstream of Sharpness (17 km upstream of Chepstow) is excluded, since it is small and the tidal range is markedly reduced there. The time delays are mean values for neap tides (appropriate since we are considering a mean tidal range in figure 3, which will be reduced by the barrage as in figure 4) based on data for the north shore of the estuary (which appear more reliable than that from the south shore) in the 2009 admiralty tide tables. Parameters for $n = 7$ and 8 are defined to give the correct averages over the area upstream of section G, when used in (9)

solution is therefore sought of the form

$$\eta(x, t) = \eta_0(x)\cos(\omega t), \tag{2}$$

where $2\pi/\omega$ is the tidal period of approximately 12 h (half a lunar day). Thus (1) becomes

$$\frac{g}{b}\frac{\mathrm{d}}{\mathrm{d}x}\left(hb\frac{\mathrm{d}\eta_0}{\mathrm{d}x}\right) + \omega^2\eta_0 = 0. \tag{3}$$

In the case of the Severn estuary, Taylor observed that the width $b(x)$ and depth $h(x)$ both increase approximately linearly with distance x downstream (referred to henceforth as 'west') of the head of the estuary at Portishead (see figure 1, originally figure 1 and table 1 in Taylor 1921). He therefore took $x = 0$ at Portishead and put

$$b = \beta x \text{ and } h = \gamma x, \tag{4}$$

where β and γ are constants. This reduces (3) to

$$\frac{\mathrm{d}}{\mathrm{d}x}\left(x^2\frac{\mathrm{d}\eta_0}{\mathrm{d}x}\right) + k\eta_0 x = 0 \text{ with } k = \omega^2/(\gamma g), \tag{5}$$

which can be solved exactly as a Bessel function:

$$\eta_0 = \frac{K J_1\{2\sqrt{kx}\}}{\sqrt{kx}}, \tag{6}$$

Taylor's section	n	Distance x_n from section G (km)	Mean depth (m)	Breadth (km)	Area S_n to next section (sq. km)	Delay t_n of high tide, relative to section A (min)	Loss angle from (9) (deg.)
A	1	114.3	36.9	40.6	800	0	3.8
B	2	92.10	28.7	37.7	585	2	3.9
C	3	77.83	24.4	30.0	695	2	5.2
D	4	46.33	16.3	22.7	383	6	6.1
E	5	28.72	16.3	13.2	220	14	5.2
F	6	14.82	9.5	15.2	166	19	
G	7	0.0001	5.3	7.8	113	29	
	8	0.0001				53	

where K is a constant. Taylor took $\gamma = \{25 \text{ fathoms}\}/\{80 \text{ UK nautical miles}\} = 0.0003084$ (β is immaterial) and the tidal period $2\pi/\omega$ as 12.4 h, so that $k = 0.00655\,\text{km}^{-1}$, and found (6) to be a good approximation to the observed variation of tidal range in the Severn estuary, shown in figure 1 (close to modern values). This paper extends Taylor's analysis to the case of a tidal power barrage in the estuary.

2. Tidal power – the need for progressive waves

Considered as a function of time, the horizontal velocity in a tidal wave (and indeed in a water wave generally) is 90° out of phase with the surface slope $\partial\eta/\partial x$, since the latter is in phase with the horizontal acceleration. And the pressure variations are in phase with the surface elevation η. Thus for a standing-wave solution of the form (2), where the surface slope is in phase with the surface elevation, the velocity and pressure are 90° out of phase. Therefore the power flux (= velocity × pressure) has a mean value of zero everywhere. This is of course to be expected, since the tidal energy is nowhere being dissipated in the estuary in potential flow and only being stored. When we extract tidal power with a barrage, however, we require an equal mean power flux inwards at the mouth of the estuary. We thus reach the important conclusion that Taylor's solution (or any solution of form (2)) is 'inadmissible west of the barrage' because it transmits no mean power. What is required west of the barrage is a 'progressive wave', in which there is a power flux, because the surface slope is 90° out of phase with the surface elevation (and thus the velocity is in phase with the pressure). Rather than a solution of form (2) we can seek a solution of the more general form,

$$\eta(x, t) = \mathrm{Re}\{\eta_0(x)\mathrm{e}^{\mathrm{i}\omega t}\}, \tag{7}$$

where $\eta_0(x)$ is now complex, and Re indicates the real part. This again leads to (5), which can be solved in the same way as

$$\eta_0 = \frac{K_1 H_1^{(1)}\{2\sqrt{kx}\} + K_2 H_1^{(2)}\{2\sqrt{kx}\}}{\sqrt{kx}}, \tag{8}$$

where $H_1^{(1)}$ and $H_1^{(2)}$ are a first and second Hankel functions of order one, and we now have two constants K_1 and K_2. The first term is a progressive wave travelling east, and the second is a progressive wave travelling west. Far to the west, both resemble tidal waves in open water of the same depth (since $H_1(x) \sim -\{\cos(x + \pi/4) \pm \mathrm{i}\sin(x + \pi/4)\}/\sqrt{x}$, for large x). East of the barrage, we can extend Taylor's solution empirically to include the observed delay times of the tide. These are caused by the need to transport energy into the estuary, to overcome natural energy losses from turbulence, and may therefore be important in the context of a tidal power barrage. (In fact they turn out to be of only minor importance; see figure 3).

3. An equivalent electric circuit

In his account of waves in channels, Lighthill (1978, p. 104) introduces the standard electrical analogy of voltage with pressure and electric current with volume flow rate. If the level variation of a reservoir of area S is written $\mathrm{Re}\{\mathrm{e}^{\mathrm{i}\omega t}\}$, then its pressure variation is $\mathrm{Re}\{\rho g \mathrm{e}^{\mathrm{i}\omega t}\}$ (where ρ is the density of water), and the volume flow rate in and out of the reservoir is $S\mathrm{d}/\mathrm{d}t(\mathrm{Re}\{\mathrm{e}^{\mathrm{i}\omega t}\}) = \mathrm{Re}\{S\mathrm{i}\omega \mathrm{e}^{\mathrm{i}\omega t}\}$. Thus on the electrical analogy its impedance is $\rho g/(S\mathrm{i}\omega)$, so it is analogous to an electrical capacitance $S/\rho g$ (Lighthill 1978, p. 200, (3)).

A similar calculation applies in our case, for a reservoir formed by a barrage at one of Taylor's sections A–E in figure 1. The reservoir area can be can be discretized into the sub-areas S_n between the successive sections, given in figure 1. The level variation at the barrage is given by Taylor's formula (6) with his x-coordinate x_n given in figure 1, and this formula can also be used to find the average amplitude of the level variations of each sub-area. The phases of these level variations is given by the average delay times t_n in figure 1. Thus the reservoir impedance Z_1 of a barrages at the nth of Taylor's sections A–E can be written as

$$Z_1 = \frac{\dfrac{\rho g J_1\{2\sqrt{kx_n}\}}{\sqrt{kx_n}}}{\sum_{j=n}^{j=7}\left[\dfrac{J_1\{2\sqrt{k(x_j + x_{j+1})/2}\}}{\sqrt{k(x_j + x_{j+1})/2}} S_j \mathrm{i}\omega \mathrm{e}^{-\mathrm{i}\omega\{(t_j+t_{j+1})/2-t_n\}}\right]}. \tag{9}$$

Evidently (9) is no longer purely imaginary, but has a real part analogous to a resistance R_L as well as an imaginary part analogous to a capacitance C. The resistance R_L gives the natural energy dissipation in the reservoir – to continue the electrical analogy, it can be expressed as a 'loss angle' $\tan^{-1}(\omega C R_L)$, which is readily calculated from the argument of (9) and is given in figure 1. West of the barrage, it is convenient to consider the water pressure variation ($= \rho g \times$ level variation) as the sum of the pressure variation $\mathrm{Re}\{P\mathrm{e}^{\mathrm{i}\omega t}\}$ which would be seen in the absence of the barrage and the additional pressure variation $\mathrm{Re}\{P'\mathrm{e}^{\mathrm{i}\omega t}\}$ caused, immediately west of it, by the presence of the barrage. The additional pressure $\mathrm{Re}\{P'\mathrm{e}^{\mathrm{i}\omega t}\}$ at the barrage produces a tidal wave which propagates out to sea – as far as the flow to the west of the barrage is concerned, the barrage is acting like a wavemaker. We require its wavemaking impedance Z_2, i.e. the ratio of pressure to volume flow rate in the tidal wave it generates. A unit wave propagating west is described by the second term in (8), with $K_2 = 1$. The water acceleration in this wave, in the direction of propagation, is minus the surface slope times g, whence we can obtain the water velocity in a westward direction by integrating, as the real part of

$$\frac{-g}{\mathrm{i}\omega}\frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{H_1^{(2)}\{2\sqrt{kx}\}}{\sqrt{kx}}\right)\mathrm{e}^{\mathrm{i}\omega t}. \tag{10}$$

The volume flow rate in the direction of propagation is this velocity times bh, and the water pressure is $\rho g \eta$. We obtain the impedance Z_2 by dividing the latter by the

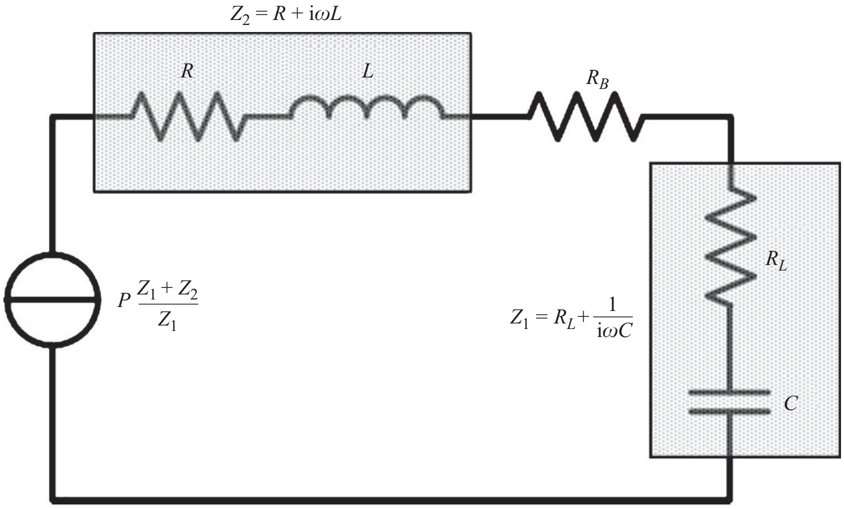

FIGURE 2. Equivalent electric circuit of barrage.

former, which gives this impedance as

$$Z_2 = \frac{-i\rho\omega H_1^{(2)}\{2\sqrt{kx}\}}{bh\sqrt{kx}} \bigg/ \frac{d}{dx}\left(\frac{H_1^{(2)}\{2\sqrt{kx}\}}{\sqrt{kx}}\right) \tag{11}$$

which we can consider as a resistance R in series with an inductance L, giving a combined impedance of $R + i\omega L$. For large x, the wave resembles a tidal wave in open water, for which the impedance is known to be purely a resistance of $\rho c/(bh)$ (Lighthill 1978, p. 104), where c is the open-water wave speed $\sqrt{(gh)}$. This gives a useful cross-check, when (11) is evaluated numerically. In the absence of the barrage, the (complex) volume flow rate at the barrage location is P/Z_1, in an eastward direction. The additional wavemaking volume flow immediately west of the barrage is P'/Z_2, in a westward direction. Thus the total (complex) volume flow rate at this location, in an eastward direction, can be written as follows:

$$\frac{P}{Z_1} - \frac{P'}{Z_2}. \tag{12}$$

If we write the total (complex) pressure at this location as $P'' = P + P'$, then (12) can be rearranged to

$$\frac{P\frac{Z_1+Z_2}{Z_1} - P''}{Z_2}. \tag{13}$$

On the electrical analogy, this is the same current as would be produced by a voltage generator $P(Z_1 + Z_2)/Z_1$ with a source impedance of Z_2. The flow in an eastward direction produced by this voltage generator passes first through the barrage and then into the reservoir beyond it. The impedance seen by the flow is thus the flow resistance of the turbines in the barrage, in series with the reservoir impedance Z_1. The turbines can be taken for simplicity as allowing flow in both directions. This is the most common arrangement (see Baker 1991, p. 31) and also the most efficient, before turbine losses (see Prandle 1984). Also for simplicity, the flow resistance of the turbines can be taken as a constant R_B, because very similar results have been obtained in simpler cases with linear and quadratic turbine characteristics (Garrett & Cummins 2004). Thus the equivalent circuit of the complete system is as shown in figure 2.

