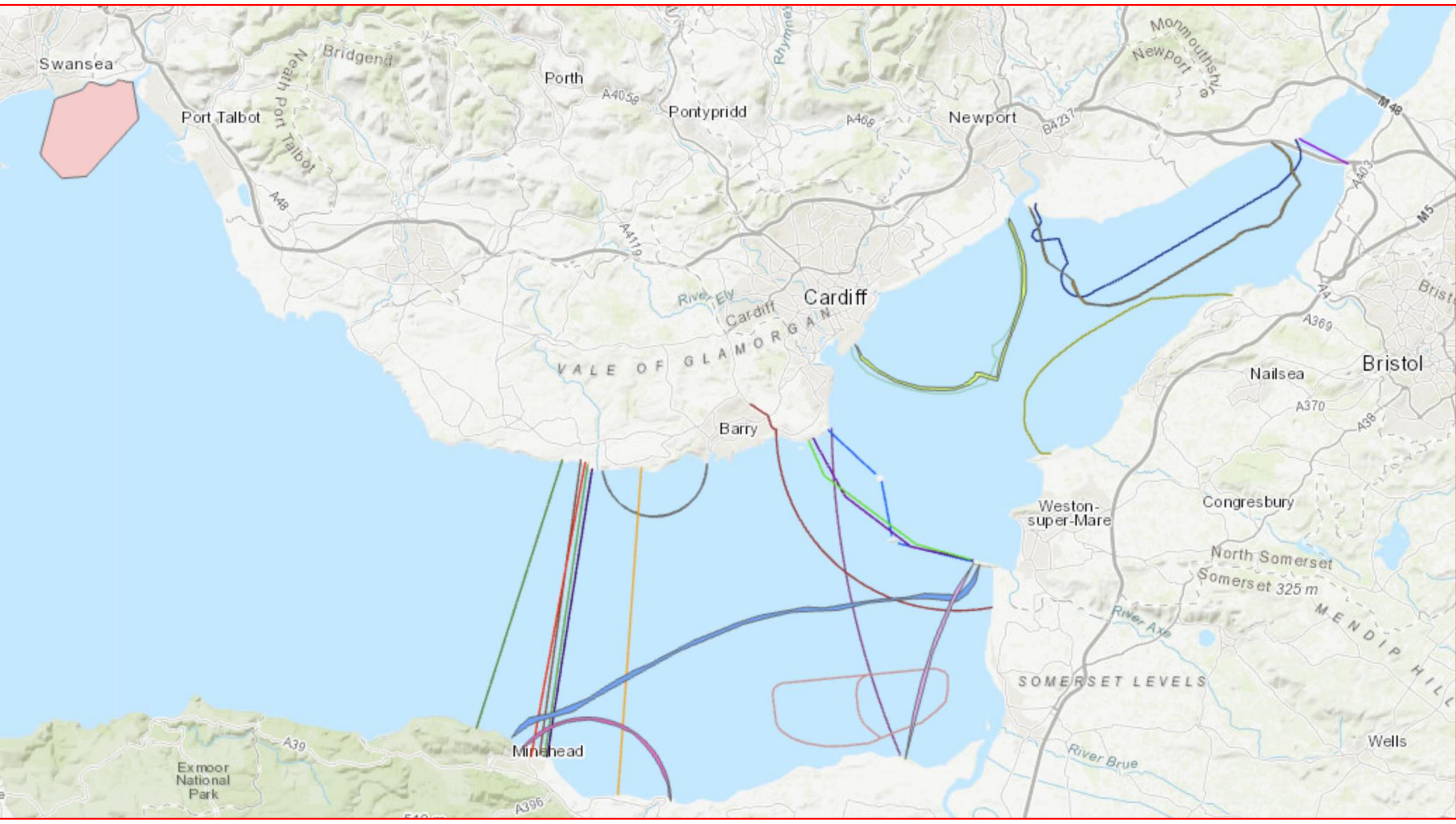
Western Gateway

SUSTAINABLE ENERGY IN THE SEVERN ESTUARY

Summary of Engineering Considerations



FEBRUARY 2025

Western Gateway

SUSTAINABLE ENERGY IN THE SEVERN ESTUARY

Summary of Engineering Considerations

PUBLIC

PROJECT NO. 70109278

DATE: FEBRUARY 2025

WSP

Kings Orchard
1 Queen Street
Bristol
BS2 0HQ

Phone: +44 117 930 6200

WSP.com

CONTENTS

EXECUTIVE SUMMARY

Engineering and Construction

The Nature of Tides

Coastal areas experience two high and two low tides every 24 hours and 50 minutes. High tides occur 12 hours and 25 minutes apart. The highest tides, spring tides, occur twice each lunar month all year long, without regard to the season. The lowest tides, neap tides, occur 7 days after a spring tide.

Which Technology?

Tidal energy is energy abstracted from the rise and fall in the tides (tidal range) or from the currents that flow as the tide changes (tidal stream). It is available for between 12 and 16 hours every day of the year.

Tidal stream technologies, see Figure 1, rely on the tidal currents to generate power. The power generated is a function of the cube of the current. High current locations are therefore needed for commercial tidal stream projects. The Severn Estuary is characterised by relatively low currents, for example 2.7 m/s versus 3.9 m/s in the Pentland Firth. A tidal stream project in the Estuary would therefore generate only 45% of an equivalent project in the Pentland Firth. Tidal stream is not considered any further in this study.

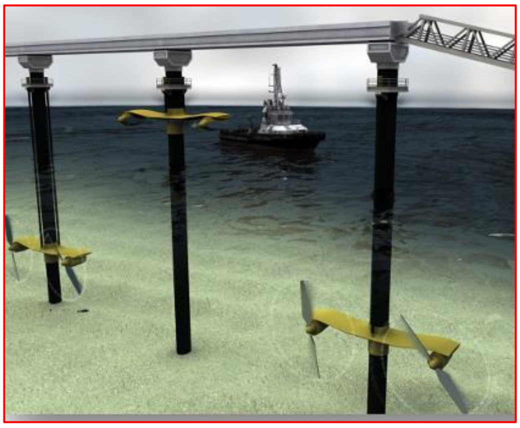


Figure 1 *– Tidal stream devices in a tidal fence (source SETS)*

The Severn Estuary has the largest tidal range in the UK and power can be generated using either a barrage crossing the Estuary or tidal lagoons constructed along one shoreline. Both impound water as the tide comes in and then release it through a classical "bulb turbine", see Figure 2, which generates the power. Some projects generate both as the tide comes in and goes out. As water level in the impounding basin is changed, there is some loss of inter-tidal habitat within the impounded area.

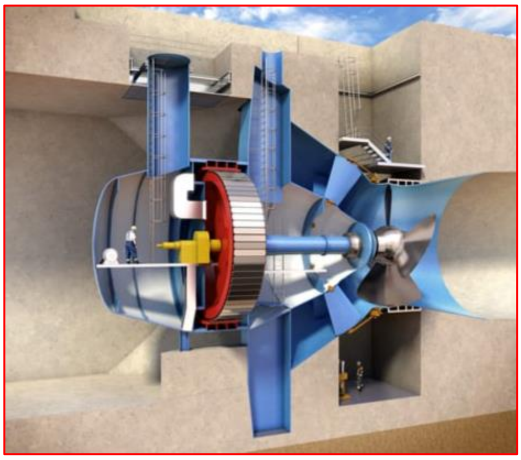


Figure 2 *– Bulb turbine cut away as proposed by GE-Andritz.*

It is possible to construct a lagoon that does not connect with the land which has the advantage that no inter-tidal habitat is lost, but it is significantly more expensive. The volume of materials required for an offshore lagoon is more than double that of a land-connected lagoon for the same energy output.

What is required to construct a tidal range project?

Any tidal range project involves the construction of a marine wall. The marine wall extends above the high-water mark and can be constructed using a rock protected sand/gravel embankment or using caissons. A caisson is a large rectangular concrete structure that can be constructed remotely and towed into position.

The marine wall incorporates one or more “power houses”. These are rectangular concrete structures that house the turbines and control equipment including sluice gates to control operation and associated water levels. The turbines include a generator housed within the bulb. The electricity generated is transmitted by buried cable to a sub-station where it is connected to the national grid.

Special care is required in the construction of the reinforced concrete structures due to the saline environment. Cathodic protection can be used to reduce the risk of corrosion of the steel reinforcement in the structures. The zone most at risk is where frequent wetting and drying occurs as the tide rises and falls. Since the aim is to generate low-carbon electricity, the carbon used in construction is important. Modern concrete technology continues to innovate and there are now lower carbon sources of concrete available, as well as improved durability high strength mixes. The carbon used to build a tidal range project when expressed per unit of energy produced is very similar to that used in an offshore wind farm. Both are rated at between 4 and 12 g/kWh measured over the project’s life. This is much lower than a fossil fuelled generation station.

The marine wall itself has to be designed and constructed to minimise seepage and to take account of future sea level rise over its anticipated operating life. The wall acts as the impounding structure allowing water within the impounded basin to be stored at a different level to the sea. Figure 3 shows a typical arrangement of a tidal range power plant.