When $R_B = 0$, it may be seen that the pressure at the barrage is its undisturbed value P, as it should be.

4. Similarity to wave power

At first sight it may seem curious that to provide the inward power flux needed to power the barrage, we have introduced an additional tidal wave travelling in an *outward* direction. The reason is that from (8) Taylor's standing-wave solution (6) can be seen (by putting $K_1 = K_2 = K$ in (8) and noting that $H_1^{(1)} + H_1^{(2)} = 2J_1$) as the superposition of a tidal wave travelling east and an equal one travelling west. Our additional wave travelling west is cancelling part of his, giving a net inward wave. This situation is familiar in wave power (see for example Mei 1989, § 7.9). Two-dimensional wave power devices likewise need to radiate waves out to sea, to cancel out wave reflections.

5. Power available at various locations in the Severn estuary

We can now calculate the power from the equivalent circuit of figure 2. The argument does not rely on the approximations above, but applies equally if accurate values for Z_1 and Z_2 are available. The (complex) volume flow rate through the barrage is

$$P\frac{Z_1 + Z_2}{Z_1(Z_1 + Z_2 + R_B)}, \tag{14}$$

and thus the average power is

$$\frac{1}{2}|P|^2\left|\frac{Z_1 + Z_2}{Z_1(Z_1 + Z_2 + R_B)}\right|^2 R_B. \tag{15}$$

This is readily calculated as a function of R_B, using expressions (9) and (11) for Z_1 and Z_2. It is given in figure 3 for Taylor's sections A–E of figure 1. The (complex) tidal pressure P in the absence of the barrage is taken as $4\rho g$ at Watchet, or 8 m tidal range, which is the approximate root-mean-square value between the mean spring range of 10 m and the mean neap range of 5 m, and thus gives the annual-average power. The values elsewhere are extrapolated from this 8 m figure, using Taylor's formula (6). Rather than being plotted against R_B, figure 3 is plotted against the pressure difference across the barrage (i.e (14) times R_B), expressed as a fraction of the tidal pressure variation $/P/$ in the absence of the barrage. Evidently the optimum value for this fraction is between 0.4 and 0.6, and the power increases steadily as the barrage is moved west. This is of course to be expected – as we move west, the reservoir area increases much more than the tidal range reduces (see figure 1).

6. Effect of the shape of the estuary west of Taylor's model

Taylor observed that the shape of the Severn estuary changes abruptly west of his outer boundary (section A in figure 2) and ceases to follow his formulae (4), even approximately. The width of the estuary approximately doubles immediately west of section A and thereafter follows another of Taylor's linearly tapering profiles, with both depth and width increasing approximately linearly with distance from a notional apex at Abergavenny, 100 km east of section A. The depth of 36.9 m at section A gives a new value of $\gamma^* = 36.9\,\text{m}/100\,\text{km} = 0.000369$ for γ, and thus a new value $k^* = 0.00547\,\text{km}^{-1}$ for k. We wish to find the effect of this transition to a new profile on the barrage wavemaking impedance Z_2. The effect of the abrupt transition will be to reflect some of the wave travelling west considered in § 3, back up the channel. This reflection will be re-reflected from the barrage and then again from the abrupt transition after section A, in an infinite sequence. We can sum all the waves travelling west into a single wave travelling west between the barrage and Taylor's section A, and we can likewise sum all the waves travelling east into a single wave travelling east in this region. We can write the (complex) volume flow rates in the direction of wave propagation as

- V_O and V_B for the wave travelling west respectively at the outer boundary of the region at section A and at the barrage;
- V'_O and V'_B for the wave travelling east respectively at the outer boundary of the region at section A and at the barrage.

We can first find the ratio of V'_O to V_O, which we can express as a reflection coefficient r, where $V'_O = rV_O$. In the wave travelling west, the impedances at the two locations just considered are given by (11); we can write them as Z_O and Z_B. In the wave travelling east the impedances can be seen from (11) to be the complex conjugates of Z_O and Z_B. (The Hankel function $H_1^{(2)}$ from (8) becomes $H_1^{(1)} = \overline{H_1^{(2)}}$ and the $-$i from (10) becomes $+$i because the acceleration in the direction of wave propagation is now plus the surface slope times g.) In the region west of section A, we have only a wave travelling west, and the impedance is given by (11) with the new parameter k^* instead of k, and with $x = 100\,\mathrm{km}$. We can write this impedance as Z^* The sum of the pressures in the two waves immediately east of the transition at section A can now be equated to that in the single wave immediately west of it. The latter is obtained from the volume flow rate $V_O - V'_O$ in the westward direction:

$$V_O Z_O + V'_O \overline{Z_O} = (V_O - V'_O) Z^*, \text{ i.e. } V'_O = \frac{Z^* - Z_O}{Z^* + \overline{Z_O}} V_O \text{ so that } r = \frac{Z^* - Z_O}{Z^* + \overline{Z_O}}. \tag{16}$$

When $Z^* = Z_O$ there is no reflection from the outer boundary, and (16) accordingly predicts that $V'_O = 0$, as expected. We can now find the required wavemaking impedance Z_2 of the barrage, in terms of the reflection coefficient r given by (16). From (8),

$$\frac{V_B Z_B}{V_O Z_O} = \frac{H_1^{(2)}(2\sqrt{kx_B})/\sqrt{kx_B}}{H_1^{(2)}(2\sqrt{kx_O})/\sqrt{kx_O}} \text{ and } \frac{V'_B \overline{Z_B}}{r V_O \overline{Z_O}} = \frac{H_1^{(1)}(2\sqrt{kx_B})/\sqrt{kx_B}}{H_1^{(1)}(2\sqrt{kx_O})/\sqrt{kx_O}}, \tag{17}$$

where x_O and x_B are the x-coordinates of section A and the barrage. Since $H_1^{(1)} = \overline{H_1^{(2)}}$ the right-hand sides of these two equations are complex conjugates of each other. Thus

$$\overline{\left(\frac{V_B Z_B}{V_O Z_O}\right)} = \frac{V'_B \overline{Z_B}}{r V_O \overline{Z_O}}, \quad \text{i.e.} \quad V'_B = V_B r \frac{V_O \overline{V_B}}{\overline{(V_O \overline{V_B})}} = V_B r \mathrm{e}^{-\mathrm{i}2\omega T}, \tag{18}$$

in which we are noting that the argument of $V_O \overline{V_B}$ is $-\omega T$, where T is the wave transit time between the barrage and section A (readily calculated from (8)). We can thus obtain the wavemaking impedance at the barrage, as the sum of the pressures divided by the sum of the volume flow rates:

$$\frac{V_B Z_B + V_B r \mathrm{e}^{-\mathrm{i}2\omega T} \overline{Z_B}}{V_B - V_B r \mathrm{e}^{-\mathrm{i}2\omega T}} = \frac{Z_B + \overline{Z_B} r \mathrm{e}^{-\mathrm{i}2\omega T}}{1 - r \mathrm{e}^{-\mathrm{i}2\omega T}}. \tag{19}$$

When $r = 0$, there is no reflection at the outer boundary, and (19) then predicts that the wavemaking impedance of the barrage is Z_B, as expected. The barrage powers can be recalculated using this new wavemaking barrage impedance Z_2 – the results are shown in figure 3. Evidently the changed shape of the estuary west of Taylor's original model increases the power considerably, which is to be expected, since the increased width of the estuary will lower Z_2 and thus, from figure 2, increase the power. The closer the barrage to this increased width, the more pronounced the effect. Thus the conclusion remains that the power increases steadily as the barrage is moved west – indeed it now increases more. The question thus arises of the boundary condition even further out, where the second Taylor profile stops abruptly at the western extremities of England and Wales. This transition can be treated exactly like the transition at section A. If the impedance is assumed to halve at this transition, for example, and the calculations are repeated, the maximum powers in figure 3 all increase, by 1 % (barrage at section E) to 11 % (barrage at section A). So again the effect is more pronounced for barrages closer to the transition – it appears that features beyond the United Kingdom are relevant to the barrages furthest down the Severn estuary. This supports the practice in the most recent studies (e.g. Burrows *et al.*, in press) of extending computer models out to the limits of the continental shelf, although the type of boundary conditions applied there are very important. (Recent studies appear to be subject to the criticism that the boundary conditions are zero impedance; see the next section.) The calculations can also be repeated with the delay times t_n in figure 1 set to zero, which will remove natural energy dissipation. This is done in figure 3 and reveals that natural energy dissipation is only of minor importance. Finally, the changes in tidal range produced by the barrage are important. They are readily calculated from the equivalent circuit in figure 2, using the full expression (19) for Z_2, and are shown in figure 4, on the same horizontal axis as figure 3. Taking into account the fact that the power peak in figure 3 is further to the left for section C, the changes to the tidal range are very similar for all barrage locations. With barrages operated at maximum power, the tidal range is cut to 70 % of its former value east of the barrage and 90 % of its former value immediately west of the barrage. A very simple view of the barrage is that (from (9) and (11)) Z_2 is small compared with Z_1 and R_L is small compared with C. From figure 2, the optimum power, as a matter of elementary electrical engineering, is when R_B has the same impedance as C. This is an existing result in the tidal power literature, due to Garrett and Cummins (2004). It would reduce the tidal range east of the barrage by a factor $\sqrt{2}$ and leave the range immediately west of it unaffected because Z_2 is small.

7. Previous computations

The question of the optimum position for a barrage in the Severn estuary, from the power point of view, was studied 30 years ago (see Bondi *et al.* 1981). The power was computed with various finite-difference numerical models, some of which extended out into the Irish Sea. They showed the average power rising strongly from 0.5 to 2.3 GW as the barrage was moved west from Taylor's section F to section D (Bondi *et al.* 1981, vol. 1, p. 18). This is similar to the results in figure 3, allowing for conversion losses. However, very little increase was found for positions further west. By Taylor's section C, the power was starting to decline, in marked contrast to the increase seen in figure 3 – although significant discrepancies were found between computer models (Bondi *et al.* 1981, vol. 2, p. 57). We now explore a possible reason for this decline, which is that all the models simply held the tidal range fixed on the model boundary, at the same value it would have if the were barrage absent. This was then, and apparently still is, the usual assumption in tidal modelling (see e.g. Prandle 1980), although it has been recognized as wrong in principle (Garrett & Greenberg 1977). It

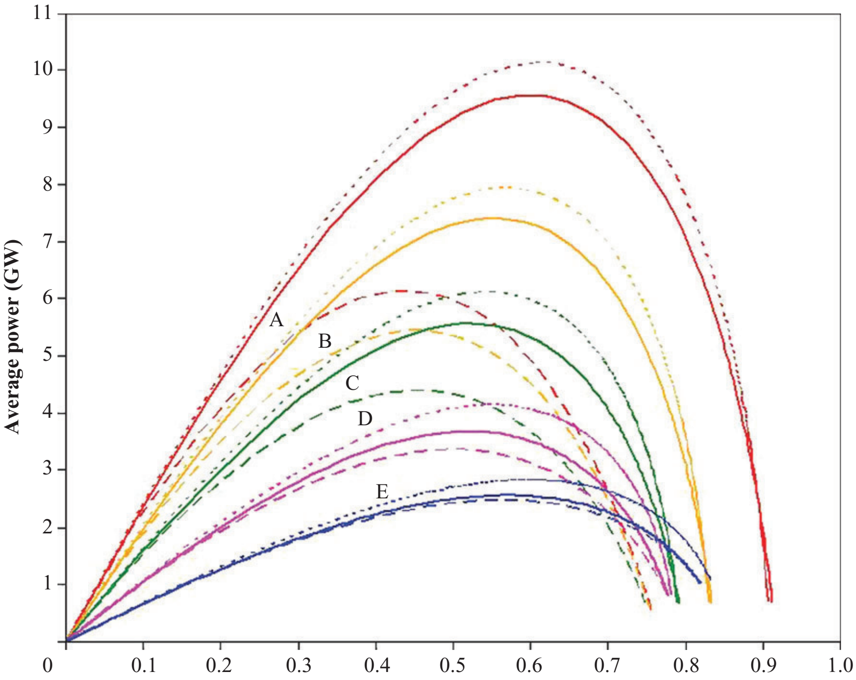

FIGURE 3. Average power (GW) for barrages at locations A–E of figure 1. The horizontal axis is the peak water level difference across the barrage, divided by the tidal amplitude (=range/2) in the absence of the barrage. The solid lines are with the outer estuary model (§ 6) included. The dashed lines are without it. The dotted lines are with it included, but with the delay times t_n in figure 1 set to zero, to remove natural energy losses.

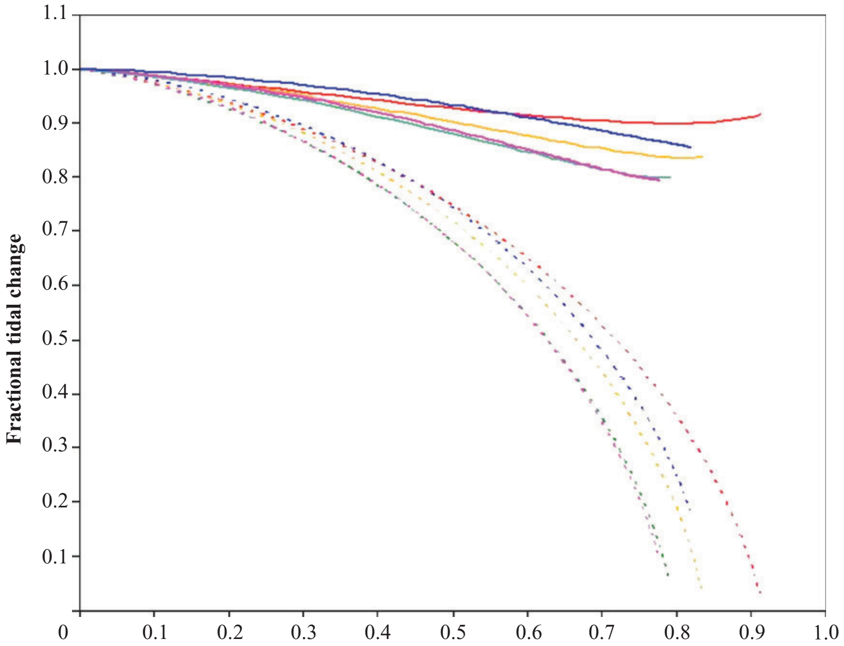

FIGURE 4. Fractional tidal change for barrages at locations A–E of figure 1. The horizontal axis and colour coding are the same as figure 3. The dashed lines are east of the barrage, and the solid lines are just west of it.

will produce a total reflection of the outgoing tidal wave – it is equivalent to setting Z^* in (16) equal to zero. This leads to

$$V_O' = \frac{-Z_O}{\overline{Z_O}} V_O, \quad \text{i.e.} \quad r = \frac{-Z_O}{\overline{Z_O}} = -\mathrm{e}^{\mathrm{i}2\varphi}, \tag{20}$$

where $\varphi = \arg(Z_O)$ is the phase advance of pressure over volume flow rate, in an outward-propagating tidal wave, at the model boundary. For a model boundary at section A, for example, it can be calculated from (8) as 45.3°. If we similarly write $\theta = \arg(Z_B)$, then $Z_B = \zeta \mathrm{e}^{\mathrm{i}\theta}$, where ζ is real and θ is the phase advance of pressure over volume flow rate, in an outward-propagating tidal wave, at the barrage. For a barrage at section E, for example, it can be calculated from (8) as 68.9°. The wavemaking impedance Z_2 of the barrage (19) thus becomes

$$\frac{\zeta \mathrm{e}^{\mathrm{i}\theta} - \zeta \mathrm{e}^{-\mathrm{i}\theta} \mathrm{e}^{\mathrm{i}2\varphi} \mathrm{e}^{-\mathrm{i}2\omega T}}{1 + \mathrm{e}^{\mathrm{i}2\varphi} \mathrm{e}^{-\mathrm{i}2\omega T}} = \frac{\zeta \mathrm{e}^{\mathrm{i}(\pi - \theta + 2\varphi - 2\omega T)} + \zeta \mathrm{e}^{\mathrm{i}\theta}}{\mathrm{e}^{\mathrm{i}(2\varphi - 2\omega T)} + 1}. \tag{21}$$

Since $\mathrm{e}^{\mathrm{i}X} + \mathrm{e}^{\mathrm{i}\psi} = \{\mathrm{e}^{\mathrm{i}(X-\psi)/2} + \mathrm{e}^{-\mathrm{i}(X-\psi)/2}\}\mathrm{e}^{\mathrm{i}(X+\psi)/2} = 2\cos\{(X - \psi)/2\}\mathrm{e}^{\mathrm{i}(X+\psi)/2}$ this impedance can be written as

$$\frac{\zeta \cos\{\pi/2 + (\varphi - \theta - \omega T)\}\mathrm{e}^{\mathrm{i}(\pi/2 + \varphi - \omega T)}}{\cos(\varphi - \omega T)\mathrm{e}^{\mathrm{i}(\varphi - \omega T)}} = \mathrm{i}\zeta \frac{\sin(\omega T + \theta - \varphi)}{\cos(\omega T - \varphi)}. \tag{22}$$

Thus the wavemaking impedance at the barrage is purely imaginary (i.e. reactive), as we would expect – the barrage can radiate no wave power because the waves it sends west are perfectly reflected back by the model boundary. Its amplitude is small if the model boundary is close to the barrage because then θ and φ are nearly equal, and the phase delay ωT of a tidal wave between the barrage and the model boundary is then also small. Thus the change in the results will be small because Z_2 is small anyway, as noted at the end of the previous section. However, when the model boundary is a long way from the barrage, φ will be small because the tidal wave at the model boundary will resemble an open-water wave. Thus when the phase delay ωT reaches 90°, the denominator in (22) will drop to zero, and the wavemaking impedance of the barrage will become very large. The power from the barrage will accordingly drop. This condition requires the transit time T of a tidal wave between the barrage and the model boundary to be a quarter of the tidal period, or $12.4/4 = 3.1$ h. This is a resonant condition, with the natural sloshing period of the basin between the barrage and the outer boundary equal to the tidal period. With a mean tidal wave speed of $25\,\mathrm{m\,s^{-1}}$, say, it corresponds to a distance from the barrage to the outer boundary of $25 \times 3600 \times 4 = 360$ km. This is comparable with the size of the larger models used by Bondi *et al.* (1981). It is thus possible that the models used by Bondi *et al.* (1981) were giving spurious results due to internal resonances, caused by the incorrect model boundary condition, in which the tidal range was held at the same value it would have if the barrage were absent. The appropriate boundary condition is an 'absorbing' one, which does not reflect waves – these are standard in naval architecture and familiar in physical model testing too, as the beach in a wave tank.

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Appendix B - Linear Modelling Calculations

Repeat of calcs in JFM paper, with switched/pumped turbine plus reservoir represented by resistive loads of various sizes (i.e. the barrage-reservoir combination is assumed to be purely resistive). Upstream tidal range is then calculated from flow rate and reservoir capacity. Both power and downstream tidal range are plotted as a function of upstream tidal range. - RCTR, 22nd Feb 10. First read in data from table.

data :=

	0	1	2	3	4	5
0	1	114.3	36.9	40.6	800	0
1	2	92.1	28.7	37.7	585	2
2	3	77.83	24.4	30	695	2
3	4	46.33	16.3	22.7	383	6
4	5	28.72	16.3	13.2	220	14
5	6	14.82	9.5	15.2	166	19
6	7	1·10-4	5.3	7.8	113	29
7	8	1·10-4	0	0	0	53

Now convert to JFM notation, using "offshore" units (metre, tonne, sec)

$n := 1 .. 8$

$x_n := 1000 \cdot data_{n-1,1}$ $\quad h_n := data_{n-1,2}$ $\quad b_n := 1000 \cdot data_{n-1,3}$

$S_n := 1000 \cdot 1000 \cdot data_{n-1,4}$ $\quad t_n := 60 \cdot data_{n-1,5}$

$$x = \begin{pmatrix} 0 \\ 1.143 \times 10^5 \\ 9.21 \times 10^4 \\ 7.783 \times 10^4 \\ 4.633 \times 10^4 \\ 2.872 \times 10^4 \\ 1.482 \times 10^4 \\ 0.1 \\ 0.1 \end{pmatrix} \quad h = \begin{pmatrix} 0 \\ 36.9 \\ 28.7 \\ 24.4 \\ 16.3 \\ 16.3 \\ 9.5 \\ 5.3 \\ 0 \end{pmatrix} \quad b = \begin{pmatrix} 0 \\ 4.06 \times 10^4 \\ 3.77 \times 10^4 \\ 3 \times 10^4 \\ 2.27 \times 10^4 \\ 1.32 \times 10^4 \\ 1.52 \times 10^4 \\ 7.8 \times 10^3 \\ 0 \end{pmatrix} \quad S = \begin{pmatrix} 0 \\ 8 \times 10^8 \\ 5.85 \times 10^8 \\ 6.95 \times 10^8 \\ 3.83 \times 10^8 \\ 2.2 \times 10^8 \\ 1.66 \times 10^8 \\ 1.13 \times 10^8 \\ 0 \end{pmatrix} \quad t = \begin{pmatrix} 0 \\ 0 \\ 120 \\ 120 \\ 360 \\ 840 \\ 1.14 \times 10^3 \\ 1.74 \times 10^3 \\ 3.18 \times 10^3 \end{pmatrix}$$

Input other constants

$\rho := 1.025$ $\quad g := 9.81$ $\quad \omega := \dfrac{2 \cdot \pi}{12.4 \cdot 3600}$ $\quad k := \dfrac{0.00655}{1000}$

Calculate tidal range at Taylor's locations. Assume plus and minus 4m at Taylor's location D (Watchet), and scale others from JFM formula:

$$\eta_0 = \frac{KJ_1\{2\sqrt{kx}\}}{\sqrt{kx}}$$

$$a_n := \frac{4\cdot\left(k\cdot x_4\right)^{0.5}\cdot J1\left[2\cdot\left(k\cdot x_n\right)^{0.5}\right]}{\left(k\cdot x_n\right)^{0.5}\cdot J1\left[2\cdot\left(k\cdot x_4\right)^{0.5}\right]}$$

$$a = \begin{pmatrix} 0 \\ 3.13 \\ 3.399 \\ 3.58 \\ 4 \\ 4.248 \\ 4.451 \\ 4.674 \\ 4.674 \end{pmatrix}$$