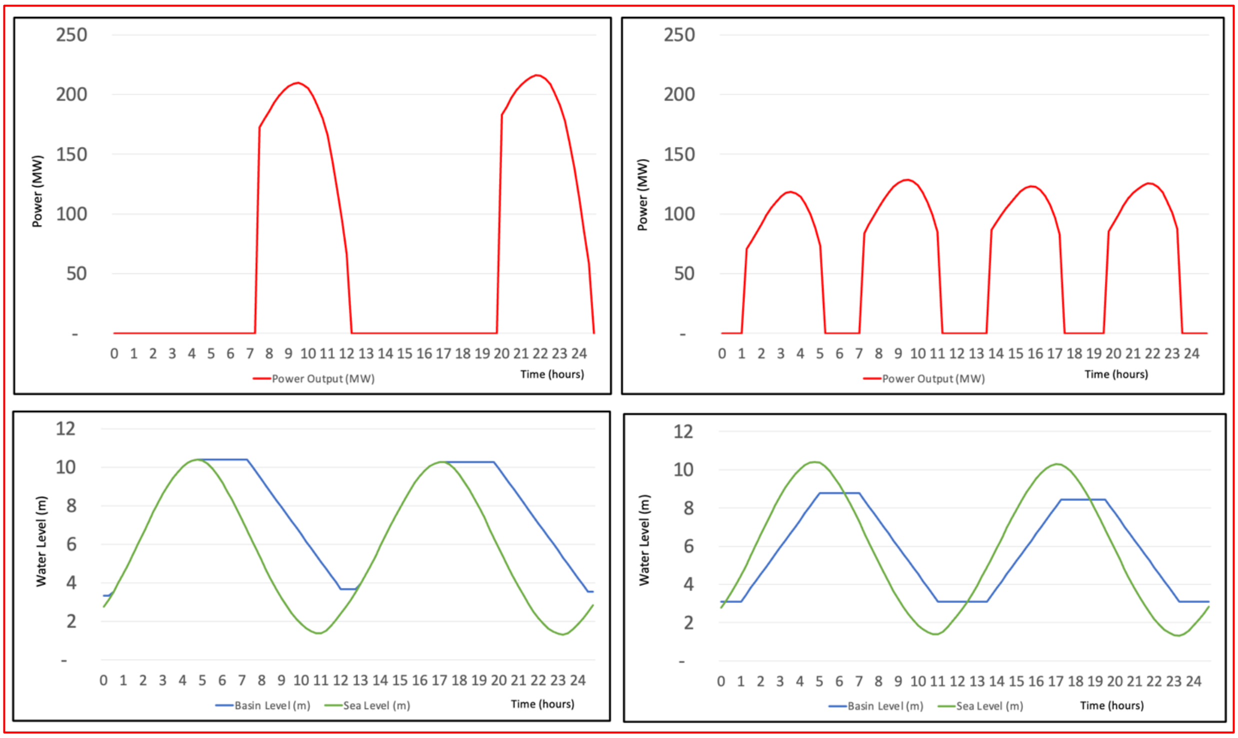
Figure 3 *Typical tidal power project, with navigation lock, © WSP*

The engineering for the civil, electrical and mechanical elements has been practised for many decades on water supply reservoirs and pumping stations, hydro-electric power plants and ports and harbours.

How does it operate?

When the tide is going out it is known as an ebb tide, when it is coming in it is a flood tide. There are two basic forms of operation as shown in Figure 4.

Ebb only – the flood tide passes through sluices to fill the impounding basin and, after the tide turns and a suitable head has developed, water passes from the basin through the turbines to the sea. This form of operation results in two phases of generation, each lasting six hours, every day.
Ebb and Flood – water passes through the turbines during both flood and ebb tides. This results in four phases of generation, each lasting four hours or so, every day. The peak power output is lower than for ebb only generation and more turbines are required to produce the same energy output.



(a)Ebb only b) Ebb and flood

Figure 4 *- Water level variations during a 24-hour period*

These modes of generation can be supplemented by pumping and sluicing to increase generation heads and increase water exchange between the basin and the sea respectively.

Cost Considerations

The various projects that have, historically, been proposed in the Severn Estuary are shown in Figure 5.

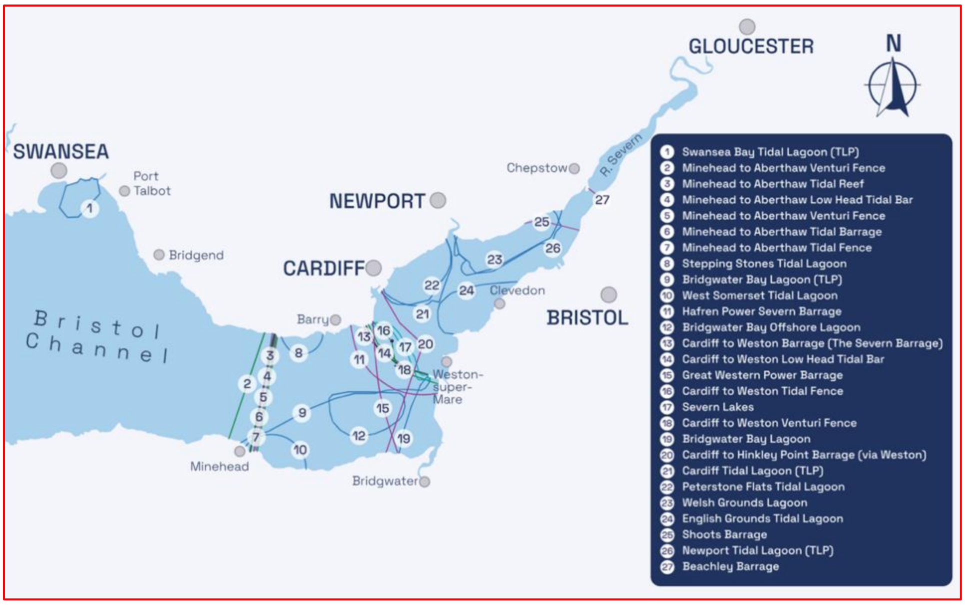


Figure 5 *- Projects that have been proposed in the Severn Estuary*

The Commission chose six of these projects, listed in Table 1, as examples to illustrate the various aspects of the study. It is stressed that the Commission is not recommending these projects, they are merely examples that have the benefit of some previous investigation. The example projects are listed below with reference to Figure 5.

No	Project	Construction Cost £bn (2021 prices)	Installed capacity. (GW)	Annual Output (GWh/y)
13	Large Barrage (Cardiff Weston)	33.4	8.64	16,700
25	Small Barrage (Shoots Barrage)	6.8	1.05	2,800
21	Large Lagoon 1 (Cardiff)	12.3	2.0	5,500
10	Large Lagoon 2 (West Somerset)	10.9	2.5	6,500
8	Medium Lagoon (Stepping Stones)	2.3	0.6	1,200
1	Small Lagoon (Swansea Bay)	1.8	0.32	520

Table 1 *– Example projects used in the study.*

The cost estimates for the two barrage examples are based on the independent and conservative cost estimates produced for the Severn Tidal Power Feasibility Study. The lagoon examples use the data published by their proposers. All cost estimates have been inflated to a 2023/4 baseline. Until definitive designs are produced, cost estimates should be treated as indicative.

The construction cost is divided approximately as 65 - 70% for civil works and ancillaries (including environmental, port, land drainage and environmental mitigation measures and compensatory habitat provision) and 30-35% for mechanical and electrical costs, including grid connection. In addition, client costs are incurred for project management and delivery partner roles in supervising contractors and interface management.

Other costs include development activities from conceptual design to securing the necessary consents and contractor bids. This cost would be expected to lie within a range of £30m to over £200m over a 5-to-8-year period for the six example projects considered here.

Annual operating costs are relatively low compared to other power projects and represent approximately 1% per year of the total construction cost. They will include a sinking fund to cover post-operation activities such as decommissioning and replacement of components when they reach the end of their life.

Frequently asked questions

What advantages does tidal range power have over other renewable technologies?

Like wind and solar, tidal range is variable and low-carbon but, unlike them it is entirely predictable. It uses large spinning generators which can help stabilise the grid's frequency and are able to generate at short notice to meet unanticipated peaks in demand. It has a similar whole-life carbon footprint to offshore wind.

A tidal power plant uses the same mechanical and electrical equipment as used in a hydro-electric power plant. The civil works, with their marine location, are similar to those adopted at ports and harbours, sea defences and nuclear power station water cooling and discharge works. It is therefore proven technology that has existed for many decades.

In the Severn Estuary, projects will be located close to centres of electricity demand with the benefit of shorter transmission links compared with, say, offshore wind farms.

Are there any innovations that could reduce environmental impact?

A UK programme[1] was run in 2009 to identify and analyse potential new technologies that could be used to generate tidal range power whilst reducing impacts on the environment, specifically reduction of potential fish mortality and reduction in inter-tidal habitat loss. The projects were technically feasible, but each proved uneconomic or impracticable for the Severn Estuary. The Welsh Government is undertaking a research programme called the Tidal Lagoon Challenge to reduce environmental uncertainty and other barriers[2]

Are there any innovations that could reduce cost?

The scope for engineering cost reduction is limited. The engineering needed to build a marine wall is well established, and the cost of building further marine walls is unlikely to be substantially less unless a future location allows for designs to mobilise rock formations to reduce concrete retaining wall volumes. Some facilities may be set up to allow partial industrialisation of the process, and that might provide some cost reduction. At present there is little demand for turbines specifically designed for tidal range projects and although there has been some improvement in their efficiency, future technology improvements, if any, would be expected to be relatively small, given the maturity of the technology. The engineering is well established and, while there may be some scope for cost reduction as the market interest improves, it will not emulate wind and PV - perhaps 5% at most.