Now calculate Z1 from the JFM formula

$$Z_1 = \frac{\dfrac{\rho g J_1\{2\sqrt{kx_n}\}}{\sqrt{kx_n}}}{\sum_{j=n}^{j=7}\left[\dfrac{J_1\{2\sqrt{k(x_j+x_{j+1})/2}\}}{\sqrt{k(x_j+x_{j+1})/2}}S_j i\omega e^{-i\omega\{(t_j+t_{j+1})/2-t_n\}}\right]}$$

$$nn := 1..5$$

$$Z1_{nn} := \frac{\rho\cdot g\cdot\dfrac{J1\left[2\cdot\left(k\cdot x_{nn}\right)^{0.5}\right]}{\left(k\cdot x_{nn}\right)^{0.5}}}{\displaystyle\sum_{j=nn}^{7}\left[\frac{J1\left[2\cdot\left[\dfrac{k\cdot\left(x_j+x_{j+1}\right)}{2}\right]^{0.5}\right]}{\left[\dfrac{k\cdot\left(x_j+x_{j+1}\right)}{2}\right]^{0.5}}\cdot S_j\cdot i\cdot\omega\cdot e^{-i\cdot\omega\cdot\left(\frac{t_j+t_{j+1}}{2}-t_{nn}\right)}\right]}$$

$$Z1 = \begin{pmatrix} 0 \\ 1.357\times10^{-6}-2.016i\times10^{-5} \\ 1.963\times10^{-6}-2.863i\times10^{-5} \\ 3.583\times10^{-6}-3.964i\times10^{-5} \\ 8.018\times10^{-6}-7.464i\times10^{-5} \\ 1.236\times10^{-5}-1.352i\times10^{-4} \end{pmatrix}$$

Calculate loss angles

$$\mathrm{ang}_{nn} := \frac{180}{\pi}\cdot\arg\left(Z1_{nn}\right) \qquad \mathrm{ang} = \begin{pmatrix} 0 \\ -86.149 \\ -86.079 \\ -84.834 \\ -83.869 \\ -84.776 \end{pmatrix} \qquad \mathrm{loss}_{nn} := 90 + \mathrm{ang}_{nn} \qquad \mathrm{loss} = \begin{pmatrix} 0 \\ 3.851 \\ 3.921 \\ 5.166 \\ 6.131 \\ 5.224 \end{pmatrix}$$

Now calculate Z2 from the JFM formula:

$$Z_2 = \frac{-i\rho\omega H_1^{(2)}\{2\sqrt{kx}\}}{bh\sqrt{kx}} \Bigg/ \frac{d}{dx}\left(\frac{H_1^{(2)}\{2\sqrt{kx}\}}{\sqrt{kx}}\right)$$

$$f(y) := \frac{d}{dy}\frac{\mathrm{H2}\left[1, 2\cdot(k\cdot y)^{0.5}\right]}{(k\cdot y)^{0.5}}$$

$$Z2_{nn} := \frac{\dfrac{-i\cdot\rho\cdot\omega\cdot\mathrm{H2}\left[1, 2\cdot\left(k\cdot x_{nn}\right)^{0.5}\right]}{b_{nn}\cdot h_{nn}\cdot\left(k\cdot x_{nn}\right)^{0.5}}}{f\left(x_{nn}\right)} \qquad Z2 = \begin{pmatrix} 0 \\ 6.953\times10^{-6} + 7.025i\times10^{-6} \\ 7.61\times10^{-6} + 8.809i\times10^{-6} \\ 9.235\times10^{-6} + 1.192i\times10^{-5} \\ 9.206\times10^{-6} + 1.688i\times10^{-5} \\ 7.63\times10^{-6} + 1.98i\times10^{-5} \end{pmatrix}$$

Cross-check at large x. See JFM paper. If we put in a large value of x, say 1000,000 km, and remove ρ/bh, the Z2 should be the wave speed c. Doing this:

$$\frac{\dfrac{-i\cdot\omega\cdot\mathrm{H2}\left[1, 2\cdot(k\cdot1000\cdot1000\cdot1000)^{0.5}\right]}{(k\cdot1000\cdot1000\cdot1000)^{0.5}}}{f(1000\cdot1000\cdot1000)} = 1.739\times10^{3} + 16.116i$$

For the speed c = root(gh) we need the depth h, which is 1000,000 km times $\gamma = \omega$^2/kg

$$\left(1000\cdot1000\cdot1000\cdot\frac{\omega^2}{k}\right)^{0.5} = 1.739\times10^{3}$$

Now input a range of barrier resistances:

$$jj := 0\,..\,2000$$

$$RB_{jj} := \frac{jj}{2000\cdot 1000}$$

Calculate the power for each, using the JFM formula, but with no Z1 in the expression in brackets in the denominator, since RB now represents barrage-reservoir combination:

$$\frac{1}{2}|P|^2\left|\frac{Z_1+Z_2}{Z_1(Z_1+Z_2+R_B)}\right|^2 R_B$$

Answer will be in kW, so divide by 1,000,000 for GW.

$$P_{nn,\,jj} := \frac{\left(\rho\cdot g\cdot a_{nn}\right)^2}{2\cdot 1000\cdot 1000}\cdot\left[\mathrm{Re}\left[\frac{Z1_{nn}+Z2_{nn}}{Z1_{nn}\cdot\left(Z2_{nn}+RB_{jj}\right)}\right]^2+\mathrm{Im}\left[\frac{Z1_{nn}+Z2_{nn}}{Z1_{nn}\cdot\left(Z2_{nn}+RB_{jj}\right)}\right]^2\right]\cdot RB_{jj}$$

P =

	0	1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0	0	0
1	0	1.397	2.602	3.638	4.525	5.281	5.923	6.465	6.922
2	0	1.199	2.265	3.21	4.045	4.779	5.422	5.984	6.473
3	0	0.805	1.546	2.224	2.844	3.409	3.923	4.388	4.81
4	0	0.688	1.34	1.957	2.54	3.089	3.605	4.088	4.54
5	0	0.741	1.455	2.142	2.801	3.431	4.033	4.606	5.15

Also calculate upstream tidal range, as a fraction of the undisturbed tidal range. Again no Z1 in the expression in brackets in the denominator, since RB now represents barrage-reservoir combination. And Z1 replaces RB in the numerator:

$$F_{nn,\,jj} := \left[\mathrm{Re}\left[\frac{\left(Z1_{nn}+Z2_{nn}\right)\cdot Z1_{nn}}{Z1_{nn}\cdot\left(Z2_{nn}+RB_{jj}\right)}\right]^2+\mathrm{Im}\left[\frac{\left(Z1_{nn}+Z2_{nn}\right)\cdot Z1_{nn}}{Z1_{nn}\cdot\left(Z2_{nn}+RB_{jj}\right)}\right]^2\right]^{0.5}$$

F =

	0	1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0	0	0
1	1.573	1.518	1.465	1.414	1.366	1.32	1.276	1.234	1.195	1.157
2	1.891	1.839	1.787	1.737	1.689	1.642	1.597	1.553	1.511	1.47
3	2.025	1.984	1.944	1.904	1.864	1.826	1.788	1.751	1.715	1.679
4	3.135	3.095	3.055	3.015	2.975	2.934	2.893	2.853	2.812	2.772
5	5.521	5.473	5.423	5.373	5.32	5.267	5.213	5.157	5.101	5.045

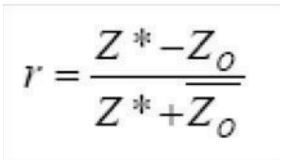
Now add model of estuary west of Taylor's section A (Ilfracombe-Gower):

$$ko := \frac{\omega^2}{\left(\frac{h_1}{100\cdot 1000}\right)\cdot g} \qquad ko = 5.473\times 10^{-6} \qquad xo := 1000\cdot 100$$

$$fo(y) := \frac{d}{dy}\frac{H2\left[1,2\cdot(ko\cdot y)^{0.5}\right]}{(ko\cdot y)^{0.5}}$$

$$Z2o := \frac{\dfrac{-i\cdot\rho\cdot\omega\cdot H2\left[1,2\cdot(ko\cdot xo)^{0.5}\right]}{2\cdot b_1\cdot h_1\cdot(ko\cdot xo)^{0.5}}}{fo(xo)} \qquad Z2o = 2.939\times 10^{-6} + 3.622i\times 10^{-6}$$

Calculate reflection coefficient from JFM formula:



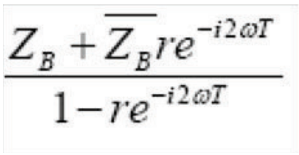
$$r = \frac{Z^* - Z_O}{Z^* + \overline{Z_O}}$$

$$r := \frac{Z2o - Z2_1}{Z2o + \overline{Z2_1}} \qquad r = -0.257 - 0.433i$$

Calculate time-delays between Sections

$$td_{nn} := \frac{1}{\omega}\cdot\left[\arg\left[H2\left[1,2\cdot\left(k\cdot x_{nn}\right)^{0.5}\right]\right] - \arg\left[H2\left[1,2\cdot\left(k\cdot x_1\right)^{0.5}\right]\right]\right] \qquad td = \begin{pmatrix} 0 \\ 0 \\ 1.129\times 10^{3} \\ 1.913\times 10^{3} \\ 3.877\times 10^{3} \\ 5.186\times 10^{3} \end{pmatrix}$$

Calculate revised Z2 from JFM formula:



$$\frac{Z_B + \overline{Z_B}re^{-i2\omega T}}{1 - re^{-i2\omega T}}$$

$$Z2R_{nn} := \frac{Z2_{nn} + \overline{Z2_{nn}}\cdot r\cdot e^{-i\cdot 2\cdot\omega\cdot td_{nn}}}{1 - r\cdot e^{-i\cdot 2\cdot\omega\cdot td_{nn}}} \qquad Z2R = \begin{pmatrix} 0 \\ 2.939\times 10^{-6} + 3.622i\times 10^{-6} \\ 2.825\times 10^{-6} + 6.307i\times 10^{-6} \\ 3.226\times 10^{-6} + 9.849i\times 10^{-6} \\ 3.045\times 10^{-6} + 1.711i\times 10^{-5} \\ 2.626\times 10^{-6} + 2.126i\times 10^{-5} \end{pmatrix}$$

Now re-calculate the power. Again no Z1 in the expression in brackets in the denominator, since RB now represents barrage-reservoir combination::

$$Q_{nn,jj} := \frac{(\rho\cdot g\cdot a_{nn})^2}{2\cdot 1000\cdot 1000}\cdot\left[\mathrm{Re}\left[\frac{Z1_{nn}+Z2R_{nn}}{Z1_{nn}\cdot\left(Z2R_{nn}+RB_{jj}\right)}\right]^2+\mathrm{Im}\left[\frac{Z1_{nn}+Z2R_{nn}}{Z1_{nn}\cdot\left(Z2R_{nn}+RB_{jj}\right)}\right]^2\right]\cdot RB_{jj}$$

Q =

	0	1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0	0	0
1	0	7.1	12.37	16.187	18.884	20.737	21.958	22.713	23.123
2	0	3.636	6.794	9.482	11.725	13.565	15.046	16.218	17.123
3	0	1.722	3.325	4.8	6.143	7.355	8.438	9.396	10.236
4	0	0.806	1.593	2.357	3.095	3.805	4.486	5.136	5.753
5	0	0.708	1.405	2.091	2.762	3.417	4.055	4.674	5.273

Also re-calculate upstream tidal range, as a fraction of the undisturbed tidal range. Again no Z1 in the expression in brackets in the denominator, since RB now represents barrage-reservoir combination. And Z1 replaces RB in the numerator:

$$G_{nn,jj} := \left[\mathrm{Re}\left[\frac{\left(Z1_{nn}+Z2R_{nn}\right)\cdot Z1_{nn}}{Z1_{nn}\cdot\left(Z2R_{nn}+RB_{jj}\right)}\right]^2+\mathrm{Im}\left[\frac{\left(Z1_{nn}+Z2R_{nn}\right)\cdot Z1_{nn}}{Z1_{nn}\cdot\left(Z2R_{nn}+RB_{jj}\right)}\right]^2\right]^{0.5}$$

G =

	0	1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0	0	0
1	3.664	3.422	3.194	2.983	2.79	2.615	2.457	2.313	2.183	2.065
2	3.304	3.202	3.095	2.986	2.875	2.766	2.66	2.556	2.457	2.362
3	2.948	2.901	2.851	2.797	2.74	2.682	2.622	2.562	2.501	2.441
4	3.37	3.352	3.331	3.308	3.283	3.256	3.228	3.197	3.165	3.132
5	5.366	5.349	5.33	5.308	5.283	5.256	5.227	5.195	5.162	5.126

Add effect of outer-outer boundary (Cornwall-Pembroke):

First define outer-outer boundary 150 km from Abergavenny

$$xoo := 1000\cdot 150$$

Now define Z2 there. Breadth is 1.5x2xb1 and depth 1.5xh1

$$Z2oo := \frac{\dfrac{-i\cdot\rho\cdot\omega\cdot H2\left[1,2\cdot(ko\cdot xoo)^{0.5}\right]}{1.5\cdot 2\cdot b_1\cdot 1.5\cdot h_1\cdot(ko\cdot xoo)^{0.5}}}{fo(xoo)} \qquad Z2oo = 2.033\times 10^{-6}+1.94i\times 10^{-6}$$

We now repeat the previous scheme of calculation, i.e.