[1] Severn Embryonic Technologies Scheme (SETS), DECC, 2009-10

[2] https://www.gov.wales/tidal-lagoon-challenge

How long can a tidal power project produce electricity?
The civil engineering elements have a life of at least 120 years. During this period, it will probably be necessary to replace or refurbish various elements including the turbine blades (60 years), generators (40 to 60 years), sluice and operating gates (80 years) and electrical / control equipment (20 years). At the end of the operating life, the electro-mechanical elements of the project would need to be decommissioned, and the civil engineering works would either be re-purposed as permanent structures or demolished.

What is required to design and consent a tidal power plant?
Tidal power projects are large civil engineering structures with marine wall lengths of between 6km and 20km in water depths up to 25m. An important consideration, given their interaction with the natural environment, is the development of conceptual and outline designs using a multi-disciplinary design teams involving engineers and environmental professionals. This co-design approach allows environmental impacts to be minimised, and consideration given to how elements of the engineered structures can be designed to replicate nature in the least exposed areas such as near the shoreline.

A decommissioning plan is also required to determine what happens to the infrastructure once it no longer operates, which may be 120 years or more after it is built.

Can you build two or more tidal power projects in the Severn Estuary?
In principle, yes, but the different sizes and locations of the candidate projects must be considered as not all will be compatible.

What about the silt load in the Severn Estuary?
The Severn Estuary is characterised by a large body of suspended silt with the highest concentrations in the upper estuary. It is normal practice for turbine designers to assess the silt and other contaminants in the water when designing the alloys and other materials that will be used in the turbine design. Limiting silt deposition within a lagoon is a function of location, configuration, depth and mode of operation.

Will the Severn Bore affected?
The Severn Bore is unlikely to be affected unless one of the two barrage schemes was built. Even then, as these typically operate as ebb only projects which maintain the natural high-water level, there may be limited impact but this would be subject to more detailed consideration as the characteristics of a specific project may have an impact on incoming flow. The bore itself is created by the incoming flow at high tide, combined with low barometric pressure and a strong SW wind. It starts to form above Sharpness some distance upstream from either barrage location.

Concluding remarks

Obstacles to the construction of tidal range projects in the Estuary are not technical or engineering in nature. A barrage or a lagoon could be built today using conventional engineering practice.

1 BACKGROUND

Scope

This summary report has been prepared to outline the engineering aspects of tidal power from the Severn Estuary to inform the Severn Estuary Commission's work on the feasibility of tidal power from the Severn Estuary.

It is a compilation of two data sources:

- Relevant Chapters from WSP's Report to Western Gateway published on the Severn Estuary Commission's website in March 2024[3] (sections 1 and 2 and Appendices A, B and C)
- A summary of engineering considerations prepared for the Commission in late 2024/2025 (The Executive Summary and Section 3).

Engineering Characteristics

Geology

The estuary is characterised by Triassic sandstone and mudstone overlain by marine deposits of mud, sand and gravel. The geology varies throughout the estuary with up to 20m of mobile sand at the surface between Newport and the Prince of Wales Bridge whilst under the bridge itself is exposed rock. Further downstream, the estuary is characterised by marine deposits overlaying rock with exposed rock on the Welsh coastline between Aberthaw and Barry.

Tidal Power Definitions

There are two principle types of tidal power technology:

i) Tidal Range

ii) Tidal Stream

There are also a number of hybrid options, mainly based on tidal stream principles. Wave energy is a further marine energy technology but generating power derived from the waves rather than the tidal range or tidal currents.

<u>Tidal Range</u>

Tidal Range technology is based on a high tide filling a basin created by an impounding structure and then releasing the water through turbines a few hours later when the tide has receded.

The impounding structure can take three forms:

i) A barrage connecting two points on opposite banks of an estuary (for example the Severn Barrage that was previously proposed between Lavernock Point and Brean Down);

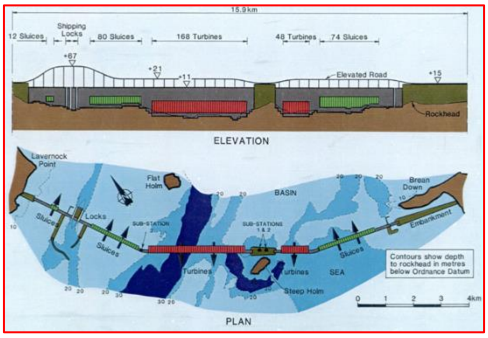


***Figure 6:** Cardiff to Weston Elevation and Plan imagery from STPG.*

[3] https://www.severncommission.co.uk/wp-content/uploads/2024/03/Severn-Estuary-Evidence-Base-and-Framework.pdf

ii) A lagoon connecting two points on the same shoreline but projecting out to sea (for example the Swansea Bay Tidal Lagoon or the Stepping Stones Lagoon shown below in Figure 7).

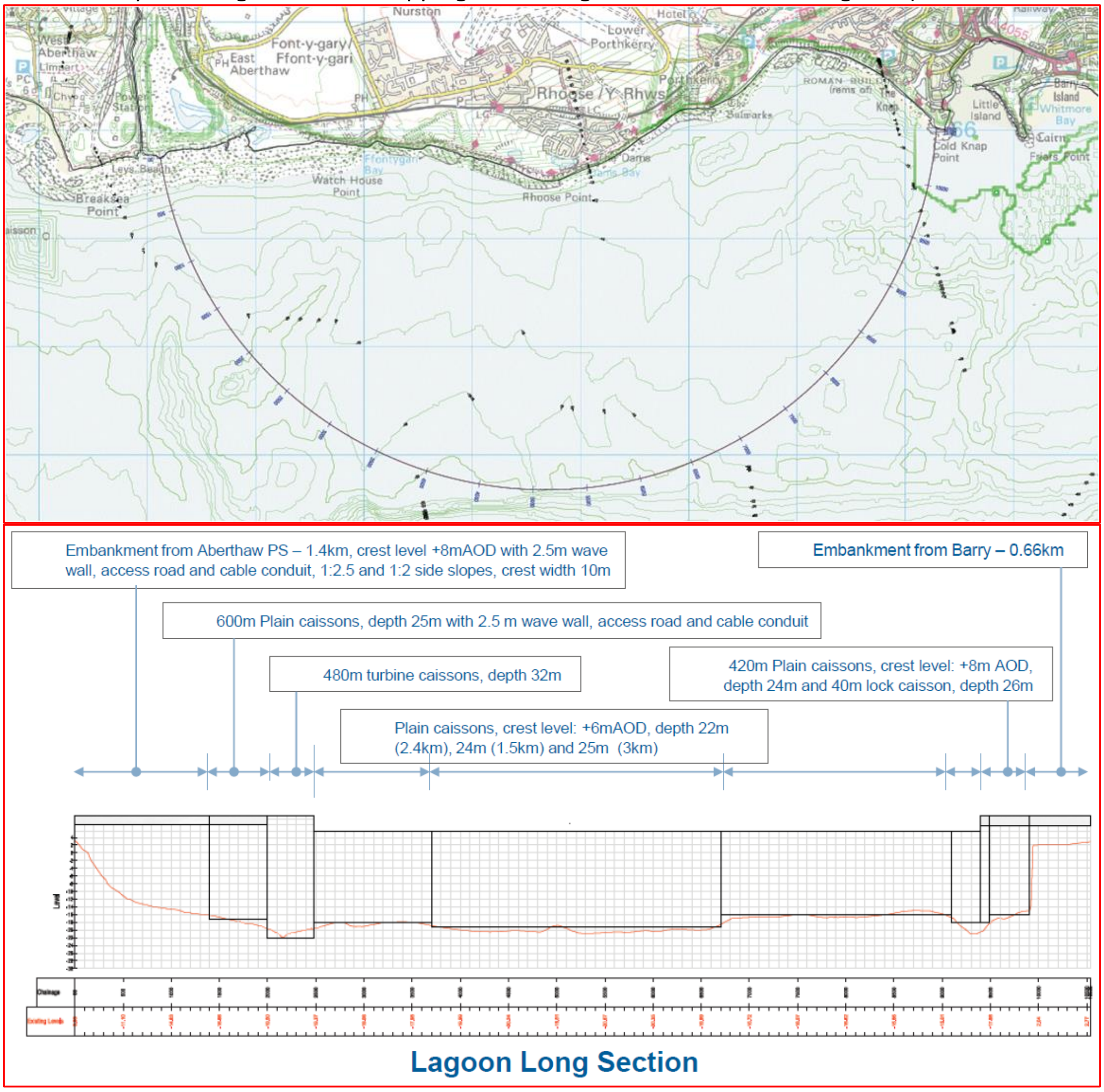


Figure 7: *Stepping Stones Tidal Lagoon Plan and Elevation.*

iii) A lagoon located entirely offshore to form a continuous structure located in the sea (for example Ecotricity proposed the concept of an offshore lagoon as an alternative to the Swansea Bay Tidal Lagoon). Compared with a land connected lagoon, this has the advantage that there is little or no loss of inter-tidal habitat (because the natural coastline tidal regime is unchanged) but does require a greater and potentially deeper length of marine wall for the same impounded volume thereby increasing costs.

Figure 8: *Offshore Lagoon (imagery from Ecotricity)*

Tidal Range technology operates in the same way as a hydro-electric plant and requires a minimum depth of water of more than 6m to be economically feasible although turbines can operate, with some loss of efficiency, on differences in water level of 1m. The power produced is a function of the head, gravity and the flow. Efficiencies are 90% or more.

Tidal Range has two potential operating modes:
Ebb only: The turbines are designed to operate in one direction only with the flood (inflow) tide passing through sluices before being held as the tide ebbs and then generating on the ebb tide when the difference in water level is sufficient. This mode of operation requires turbines with a higher power rating as the differential head is greater during the periods of generation. Although the period of generation is shorter, the energy generated is similar to other operational modes but just delivered over a shorter period of time and requiring greater grid connection capacity. The turbine can also be used in pumping mode for a limited time at high water to increase the volume of storage in the impounding basin above the height of the natural high tide. Tidal turbines operate with a higher efficiency in one direction (c93%) but pumping efficiency is lower. Figure 9 shows the upstream and downstream water levels over several days typical of an ebb only operating mode.

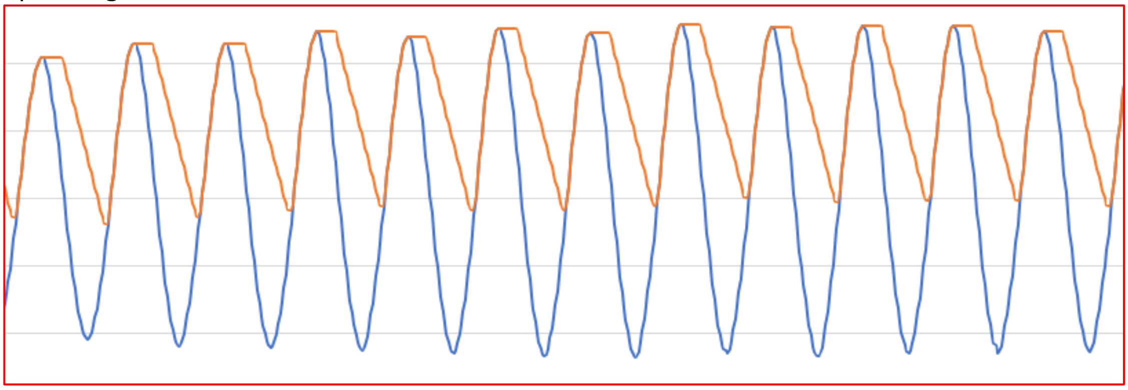


Figure 9: *Impounding (orange) and Natural (blue) Tide Levels – Ebb only operation – with significant loss of intertidal areas in the lower half of the tidal prism*

Ebb and Flood: The turbines are designed to operate in two directions (but with a lower efficiency compared with single direction turbines) and generate on both the flood and ebb tides so that water flowing into the basin generates power as well as the outflow. The total amount of energy generated can be similar or greater than ebb only (depending upon turbine capacity installed) and it is generated in four periods during the day (as opposed to two with ebb only) but the total power output on each cycle is lower. Pumping can also be used to increase power output by pumping at low heads (when the tide turns) and generate the same volume at higher heads as the tide ebbs and floods. Sluicing can also be used to enhance the generation head towards the end of the generation phase. Turbine efficiencies for two-way generation are between 80 and 93% depending upon direction and turbine two-way design optimisation. If used in pumping mode, efficiencies are lower. Two-way generation also requires a draft tube (the outlet passage from the turbine) to be replicated on both sides of the turbine, increasing the width and cost of turbine caissons.

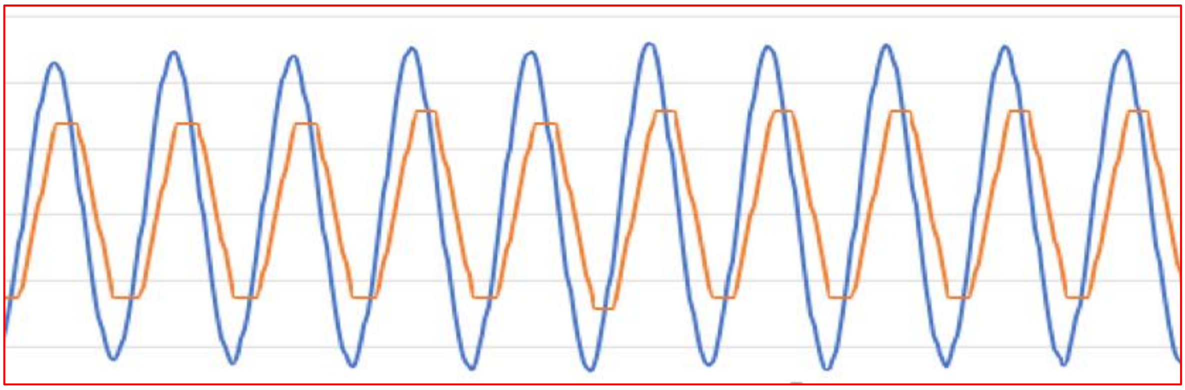
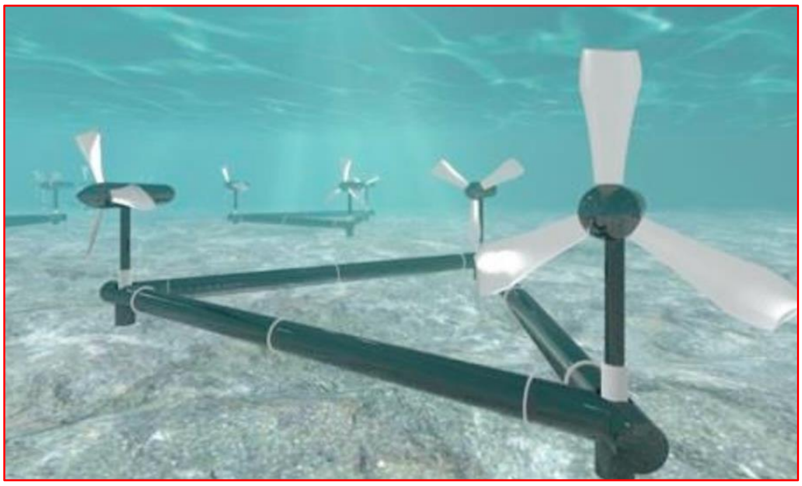


***Figure 10**: Ebb and Flood operation – with impounding levels showing symmetrical losses at high and low tides.*

Tidal Stream

Tidal stream operates in the same way as a wind turbine using the tidal currents to rotate the turbine rotor blades. The principles of power generation are the same as for wind in that power is a function of the swept area of the rotor blades and the cube of the fluid velocity. The difference is that the density of the fluid is significantly higher for sea than it is for air. Tidal stream turbines are therefore significantly heavier than their wind equivalents but the turbine blades can be shorter. However, they are still large for relatively low power outputs as the power density of a tidal stream turbine is much lower than a tidal range turbine.



Examples of tidal stream turbine include Strangford Lough (an early 1.2MW prototype with twin rotors mounted on piles that projected above the water line to enable the rotors to be raised for maintenance) and the MayGen project in Scotland which is currently powered by 4 nr 1.5MW turbines and has been operating since 2017.

***Figure 11:** An illustration of tidal stream turbines proposed for Ramsey Sound (from Tidal Electric Limited)*

Hybrid Options

A Tidal Fence is primarily based on tidal stream technologies and include configuring a large number of tidal stream devices as a fence running across an estuary. The resistance caused by a large number of tidal stream turbines aligned in a row creates a small level difference across the turbines which increases the power output. The level difference is an order of magnitude lower than with tidal range. The lower power densities result in significantly less energy being taken out of the estuary than a tidal range equivalent but the environmental impact is correspondingly lower. An example was published as part of the Severn Embryonic Technologies project in 2010 (SETS) although it was relatively expensive. This technology is best categorised as a variant of tidal stream.

Figure 12*: An illustration of a tidal fence (reproduced from IT Power)*

Other hybrid options have included a “low head” turbine which Rolls Royce started to develop for tidal range applications. This used large counter rotating turbine rotors to enable high water volumes to pass at lower heads when compared with conventional tidal range technologies. This was also developed as part of the SETS programme in 2010 but Rolls Royce decided not to pursue the concept. There were concerns on cost and the large number of contra rotating turbine blades which had not been tested for safe fish passage although the rotor tip speeds (a key metric when considering fish passage) were considered to be satisfactory. Although taking elements from tidal stream technology such as the large turbine blades this is more of a tidal range application. UKRI are currently funding a programme to develop a prototype and test a variation of this design concept[4].

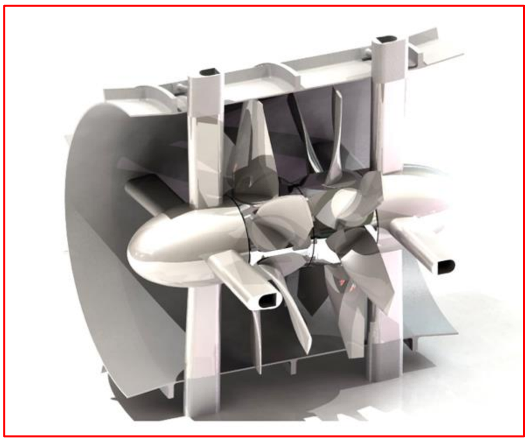


Figure 13*: A cut-away of a low head turbine developed by Rolls-Royce and reproduced from their published SETS report.*

Wave Energy

Wave energy devices float on the surface of the ocean and are typically articulated or axis mounted so that they can move with the waves. The movement of the device absorbs the energy from the waves. Because it is a reciprocating rather than rotational movement, the energy absorbed is used to compress a fluid which then drives a turbine to produce energy. Compressed air is commonly used as the compression medium directly driving a Wells Turbine (a compressed air turbine).