(i) Calculate reflection coefficient at outer-outer boundary (Cornwall-Pembroke)

(ii) Hence revise impedance at outer boundary (Taylor Section A)

(iii) Hence revise reflection coeficient at outer boundary

(iv) Hence re-revise impedance at barrage

(v) Hence re-revise power

Taking these steps in turn……

(i) Calculate outer-outer reflection coefficient from JFM formula. Assume impedance halves there:

$$r=\frac{Z^*-Z_O}{Z^*+\overline{Z_O}}$$

$$\mathrm{roo} := \frac{\frac{\mathrm{Z2oo}}{2}-\mathrm{Z2oo}}{\frac{\mathrm{Z2oo}}{2}+\overline{\mathrm{Z2oo}}} \qquad \mathrm{roo} = -0.211-0.385i$$

Calculate time-delays between Section A and outer-outer boundary:

$$\mathrm{tdo} := \frac{1}{\omega}\cdot\left[\arg\left[\mathrm{H2}\left[1,2\cdot(\mathrm{ko}\cdot\mathrm{xo})^{0.5}\right]\right]-\arg\left[\mathrm{H2}\left[1,2\cdot(\mathrm{ko}\cdot\mathrm{xoo})^{0.5}\right]\right]\right] \qquad \mathrm{tdo} = 2.119\times10^{3}$$

(ii) Calculate revised Z2o from JFM formula:

$$\frac{Z_B+\overline{Z_B}re^{-i2\omega T}}{1-re^{-i2\omega T}}$$

$$\mathrm{Z2oR} := \frac{\mathrm{Z2o}+\overline{\mathrm{Z2o}}\cdot\mathrm{roo}\cdot e^{-i\cdot2\cdot\omega\cdot\mathrm{tdo}}}{1-\mathrm{roo}\cdot e^{-i\cdot2\cdot\omega\cdot\mathrm{tdo}}} \qquad \mathrm{Z2oR} = 1.201\times10^{-6}+3.025i\times10^{-6}$$

(iii) Hence revise reflection coefficient r at Section A, using same JFM formula:

$$r = \frac{Z^{*} - Z_{O}}{Z^{*} + \overline{Z_{O}}}$$

$$rr := \frac{Z2oR - Z2_{1}}{Z2oR + \overline{Z2_{1}}} \qquad rr = -0.375 - 0.674i$$

(iv) Hence re-revise Z2 from previous JFM formula:

$$\frac{Z_{B} + \overline{Z_{B}}\, r e^{-i2\omega T}}{1 - r e^{-i2\omega T}}$$

$$Z2RR_{nn} := \frac{Z2_{nn} + \overline{Z2_{nn}} \cdot rr \cdot e^{-i \cdot 2 \cdot \omega \cdot td_{nn}}}{1 - rr \cdot e^{-i \cdot 2 \cdot \omega \cdot td_{nn}}} \qquad Z2RR = \begin{pmatrix} 0 \\ 1.201 \times 10^{-6} + 3.025i \times 10^{-6} \\ 1.13 \times 10^{-6} + 5.888i \times 10^{-6} \\ 1.277 \times 10^{-6} + 9.48i \times 10^{-6} \\ 1.189 \times 10^{-6} + 1.701i \times 10^{-5} \\ 1.024 \times 10^{-6} + 2.131i \times 10^{-5} \end{pmatrix}$$

(v) Now re-re-calculate the power. Again no Z1 in the expression in brackets in the denominator, since RB now represents barrage-reservoir combination:

$$QR_{nn,jj} := \frac{\left(\rho \cdot g \cdot a_{nn}\right)^{2}}{2 \cdot 1000 \cdot 1000} \cdot \left[\mathrm{Re}\left[\frac{Z1_{nn} + Z2RR_{nn}}{Z1_{nn} \cdot \left(Z2RR_{nn} + RB_{jj}\right)}\right]^{2} + \mathrm{Im}\left[\frac{Z1_{nn} + Z2RR_{nn}}{Z1_{nn} \cdot \left(Z2RR_{nn} + RB_{jj}\right)}\right]^{2} \right] \cdot RB_{jj}$$

QR =

	0	1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0	0	0
1	0	15.11	26.008	33.198	37.53	39.827	40.747	40.767	40.22
2	0	5.006	9.531	13.479	16.808	19.526	21.673	23.311	24.51
3	0	2.051	4.015	5.866	7.586	9.161	10.584	11.853	12.967
4	0	0.837	1.663	2.474	3.267	4.037	4.782	5.5	6.187
5	0	0.713	1.421	2.121	2.812	3.49	4.154	4.803	5.434

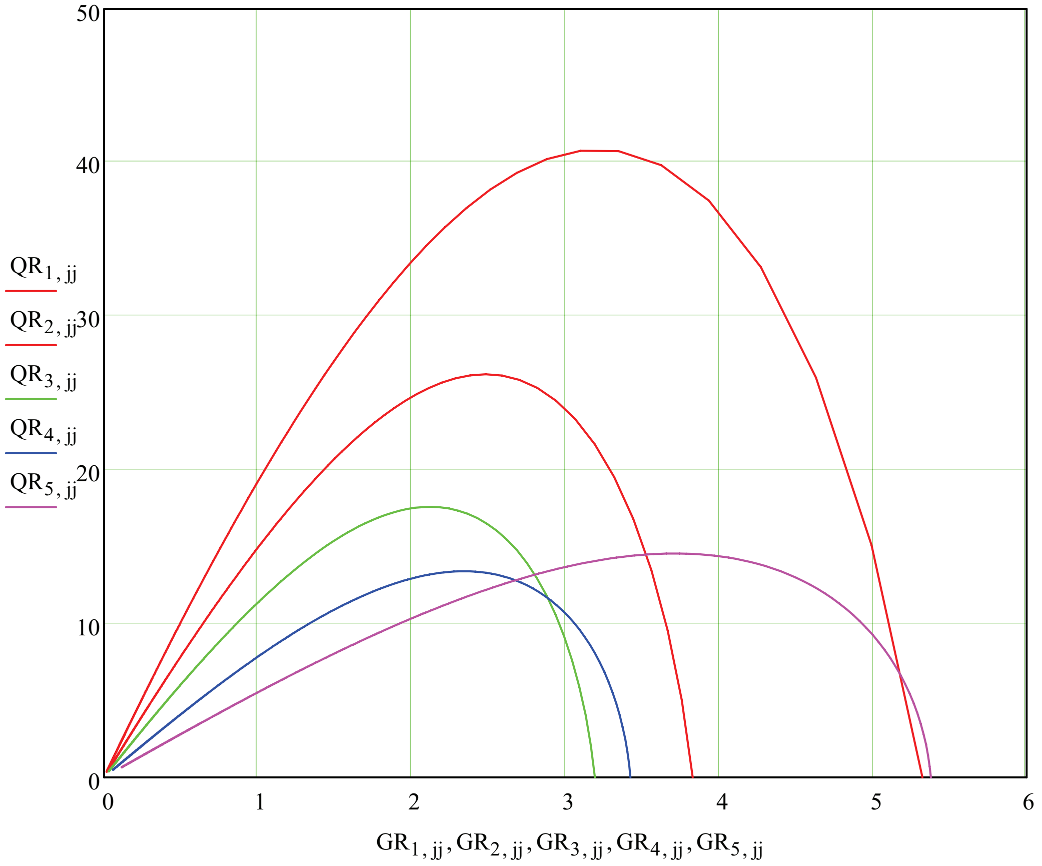
Also re-calculate upstream tidal range, as a fraction of the undisturbed tidal range. Again no Z1 in the expression in brackets in the denominator, since RB now represents barrage-reservoir combination. And Z1 replaces RB in the numerator:

$$GR_{nn,jj} := \left[\mathrm{Re}\left[\frac{\left(Z1_{nn} + Z2RR_{nn}\right)\cdot Z1_{nn}}{Z1_{nn}\cdot\left(Z2RR_{nn} + RB_{jj}\right)}\right]^2 + \mathrm{Im}\left[\frac{\left(Z1_{nn} + Z2RR_{nn}\right)\cdot Z1_{nn}}{Z1_{nn}\cdot\left(Z2RR_{nn} + RB_{jj}\right)}\right]^2 \right]^{0.5}$$

GR =

	0	1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0	0	0
1	5.323	4.992	4.631	4.272	3.933	3.624	3.346	3.099	2.879	2.684
2	3.829	3.757	3.666	3.56	3.443	3.319	3.192	3.065	2.94	2.818
3	3.193	3.167	3.133	3.092	3.045	2.993	2.937	2.877	2.815	2.751
4	3.424	3.415	3.404	3.39	3.373	3.354	3.332	3.309	3.283	3.255
5	5.378	5.37	5.36	5.346	5.33	5.312	5.29	5.266	5.24	5.212

Now plot revised power:

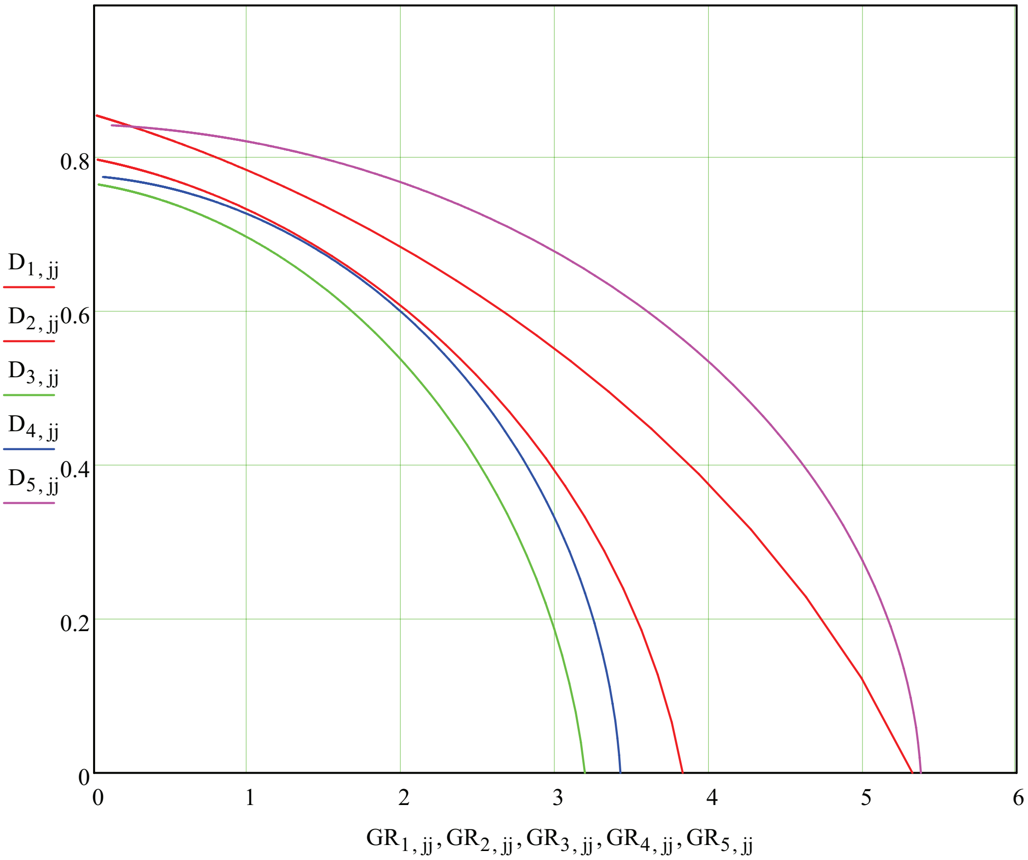


Effect on tides

Tide downstream of the barrage, as a proportion of undisturbed tide is:

$$D_{nn,jj} := \left[\mathrm{Re}\left[\frac{\left(Z1_{nn} + Z2RR_{nn}\right)\cdot RB_{jj}}{Z1_{nn}\cdot\left(Z2RR_{nn} + RB_{jj}\right)} \right]^2 + \mathrm{Im}\left[\frac{\left(Z1_{nn} + Z2RR_{nn}\right)\cdot RB_{jj}}{Z1_{nn}\cdot\left(Z2RR_{nn} + RB_{jj}\right)} \right]^2 \right]^{0.5}$$

Plot these out:

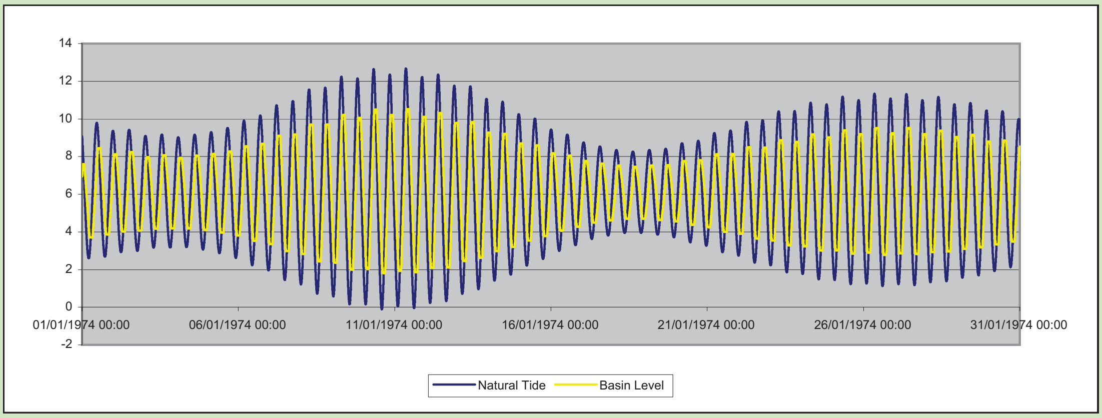


Appendix C - Flat Estuary Model Output

20% reduction in tidal input - no pumping

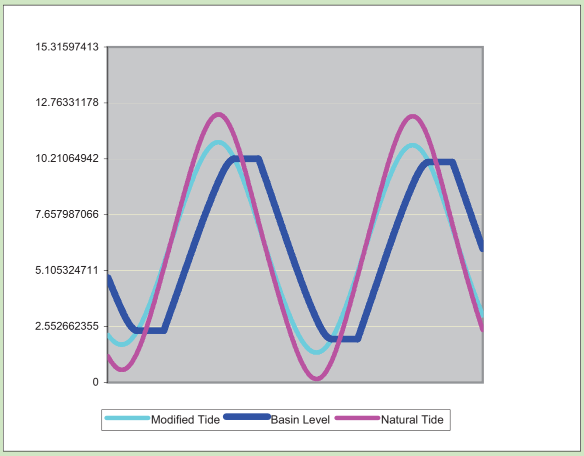
Main Parametres		
ebb or dual	dual	
Basin Size in km2	504	
Variable volume	no	
Turbines Characteristics		
Turbine No 1 dia	14	m
Turbine No2 dia	9	m
No of turbines No 1	165	
No of turbines No 2	900	
Rated Capacity Turbine 1	10.5	MW
Rated Capacity Turbine 2	4.5	MW
Draft Tube Exist Area No 1	196	
Draft Tube exit area No 2	81	
Total exit area	105240	m2
Total turbine area	105240	m2
Maximum rated capacity	5783	
Total number of turbines	1065	
High water holding head	3	
Low water sluicing	no	
2-way generation		
low water holding head	3	
high water filling	0	hr
Control		
Turbine flow adjustment	yes	
Adjustment factor	0.97	
Pumping		
direct pumping	no	
reverse pumping	no	
head above hw	0	
head below lw	0	
Pump head	1	m
Open Sluice Caissons		
Sluice Width	1	
Sill level	1	
No of sluices	0	
low water ebb sluice	0	hr
Venturi Sluice Caissons		
Sluice Area	0	
No of Sluices	0	
Cd Value	1.8	

Tidal Prediction			
Start Date		01/01/1974 00:00	
End Date		31/12/1974 23:58	
Duration		8759.97	hrs
M2	Reduced by 20%	3.10	
S2	Reduced by 20%	1.1	
Energy Output			
Max Head		3.1	
Max Output		8026	MW
Total Output in TWh		1.555	
Peak Generator Efficiency		97.5%	
Transformer Eff		99%	
Availability		95%	
Resonance reduction		100%	
Total Output TWh		1.4255	
Scale to year (approx)		11.7583	
Adjust factor ave year		1	
Total TWh		16.761	
Averaged Water Levels			
Low water level basin		3.37	mCD
Low water level tides		2.03	mCD
High water level basin		8.81	mCD
High water level sea		10.31	mCD
% loss of range in basin (ave)		34.4%	
% loss of peak tidal range		31.8%	
& loss of range to sea		20%	
Entry/Exit Head Loss			
Max exit head loss		0.390	m
Efficiency			
E=		16.8	GWh
Emax (4pgA^2S)		38.2	GWh
E/Emax=		0.44	
Habitat Loss for Peak Spring Tide			
Area lost at high tide		832	ha
Area lost at low tide		7991	ha
Area outside 20% of 9000		1800	ha
Total		10623	ha



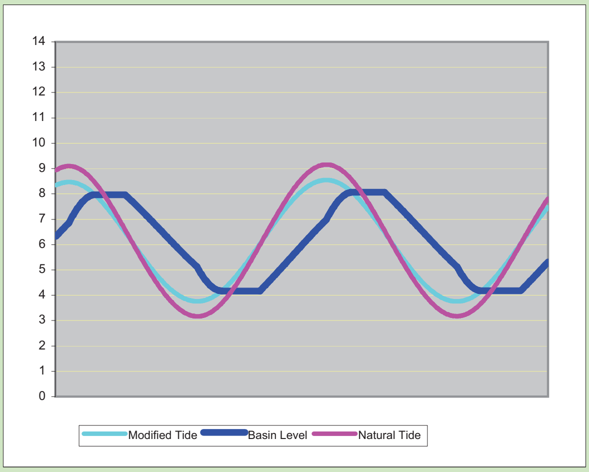
Spring-Neap Tidal Elevations for Natural Tide and Basin

20% reduction in tidal input - no pumping



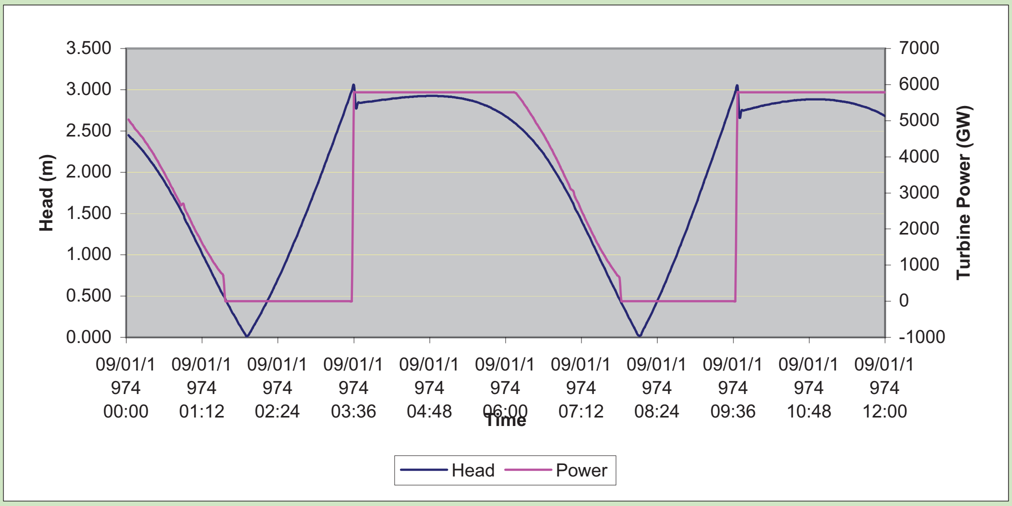
Mean Spring Tide
Power Output Uncapped

Max Head	3.1	m
Max Power Ebb	8021	MW
Max Power Flood	7945	MW
Ebb energy	20786	MWh
Flood energy	20606	MWh
pump on hw	0	MWh
pump on lw	0	MWh
Total	41392	



Mean Neap Tide
Power Output Uncapped

Max head	2.1	m
Max Power Ebb	4554	MW
Max Power Flood	3998	MW
Ebb energy	6464	MWh
Flood energy	7616	MWh
pump on hw	0	MWh
pump on lw	0	MWh
Total	14080	

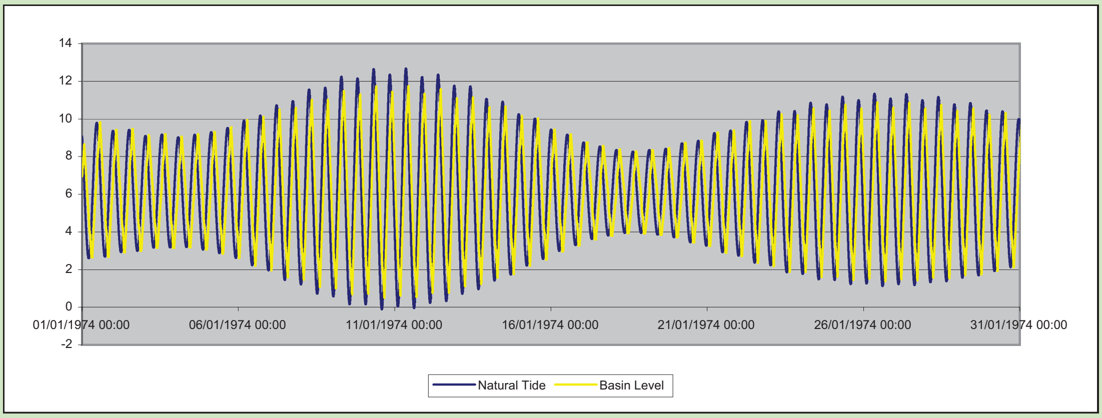


Turbine Power Output for a Spring Tide

20% reduction in tidal input - with pumping

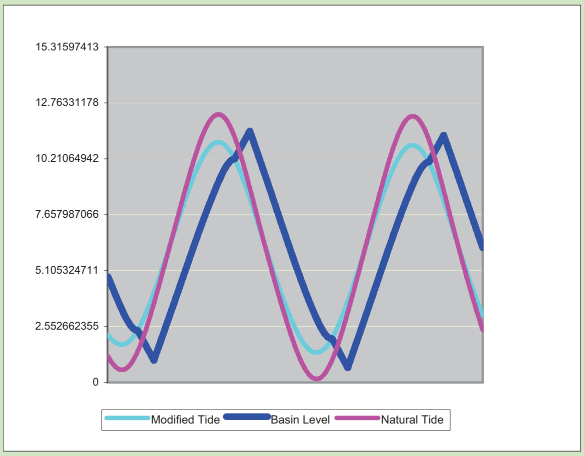
Main Parametres		
ebb or dual	dual	
Basin Size in km2	504	
Variable volume	no	
Turbines Characteristics		
Turbine No 1 dia	14	m
Turbine No2 dia	9	m
No of turbines No 1	165	
No of turbines No 2	900	
Rated Capacity Turbine 1	10.5	MW
Rated Capacity Turbine 2	4.5	MW
Draft Tube Exist Area No 1	196	
Draft Tube exit area No 2	81	
Total exit area	105240	m2
Total turbine area	105240	m2
Maximum rated capacity	5783	
Total number of turbines	1065	
High water holding head	3	
Low water sluicing	no	
2-way generation		
low water holding head	3	
high water filling	0	hr
Control		
Turbine flow adjustment	yes	
Adjustment factor	0.97	
Pumping		
direct pumping	yes	
reverse pumping	yes	
head above hw	0	
head below lw	0	
Pump head	1	m
Open Sluice Caissons		
Sluice Width	1	
Sill level	1	
No of sluices	0	
low water ebb sluice	0	hr
Venturi Sluice Caissons		
Sluice Area	0	
No of Sluices	0	
Cd Value	1.8	

Tidal Prediction			
Start Date		01/01/1974 00:00	
End Date		31/12/1974 23:58	
Duration		8759.97	hrs
M2	Reduced by 20%	3.10	
S2	Reduced by 20%	1.1	
Energy Output			
Max Head		3.0	
Max Output		7908	MW
Total Output in TWh		1.933	
Peak Generator Efficiency		97.5%	
Transformer Eff		99%	
Availability		95%	
Resonance reduction		100%	
Total Output TWh		1.7730	
Scale to year (approx)		11.7583	
Adjust factor ave year		1	
Total TWh		20.847	
Averaged Water Levels			
Low water level basin		2.15	mCD
Low water level tides		2.03	mCD
High water level basin		10.04	mCD
High water level sea		10.31	mCD
% loss of range in basin (ave)		4.9%	
% loss of peak tidal range		11.9%	
& loss of range to sea		20%	
Entry/Exit Head Loss			
Max exit head loss		0.375	m
Efficiency			
E=		20.8	GWh
Emax (4pgA^2S)		38.2	GWh
E/Emax=		0.55	
Habitat Loss for Peak Spring Tide			
Area lost at high tide		832	ha
Area lost at low tide		2616	ha
Area outside 20% of 9000		1800	ha
Total		5248	ha



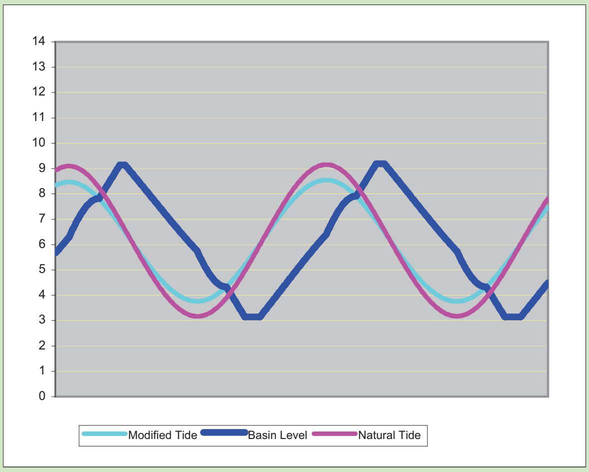
Spring-Neap Tidal Elevations for Natural Tide and Basin

20% reduction in tidal input - with pumping



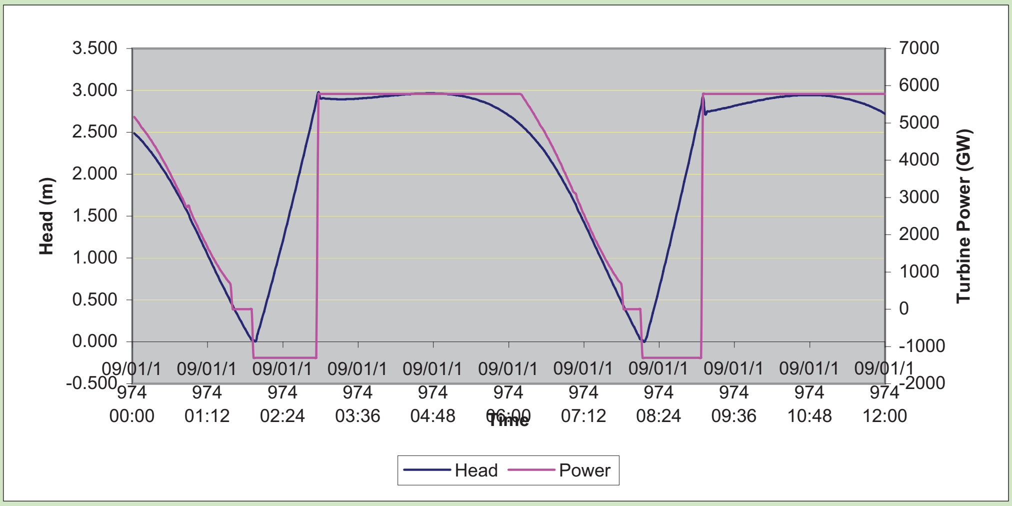
Mean Spring Tide
Power Output Uncapped

Max Head	3.0	m
Max Power Ebb	7656	MW
Max Power Flood	7518	MW
Ebb energy	24207	MWh
Flood energy	24294	MWh
pump on hw	-1261	MWh
pump on lw	-1305	MWh
Total	45934	



Mean Neap Tide
Power Output Uncapped

Max head	2.9	m
Max Power Ebb	7422	MW
Max Power Flood	6892	MW
Ebb energy	12099	MWh
Flood energy	12794	MWh
pump on hw	-1305	MWh
pump on lw	-1174	MWh
Total	22414	

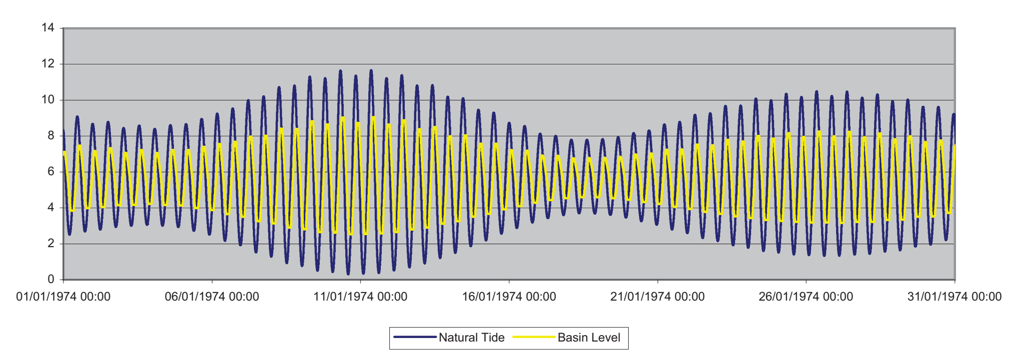


Turbine Power Output for a Spring Tide

30% reduction in tidal input - no pumping

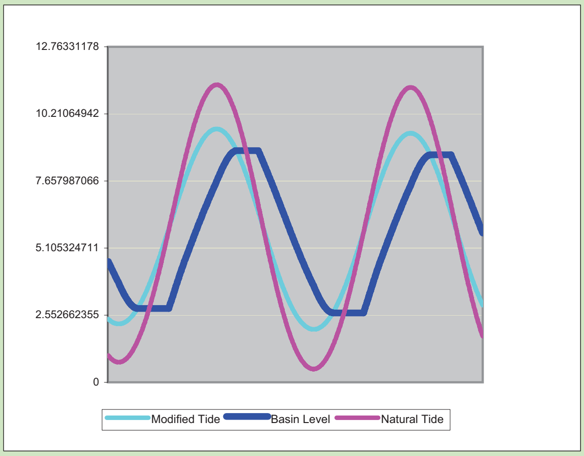
Main Parametres		
ebb or dual	dual	
Basin Size in km2	1,060	
Variable volume	no	
Turbines Characteristics		
Turbine No 1 dia	14	m
Turbine No2 dia	9	m
No of turbines No 1	800	
No of turbines No 2	352	
Rated Capacity Turbine 1	10.5	MW
Rated Capacity Turbine 2	4.5	MW
Draft Tube Exist Area No 1	196	
Draft Tube exit area No 2	81	
Total exit area	185312	m2
Total turbine area	185312	m2
Maximum rated capacity	9984	
Total number of turbines	1152	
High water holding head	3	
Low water sluicing	no	
2-way generation		
low water holding head	3	
high water filling	0	hr
Control		
Turbine flow adjustment	yes	
Adjustment factor	0.97	
Pumping		
direct pumping	no	
reverse pumping	no	
head above hw	0	
head below lw	0	
Pump head	1	m
Open Sluice Caissons		
Sluice Width	1	
Sill level	1	
No of sluices	0	
low water ebb sluice	0	hr
Venturi Sluice Caissons		
Sluice Area	0	
No of Sluices	0	
Cd Value	1.8	

Tidal Prediction			
Start Date		01/01/1974 00:00	
End Date		31/12/1974 23:58	
Duration		8759.97	hrs
M2	Reduced by 30%	2.51	
S2	Reduced by 30%	0.87	
Energy Output			
Max Head		3.1	
Max Output		13657	MW
Total Output in TWh		2.232	
Peak Generator Efficiency		97.5%	
Transformer Eff		99%	
Availability		95%	
Resonance reduction		100%	
Total Output TWh		2.0469	
Scale to year (approx)		11.7583	
Adjust factor ave year		1	
Total TWh		24.068	
Averaged Water Levels			
Low water level basin		3.59	mCD
Low water level tides		2.05	mCD
High water level basin		7.72	mCD
High water level sea		9.58	mCD
% loss of range in basin (ave)		45.1%	
% loss of peak tidal range		40%	
& loss of range to sea		30%	
Entry/Exit Head Loss			
Max exit head loss		0.166	m
Efficiency			
E=		24.1	GWh
Emax (4pgA^2S)		52.6	GWh
E/Emax=		0.46	
Habitat Loss for Peak Spring Tide			
Loss inside = 31,500ha x 0.4		12600	ha
Loss outside allow		500	ha
Total		13100	ha



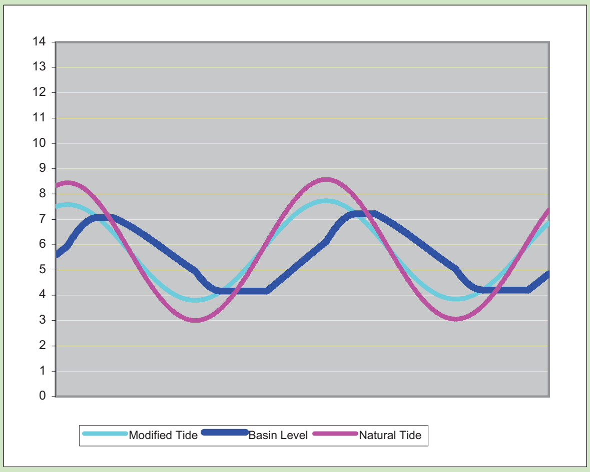
Spring-Neap Tidal Elevations for Natural Tide and Basin