[4] https://gtr.ukri.org/projects?ref=10072702

An articulated device called Pelamis was tested at the EMEC test centre in Orkney and became the first offshore wave machine to generate electricity into the grid in 2004. Pelamis Wave Power then went on to build and test five additional Pelamis machines including the Pelamis P2, shown in Figure 11, which was tested off Orkney between 2010 and 2014. Pelamis Wave Power went into administration in November 2014, with the intellectual property transferred to the Scottish Government body Wave Energy Scotland. Development of wave power devices has been challenging and the Wave Hub, a £28m wave device grid connection facility 10 miles offshore from Hayle in Cornwall has been repurposed as a floating wind connection hub having been unable to host any wave devices since its commissioning in 2010.

Figure 14*: The Pelamis 2 Wave Device*

2 ANALYSIS OF EXAMPLE PROJECTS

Example Projects

This section is based on the 2024 Report[5] produced by WSP for Western Gateway and available for download from the Commission's website. The six example projects selected as representative of the Estuary's range of potential projects was selected from this analysis.

A literature review was undertaken to identify the data sources and details of tidal energy projects studied in the Severn Estuary, elsewhere in the UK and internationally. The published data for each project has been updated to a March 2023 cost base.

The analyses use the developer or original study data, and the independent assessment is then undertaken on a quantitative and qualitative basis to assess whether estimates of cost and energy outputs are realistic or not. The data used in the independent assessment to reach such conclusions is set out in Appendices A (cost data) and B (energy) of this report.

Severn Estuary Projects Considered

Table 2: *Summary of Severn Estuary Tidal Projects*

Programme	Project	Data Source
Bondi Commission (1981)	Cardiff to Weston Tidal Barrage	Energy Paper 46 (not available on line)
Severn Tidal Power Group – STPG (1989)	Cardiff to Weston Tidal Barrage English Stones Barrage	Energy Paper 57 (not available on line) 2002 Update
Sustainable Development Commission – SDC (2007)	Cardiff to Weston Barrage English Stones / Shoots Barrage Tidal Lagoons	SDC Reports
Severn Tidal Power Feasibility Study – STPFS Phase 1 (2009)	B1 Aberthaw to Minehead Barrage B2 Cardiff to Hinkley Point Barrage via Weston B3 Cardiff to Weston Barrage B4 Shoots Barrage B5 Beachley Barrage	STPFS Phase 1 Reports (not available on line)

[5] https://www.severncommission.co.uk/wp-content/uploads/2024/03/Severn-Estuary-Evidence-Base-and-Framework.pdf

Programme	Project	Data Source
	R1 Tidal Reef	
	L2 Welsh Grounds Lagoon	
	L3 Tidal Lagoon Concept - Peterstone Flats - English Grounds - Bridgwater Bay - Offshore (Bridgwater Bay)	
	U1 Severn Lakes	
	F1 Severn Tidal Fence	
Severn Tidal Power Feasibility Study – STPFS Phase 2 (2010)	B3 Cardiff to Weston Barrage	STPFS Final Reports
	B4 Shoots Barrage	
	B5 Beachley Barrage	
	L2 Welsh Grounds Lagoon	
	L3d Bridgwater Bay Lagoon	
Severn Embryonic Technologies Scheme – SETS (2010)	Minehead to Aberthaw Tidal Fence	STFC SETS Report
	Minehead to Aberthaw or Cardiff to Weston Venturi Fence	VerdErg SETS Report
	Minehead to Aberthaw or Cardiff to Weston Tidal Bar	Atkins Rolls Royce SETS Report
Post STPFS (2012)	Stepping Stones Lagoon	Bristol Tidal Forum Presentation
Hafren Power (2011 - 2013)	Hafren Power Barrage	Select Committee Inquiry
Tidal Lagoon Power (2011 - 2018)	Swansea Bay Tidal Lagoon	NSIP Planning Portal Hendry Review Select Committee Inquiry Government Response
	Cardiff Lagoon	NSIP Planning Portal

Programme	Project	Data Source
	Newport Lagoon	Hendry Review
	Bridgwater Bay Lagoon	Hendry Review
TEES (2016 to date)	West Somerset Lagoon	Project Website Summary Report (not available on line)
DST Innovations (2021)	Blue Eden Project (formerly Dragon Energy Island)	Swansea City Press Release
(2023 to date)	Great Western Power Barrage	Project Website

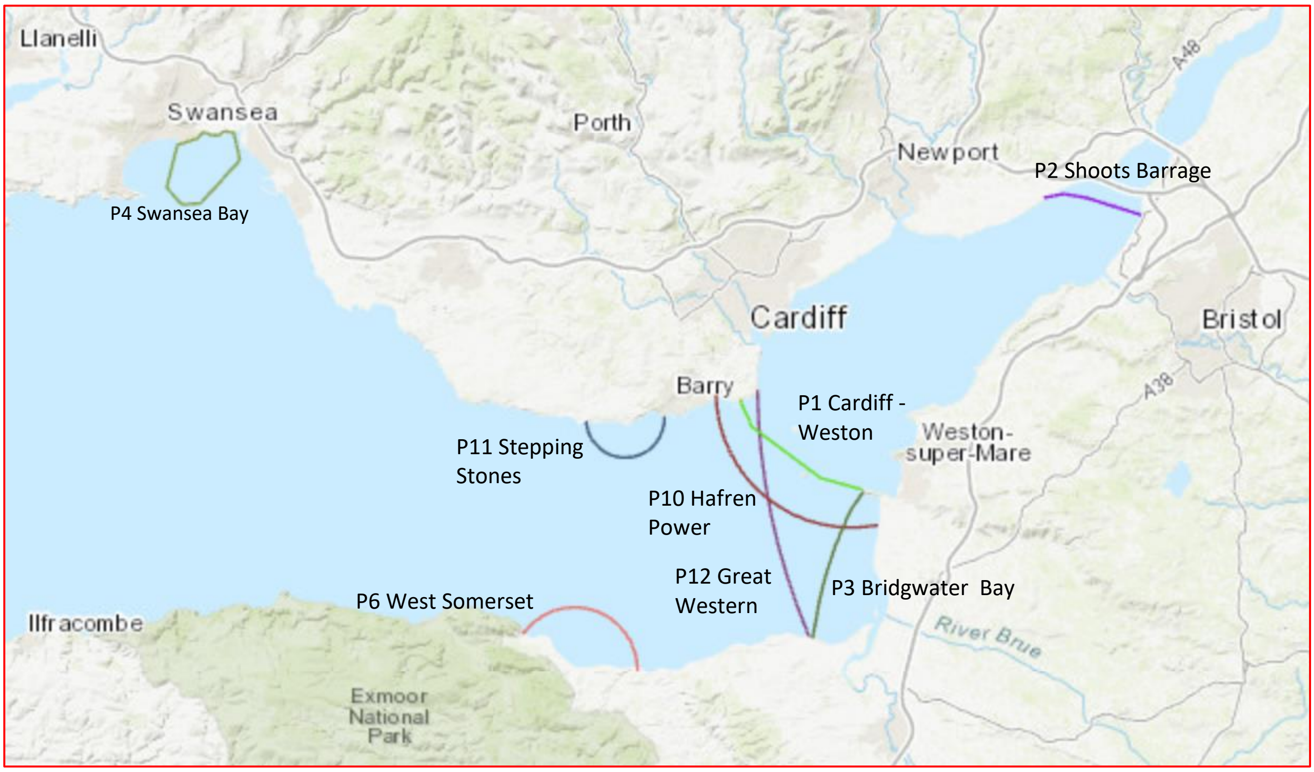


Figure 15 *Severn Estuary Tidal Power Projects*

Figure 15 shows the location of the different projects referenced above that are either active or identified as potentially feasible in the STPFS. The Hafren Power proposal has also been included because, although it failed to secure support when promoted in 2013, nevertheless, it has similar unit costs to the STPFS shortlisted projects.

Global Tidal Power Projects

France and South Korea are the only countries to have developed large scale tidal power plants, both based on tidal range technology. La Rance was constructed in 1967 and has been operational ever since with only one major refurbishment (servicing of the turbines and replacement of the control system). It was constructed in a cofferdam that spanned the estuary and consequently the original eco-system declined and has been replaced with a new, different eco-system reflecting the changes in water levels. This would not be acceptable today. It was the most expensive form of power on the EdF system when it was first built but it is now the least expensive and has the benefit of being operated flexibly to stabilise the grid as well as producing low carbon energy. The Sihwa plant was constructed more recently in 2011 and is a tidal power plant retrofit into an existing tidal lagoon.

Other international projects have been small in scale – the largest at Annapolis Royal in the Bay of Fundy was a single 20MW turbine installed to enable monitoring of environmental conditions as a fore-runner to a larger tidal barrage. It was constructed in 1984 and continued in operation until 2019 when it suffered an equipment failure. It was decommissioned in 2021 after it was refused an environmental licence that would have enabled the failed equipment to be replaced. The Bay of Fundy has subsequently focused on the development of tidal stream technologies using its FORCE programme to help tidal stream developers undertake the appropriate consenting and monitoring required for testing.

China has developed two power plants, both relatively small, and only one continues to operate. The Netherlands has trialled a retrofit turbine on its flood defence structures but again this is small scale at present.

In the UK, the only examples of tidal power in operation have been using tidal stream technologies, again mainly as test beds for future development. A 1.2MW twin rotor turbine at Strangford Lough in Northern Ireland was the first grid connected turbine and this operated from 2008 to 2019. There have been many proposals for tidal stream developments in the key resource areas of Anglesey, Orkney and Northern Ireland but with some exceptions, these have been characterised by developers withdrawing or mothballing their proposals. The exceptions are the MeyGen project in the Orkneys being developed by Simec Atlantis Renewables (SAR) and the Anglesey projects by Mentor Mon at Morlais and Minesto at Holyhead.

The MeyGen project is the most advanced of these, having secured a Crown Estate lease in 2010 and now has 6MW of tidal stream capacity deployed. There is potential for 398MW of tidal stream in total, but costs require extensive subsidy at the moment through grants from The Crown Estate and Scottish Government. The UK Government allocated £20m of ring fencing to tidal stream in the fourth CfD auction, the majority of which benefitted the MeyGen project which received a CfD contract of £178.54/MWh for 28MW of new tidal stream development.

The Morlais project in North Wales is also making progress having received planning consent and is now focusing on grid connections which will be shared with the Minesto Holyhead development.

There have been no tidal range developments in the UK although there have been many projects studied since the early 1980’s. In 2023, projects are being promoted by public authorities including the Liverpool City Region Combined Authority (Mersey Tidal Power) and Swansea Council (who are facilitating the Blue Eden project in Swansea Bay). There are also projects being studied by the private sector including a tidal lagoon on the Somerset coast, a tidal lagoon at the Port of Mostyn and the Blue Eden project. A challenge for the private sector is the scale of tidal range projects which have more in common with large infrastructure projects conventionally promoted by public agencies. New nuclear projects have faced the same challenge and, assisted by UK Government energy policy, they now have access to Regulated Asset Base (RAB) financing which reduces the cost of energy by up to 40% albeit at the expense of charging consumers during the construction period.

Analysis of Severn Estuary Projects

The numerical analyses have been undertaken on those projects in the Severn Estuary are reported on in summary form in this section. The analysis has looked at all the credible projects that have been studied over the past five decades. They are presented as individual projects for those that have been shortlisted for more detailed study from the various research programmes along with individual projects being promoted by the private sector. Projects that were not shortlisted from the research programmes are also included although the depth of analysis is less detailed.

The projects that were analysed in detail are set out in Table 6:

***Table 6**: Potential Severn Estuary Tidal Power Projects*

Reference	Project	Notes
P1	Cardiff to Weston Barrage (STPFS)	This is traditionally referred to as The Severn Barrage originally proposed by the Bondi Review in 1981, developed in more detail by STPG in the 1980's and studied by STPFS in 2008.
P2	Shoots Barrage (STPFS)	This was originally referred to as the English Stones or Hooker Barrage as a smaller alternative to the Severn Barrage.
P3	Bridgwater Bay Lagoon (STPFS)	This was identified as a viable tidal lagoon by STPFS in 2009.
P4	Swansea Bay Tidal Lagoon (TLP and Blue Eden)	The Swansea Bay Tidal Lagoon was first conceived by an American entrepreneur in the early 2000's but rejected in a subsequent DTi report in 2006. Other developers considered the concept before TLP developed it in detail between 2011 and 2018. Swansea Council then facilitated an alternative approach which has resulted in the Blue Eden project.
P6	West Somerset Tidal Lagoon (TEES)	The West Somerset Tidal Lagoon is located in the middle estuary to the West of the Hinkley Point Nuclear Power Station. It is promoted by a small group of retired tidal power professionals.
P10	Cardiff Weston Tidal Bar (Hafren Power)	The tidal bar was proposed by Hafren Power as a low head tidal barrage using a new type of large diameter high flow turbine (not in commercial development). It was the subject on a Select Committee Inquiry in 2013 and did not progress.
P11	Stepping Stones Tidal Lagoon (post STPFS)	The Stepping Stones Tidal Lagoon is located in the middle estuary to the East of Aberthaw Power Station. It was conceived after the STPFS

Reference	Project	Notes
		concluded to assess whether there were benefits to developing a proposal in this location.

There was also a project referenced P12 which has been initiated in 2023 called the Great Western Power Barrage. This has not been studied in detail because the developer has not yet undertaken any detailed studies.

GIS data has also been developed giving a snapshot of the different tidal projects in the Severn Estuary with a brief summary. An example of the GIS output is shown in Figure 16. The outer estuary is considered to be west of Minehead and the inner estuary east of Barry.

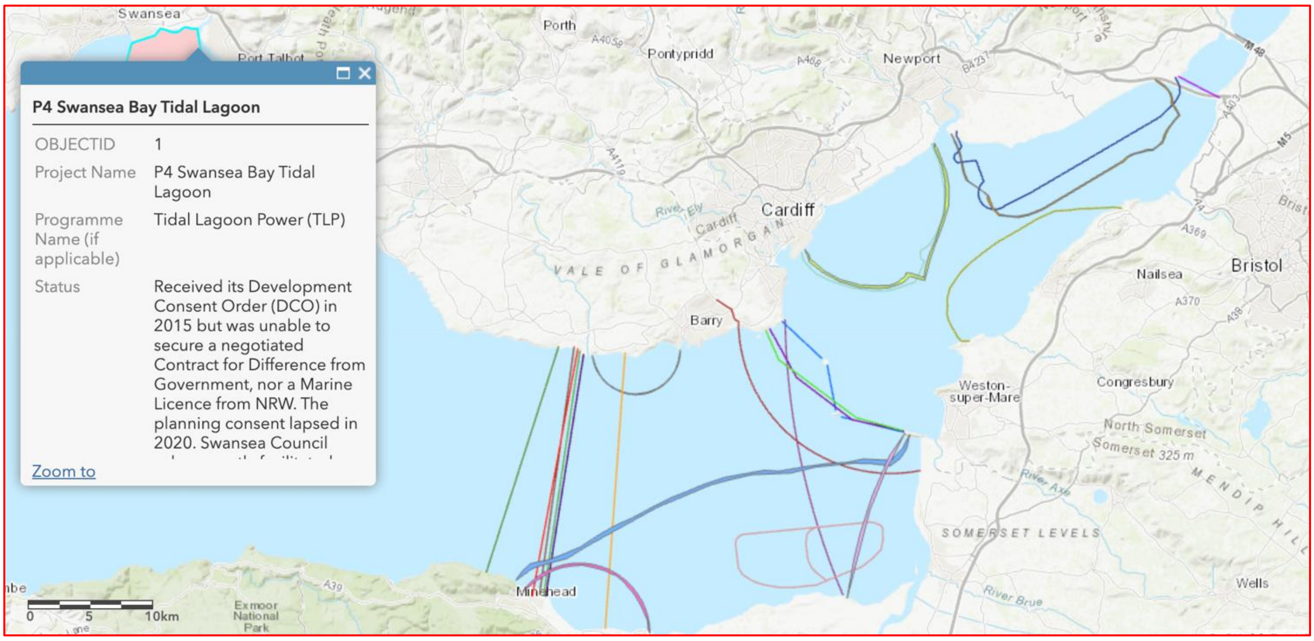


Figure 16: Screenshot of GIS Output showing tidal power projects and an example of a call-out data card.

The project analysis has been undertaken in terms of cost of energy based on an 8% discount rate (the private sector proxy rate) which amplifies differences between the proposals to aid interpretation. The graph below shows the distribution of project cost of energy performance against installed capacity. The larger the circle, the greater the error bounds of the developer's data.

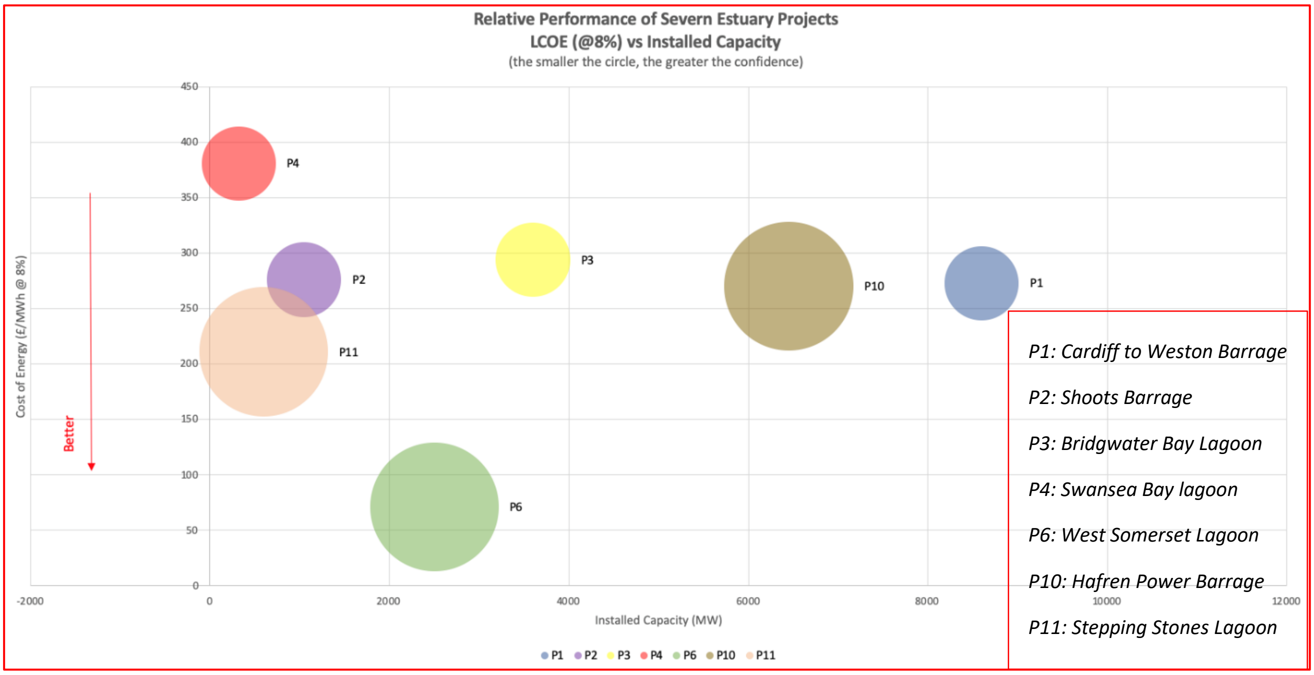


***Figure 17**: The relative performance of tidal power projects shown in unit energy costs and installed capacity*

The second graph in Figure 18 is similar except that the results are plotted against the ratio of energy output and capital expenditure. The best projects are those located closest to the x axis and furthest to the right from the y-axis.