30% reduction in tidal input -no pumping



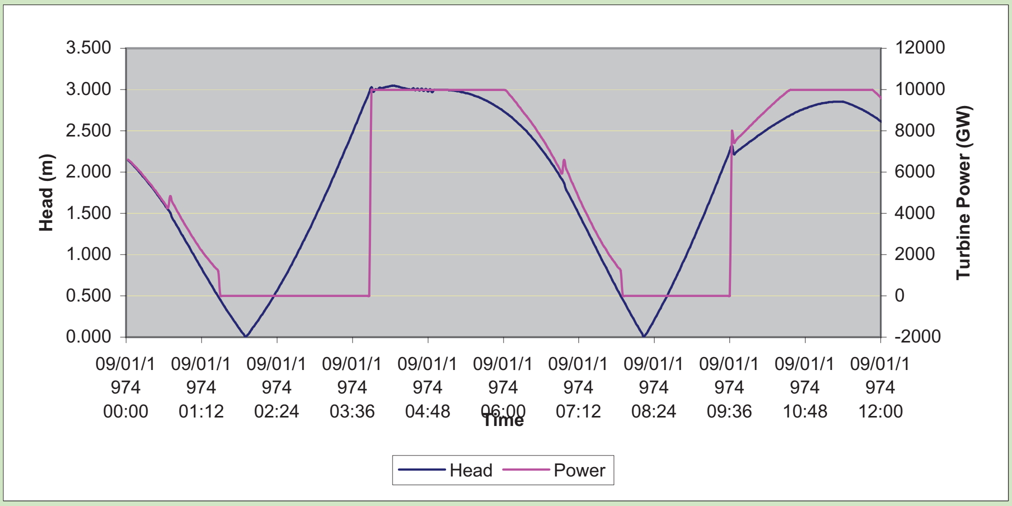
Mean Spring Tide
Power Output Uncapped

Max Head	3.1	m
Max Power Ebb	14211	MW
Max Power Flood	12584	MW
Ebb energy	33543	MWh
Flood energy	32024	MWh
pump on hw	0	MWh
pump on lw	0	MWh
Total	65567	



Mean Neap Tide
Power Output Uncapped

Max head	2.1	m
Max Power Ebb	7685	MW
Max Power Flood	5103	MW
Ebb energy	8030	MWh
Flood energy	11815	MWh
pump on hw	0	MWh
pump on lw	0	MWh
Total	19845	



Turbine Power Output for a Spring Tide

30% reduction in tidal input - with pumping

Main Parametres

ebb or dual	dual	
Basin Size in km2	1,060	
Variable volume	no	

Turbines Characteristics

Turbine No 1 dia	14	m
Turbine No2 dia	9	m
No of turbines No 1	800	
No of turbines No 2	352	
Rated Capacity Turbine 1	10.5	MW
Rated Capacity Turbine 2	4.5	MW
Draft Tube Exist Area No 1	196	
Draft Tube exit area No 2	81	
Total exit area	185312	m2
Total turbine area	185312	m2
Maximum rated capacity	9984	
Total number of turbines	1152	
High water holding head	3	
Low water sluicing	no	

2-way generation

low water holding head	3	
high water filling	0	hr

Control

Turbine flow adjustment	yes
Adjustment factor	0.97

Pumping

direct pumping	yes	
reverse pumping	yes	
head above hw	0	
head below lw	0	
Pump head	1	m

Open Sluice Caissons

Sluice Width	1	
Sill level	1	
No of sluices	0	
low water ebb sluice	0	hr

Venturi Sluice Caissons

Sluice Area	0
No of Sluices	0
Cd Value	1.8

Tidal Prediction

Start Date		01/01/1974 00:00	
End Date		31/12/1974 23:58	
Duration		8759.97	hrs
M2	Reduced by 30%	2.51	
S2	Reduced by 30%	0.87	

Energy Output

Max Head	3.2	
Max Output	14991	MW
Total Output in TWh	2.819	
Peak Generator Efficiency	97.5%	
Transformer Eff	99%	
Availability	95%	
Resonance reduction	100%	
Total Output TWh	2.5848	
Scale to year (approx)	11.7583	
Adjust factor ave year	1	
Total TWh	**30.393**	

Averaged Water Levels

Low water level basin	2.35	mCD
Low water level tides	2.05	mCD
High water level basin	8.56	mCD
High water level sea	9.58	mCD
% loss of range in basin (ave)	17.5%	
% loss of peak tidal range	20%	
& loss of range to sea	30%	

Entry/Exit Head Loss

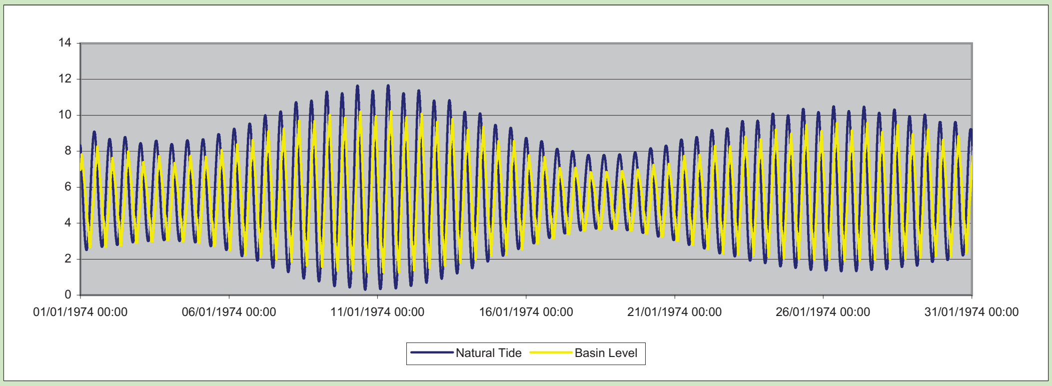
Max exit head loss	0.233	m

Efficiency

E=	30.4	GWh
Emax (4pgA^2S)	52.6	GWh
E/Emax=	0.58	

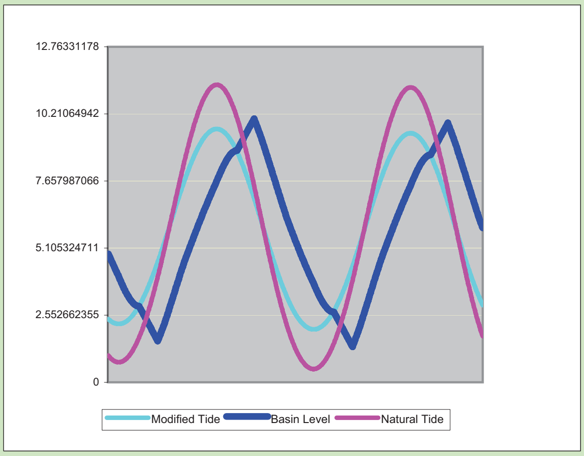
Habitat Loss for Peak Spring Tide

Loss inside = 31,500ha x 0.4	6300	ha
Loss outside allow	500	ha
Total	6800	ha



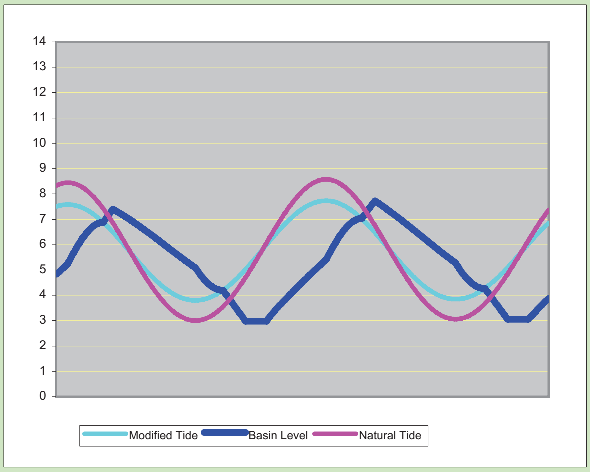
Spring-Neap Tidal Elevations for Natural Tide and Basin

30% reduction in tidal input - with pumping



Mean Spring Tide
Power Output Uncapped

Max Head	3.1	m
Max Power Ebb	14749	MW
Max Power Flood	14377	MW
Ebb energy	38289	MWh
Flood energy	39031	MWh
pump on hw	-2528	MWh
pump on lw	-2757	MWh
Total	72035	



Mean Neap Tide
Power Output Uncapped

Max head	3.0	m
Max Power Ebb	13794	MW
Max Power Flood	6631	MW
Ebb energy	9849	MWh
Flood energy	22086	MWh
pump on hw	-1072	MWh
pump on lw	-2528	MWh
Total	28335	

Turbine Power Output for a Spring Tide

Appendix D - Cost Estimates

Cardiff Weston VLH Barrage			
PRE-CONSTRUCTION COSTS	**Unit Cost (£)**	**Quantity (m3)**	**Cost (£m)**
TOTAL PRE-CONSTRUCTION COST	-	-	**209**
CONSTRUCTION COSTS	**Unit Cost (£/m3)**	**Quantity (m3)**	**Cost (£m)**
Preliminaries and site overheads	-	-	866
Caissons	215	19,000	4,085
Embankments	145,000	4,170	605
Navigation locks	-	-	1002
Surface buildings	-	-	83
TOTAL CONSTRUCTION COST			**6641**
MECHANICAL AND ELECTRICAL COSTS	**Unit Cost (£m)**	**Quantity**	**Cost (£m)**
Generating Equipment (per MW)	0.85	5783	4916
Grid Connection	-	-	500
Gates	-	-	1544
TOTAL MECHANICAL AND ELECTRICAL COST			**6959**
ADDITIONAL ITEMS	**Unit Cost (£m)**	**Quantity**	**Cost (£m)**
Design and Supervision (includes outline and detailed design and construction supervision)	-	-	205
Site investigation (during outline and detailed design and construction)	-	-	4
Ancillaries	-	-	300
Contingencies	-	-	1098
Contractor's Oncosts and Profit	-	-	677
TOTAL for Additional Items			**2284**
TOTAL CONSTRUCTION COST			**16093**
Compensatory Habitats (based on 2:1 ratio)	10496	0.065	682
Promotional costs	-	-	80
TOTAL OVERALL COST			**16856**

Minehead Aberthaw Construction Cost Estimate

PRE-CONSTRUCTION COSTS	**Unit Cost (£)**	**Quantity (m3)**	**Cost (£m)**
TOTAL PRE-CONSTRUCTION COST	-	-	**418**
CONSTRUCTION COSTS	**Unit Cost (£/m3)**	**Quantity (m3)**	**Cost (£m)**
Preliminaries and site overheads	-	-	1337
Caissons	215	33,600,000	7,224
Embankments	131,000	2,380	605
Navigation locks	-	-	1002
Surface buildings	-	-	83
TOTAL CONSTRUCTION COST			**10251**
MECHANICAL AND ELECTRICAL COSTS	**Unit Cost (£m)**	**Quantity**	**Cost (£m)**
Generating Equipment (per MW)	0.85	9984	8486
Grid Connection	-	-	1000
Gates	-	-	1661
TOTAL MECHANICAL AND ELECTRICAL COST			**11147**
ADDITIONAL ITEMS	**Unit Cost (£m)**	**Quantity**	**Cost (£m)**
Design and Supervision (includes outline and detailed design and construction supervision)	-	-	272
Site investigation (during outline and detailed design and construction)	-	-	4
Ancillaries	-	-	600
Contingencies	-	-	1586
Contractor's Oncosts and Profit	-	-	978
TOTAL for Additional Items			**3441**
TOTAL CONSTRUCTION COST			**25257**
Compensatory Habitats (based on 2:1 ratio)	13600	0.065	884
Promotional costs	-	-	126
TOTAL OVERALL COST			**26267**