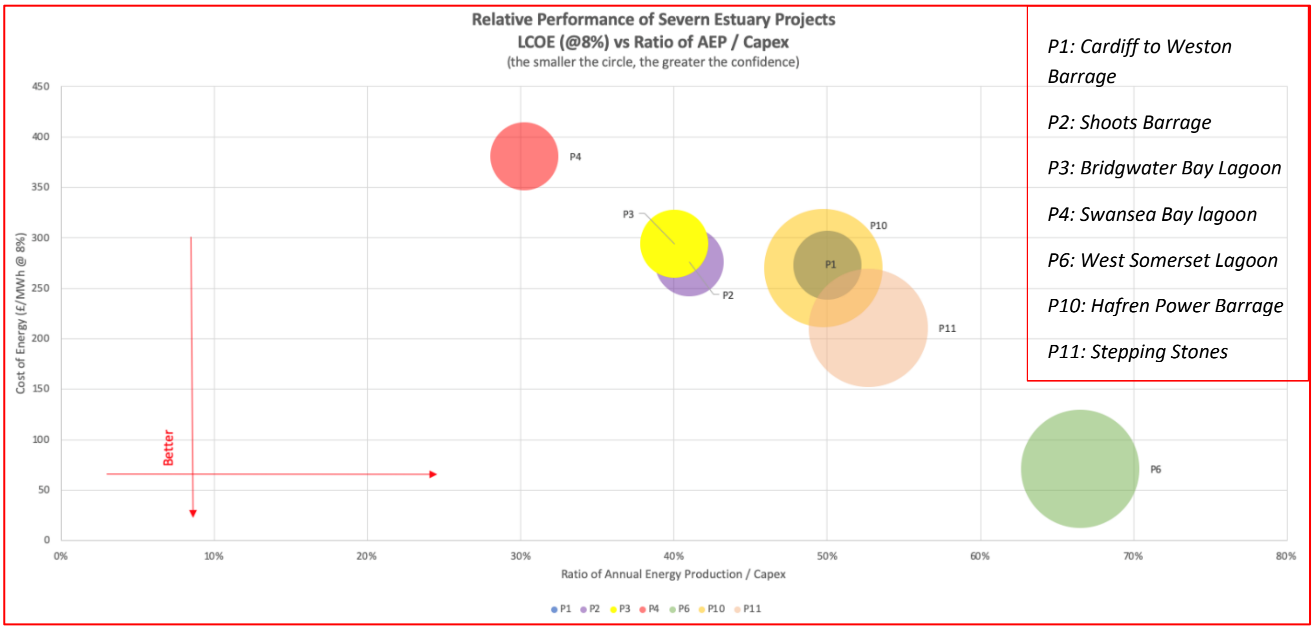


***Figure 18**: The relative performance of tidal power projects shown in unit energy costs against ratio of Energy to Capex.*

These graphs show that Projects P6 (West Somerset Tidal Lagoon) and P11 (Stepping Stones Tidal Lagoon) are the best in terms of performance but with significant caveats around confidence of costs and energy outputs as they have not been subjected to detailed study. However, both these projects are located in the middle estuary which has fewer environmental designations and suggests that this should be a priority area for the Independent Commission to review when assessing potential tidal power locations. The previously favoured Cardiff to Weston alignment (P1 and P10) also comes out strongly in this analysis whilst the Shoots Barrage (P2) and Bridgwater Bay Lagoon (P3) appear less efficient. Swansea Bay Tidal Lagoon (P4) is the least efficient and most expensive of the options considered.

The Projects not shortlisted for detailed study are included in the programmes set out in Table 7:

***Table 7**: Tidal Power Programmes featuring projects not shortlisted for further study.*

Reference	Programme	Notes
P5	Tidal Lagoon Power (TLP)	TLP's programme of Severn Estuary lagoons after Swansea Bay were Cardiff, Newport and Bridgwater Bay
P7	Severn Embryonic Technologies (SETS)	SETS projects were undertaken as a parallel workstream to the STPFS and the programme was designed to explore whether embryonic technologies could provide a more environmentally acceptable solution.
P8	Severn Tidal Power Feasibility Studies (STPFS) – Phase 2	Phase 2 of the STPFS studied five projects in detail but two of these were not considered to be viable projects and are covered in worksheet P8.
P9	Severn Tidal Power Feasibility Studies (STPFS) – Phase 1	Phase 1 considered a long list of potential tidal power projects – of these five then progressed to be considered in more detail in Phase 2 – those that didn't progress to Phase 2 are covered in worksheet P9.

An accompanying Excel workbook (not published) also includes an analysis of both the projects and programme cost ranges in terms of cost of energy using the 8% (private sector) and HMT (public sector) discount rates and the RAB modelling outputs to highlight the different cost of energy arising from the different financing scenarios.

Conclusions

Reflecting on the progress made to date, internationally, nationally and in the Severn Estuary, it is clear that the status quo is unsatisfactory, particularly so far as tidal range (which is the best tidal resource in the Severn Estuary) is concerned.

In addition to influencing future policy improvements for tidal range projects, the analysis of past projects and programmes confirms the following:

- Tidal lagoons are preferred to the larger tidal barrages in the Severn Estuary because of the potential economic impacts associated with the latter in enabling commercial shipping to continue uninterrupted but smaller barrages such as the Shoots may also be a viable option;

- On the basis of the analyses above, the middle estuary appears to offer the best possibilities for development of new tidal range projects with a high tidal range and fewer environmental designation areas, although changes in the hydrodynamic regime may impact adjacent designated areas. Accordingly, the Cardiff Lagoon or the Shoots Barrage, which are both located in protected areas, also merit continued consideration whilst all options, including the larger barrage proposals, should not be prematurely discounted, pending discussion with key stakeholders;
- Existing projects have used conventional methods of marine wall construction and the tidal power sector would benefit from a research programme to review and test new, less expensive and/or material intensive forms of impounding wall construction, particularly in areas such as the middle estuary where ground conditions include rock. Similarly, research into more innovative forms of infrastructure financing and overcoming environmental uncertainties would be merited;
- Environmental impacts have traditionally been considered in parallel with or after the development of conceptual designs – there is merit in including environmental matters in at the initial concept design stages to promote the best engineering and environmental solution.
- Achieving 10% biodiversity net gain has not been considered in previously studied projects – this will also require a different approach.

3 FREQUENTLY ASKED QUESTIONS

The concept of tidal power

Coastal areas experience two high and two low tides every 24 hours and 50 minutes. High tides occur 12 hours and 25 minutes apart. The highest tides, spring tides, occur twice each lunar month all year long, without regard to the season. The lowest tides, neap tides, occur 7 days after a spring tide.

Tidal energy is energy abstracted from the rise and fall in the tides (tidal range) or from the currents that flow as the tide changes (tidal stream). It is available except when the level difference and currents reduce to zero as the tide turns.

What advantages does tidal range power have over other renewable technologies?
Like wind and solar, tidal range is variable and low-carbon, but unlike wind and solar, it is entirely predictable. It uses proven technology. It provides certain advantages to the national grid in that it uses large spinning generators which help stabilise the grid's frequency and it can generate at short notice to meet peaks in demand, although this facility requires some sacrifice in total energy generation at such times. It has a similar whole-life carbon footprint to offshore wind.

A tidal power plant uses the same mechanical and electrical equipment as used in a hydro-electric power plant. The civil works, with their marine location, are similar to those adopted at ports and harbours, sea defences and nuclear power station water cooling and discharge works. It is therefore proven technology that has existed for many decades.

Which Technology?
Tidal Stream technologies (see Figure 19) rely on the tidal currents to generate energy. The power generated is a function of the swept area and the cube of the current. The Severn Estuary is characterised by relatively low currents by comparison with other tidal stream sites (2.7m/s vs 3.9m/s in the Pentland Firth and Anglesey) and can therefore only generate 45% of the power of those other sites on a like for like basis.

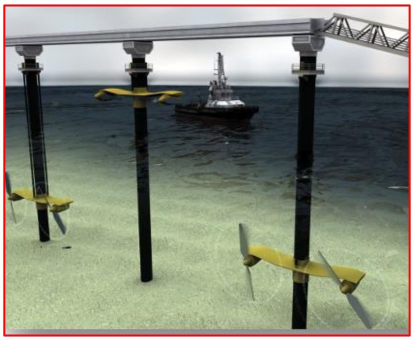


Figure 19 – Tidal Stream Devices in a Tidal Fence (source: SETS)

The high tidal range in the estuary makes it the best option for generating energy at scale from the Severn. It has the largest tidal range in the UK and power can be generated using either a barrage crossing the estuary or tidal lagoons constructed along one shoreline. These lagoons impound water which is then held at a static level for a short period after the tide turns to develop a difference in water level. The difference in water level (the head) causes water to flow through the classical Bulb Turbine (see Figure 20) which generates the power. As water levels in the impounding basin are changed, there is some loss of inter-tidal habitat within the impounded area.

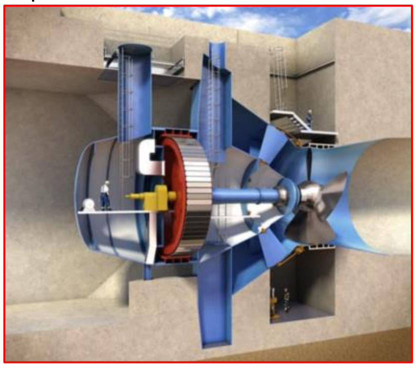


Figure 20 – Bulb Turbine Cut Away as proposed by Andritz

It is also possible to construct a lagoon within the estuary that does not connect with the land. This approach has the advantage that no inter-tidal habitat is lost, but it is significantly more expensive since the volume of materials required for an offshore lagoon is more than double that of a land-connected lagoon for the same energy output.

How does it operate?

The way in which a turbine is operated changes water levels in the impounding basin upstream of the marine wall as set out in Table 8.

Although pumping uses imported energy from the grid, it also increases the net energy output from a tidal power plant. This is because pumping is used once generation stops as the tide turns when the difference in water levels is close to zero. Water is pumped into the impounding basin to increase the volume available for power generation. As the head difference is much larger during generation than when pumping, more energy is produced than consumed by pumping resulting in a net increase in total energy generated.

There are two forms of pumping:

1. Maximum pumping - raises the water level in the impounding basin to a higher level than would occur naturally and results in a larger net increase in energy production.
2. Mitigation pumping - restricts the rise in water level to the maximum natural water level that would occur for a particular tide state if there was no marine wall to reflect more closely the natural environment's water level, but it produces less additional energy than maximum pumping.

Pumping can be used both to increase the water level in the basin at the end of the flood generation phase and to reduce water levels in the basin at the end of the ebb generation phase. In both instances, this increases the generation head and thus net energy production. Sluicing can also be used to reduce water levels in the basin at the end of the ebb generation phase, again to increase the head available for the next generation phase during the flood tide.

There may be an increased risk to fish passing through the turbines if pumping is adopted due to increased turbulence and length of operation.

Mode	Description	Effect on Water Levels
Ebb only	The flood tide fills the basin through sluice gates. Generation begins 1 to 2 hours after the tide ebbs	The high-water mark is close to the natural tide level and there is a period after the tide turns where water levels are static. When generation begins, the rate of reduction in water level is lower than the natural tide and the low water mark rises to the midpoint of the original tidal range.
Ebb and Flood	Generation occurs both on the flood and ebb tides	The high-water mark is reduced whilst the low water mark is increased by around the same amount (approximately 1 to 2m). A period of static water occurs each time the tide turns.
Ebb and Flood with sluicing	As ebb and flood mode but sluicing is used to reduce water levels in the basin towards the end of the generation cycle	Similar to the Ebb and Flood mode but the low water mark is closer to the natural tide low water mark.

Ebb and Flood with pumping	As ebb and flood mode but pumping is used as the tide turns to increase or reduce the water levels in the basin to increase energy production. Sluicing can also be used to reduce water levels in the basin towards the end of the generation cycle	Similar to ebb and flood but the water levels return to close to, but not equal to the natural tide level.

Table 8 *Description of water level changes for different operating modes.*

What do these changes in water level look like to the casual observer?
From the shoreline of the impounding basin, there will still be the rise and fall of the tide, but it will not be as large as the natural tide. There will also be a period of still water for between 1 and 2 hours between each generation cycle.

Are there any new innovations that could be used to reduce environmental impact?
A programme[6] was run in 2009 to identify and analyse potential new technologies that could be used to generate tidal range power whilst reducing impacts on the environment, specifically reduction of potential fish mortality and reduction in inter-tidal habitat loss. Three such potential innovations were: selected:

- A tidal fence using tidal stream technology.
- A Venturi fence using conventional turbines but in a secondary circuit driven by Venturi pressure difference and
- A new low-head turbine design that could operate with a small head differential across the full tidal range to reduce before and after water differences.

The projects were technically feasible, but each encountered some limitations for a Severn Estuary application. The tidal fence performed best with a significant reduction in environmental impact but required more than 700 tidal stream devices in a twin line between Aberthaw and Minehead. Even then, its energy output was low because of the relatively low current velocities, and its energy cost was approximately double that of a conventional tidal range project even with its associated mitigation and compensation costs. The Venturi fence was considered more appropriate for small scale river applications rather than in a tidal environment as it required a large barrage. The low head turbine design offered more potential in reducing inter-tidal habitat loss but had a relatively low power density and two sets of contra-rotating turbine blades were considered to be problematic for safe fish passage. The technology was proposed in a barrage by Hafren Power in 2013 and required over 1,000 large diameter turbine units to generate the same power as 200 conventional bulb units. Such a quantity would be a huge challenge to the supply chain.

A more promising innovative approach was taken by GE-Andritz in its proposals for the 320MW Swansea Bay Tidal Lagoon. This involved modifying its conventional design to allow for nearly equal efficiencies in both flow directions and variable speed generators to improve efficiency over the full operating range whilst reducing rotor speeds. Discussions with established turbine manufacturers confirmed that their preferred approach was to evolve their existing designs citing significantly reduced development costs and timescales.

[6] Severn Embryonic Technologies Scheme (SETS), DECC, 2009-10

There are also opportunities to innovate the design of the civil engineering structures through, for example, modularisation and use of piles to reduce marine wall volumes where there is a rock seabed.

What is required to construct a tidal range project?

Any tidal range project involves the construction of a marine wall to store water as the tide recedes. The marine wall extends above the high-water mark and can be constructed using a rock protected sand/gravel embankment or using caissons. The latter comprise a large rectangular concrete structure that can be constructed remotely and towed into position. The marine wall incorporates one or more powerhouses. These are rectangular concrete structures that house the turbines and control equipment including sluice gates to control operation and associated water levels. The turbines include a generator housed within a steel bulb. The electricity generated is transmitted by buried cable to a sub-station where it is connected to the national grid.

Caisson construction is an efficient way to make large concrete structures in the dry. When complete they are towed out to their final location and lowered onto the seabed by adding ballast. There are many examples of caissons that have been towed into position, including bridge foundations (Bideford Bridge constructed in the early 1980's) and the Hinkley Point C cooling head Intakes which were constructed at Avonmouth Docks in 2024. Such an approach can allow construction employment to be distributed around the country.

Special care is required in the construction of the reinforced concrete structures due to the saline environment. Cathodic protection can be used to reduce the risk of corrosion of the steel reinforcement in the structures. The zone most at risk is where frequent wetting and drying occurs as the tide rises and falls. Since the aim is to generate low-carbon electricity, the carbon used in construction is important. Modern concrete technology continues to innovate and there are now lower carbon sources of concrete available, as well as improved durability high strength mixes.

Cost Considerations

The cost estimates used are based on the independent and conservative cost estimates produced for the Severn Tidal Power Feasibility Study for the two barrage examples. The lagoon examples use the data published by their proposers. All cost estimates have been inflated to a 2023/4 baseline. Until definitive designs are produced, cost estimates should be treated as indicative.

The construction cost is divided approximately as 70% for civil construction and 30% for mechanical and electrical costs, including local grid connection. In addition, client costs are incurred for project management and delivery partner roles in supervising contractors and interface management.

Other costs include development activities from conceptual design to securing the necessary consents and contractor bids. This would be expected to lie within a range of £35m to over £200m over a 5-to-8-year period for the six example projects considered here.

Annual operating costs are relatively low compared to other power projects and represent approximately 1% per year of the total construction cost. They will include a sinking fund to cover post-operation activities such as decommissioning and replacement of components when they reach the end of their life.

The marine wall itself has to be designed and constructed to minimise seepage and to take account of future sea level rise over its anticipated operating life. The marine wall acts as the impounding structure allowing water within the impounded basin to be stored at a different level to the sea. Figure 21 shows a typical arrangement of a tidal range power plant.

Figure 21: *Tidal Power Project, with navigation lock, © WSP*

The engineering for the civil, electrical and mechanical elements has been practised for many decades on water supply reservoirs and pumping stations, hydro-electric power plants and ports and harbours.

How long can a tidal power project produce electricity?
The civil engineering elements have a life of at least 120 years. During this period, it will probably be necessary to replace or refurbish various elements including the turbine blades (60 years) , generators (40 to 60 years), sluice and operating gates (80 years) and electrical / control equipment (20 years). At the end of the operating life, the electro-mechanical elements of the project would need to be decommissioned, and the civil engineering works would either be re-purposed as permanent structures or demolished.

What is required to design and consent a tidal power plant?
Tidal power projects are large civil engineering structures with marine wall lengths of between 6km and 20km in water depths up to 25m. An important consideration, given their interaction with the natural environment, is the development of conceptual and outline designs using a multi-disciplinary design teams involving engineers and environmental professionals. This co-design approach allows environmental impacts to be minimised and consideration given to how elements of the engineered structures can be designed to replicate nature less exposed areas near the shoreline. Compensatory habitat and environmental mitigation measures are also key elements of any construction works.

As they are multi-billion-pound infrastructure projects, tidal power projects are consented under the Planning Inspectorate's Nationally Significant Infrastructure[7] requirements. This process involves developing a suitably detailed design, preparation of an Environmental Statement and public consultation before a Development Consent Order (DCO)application can be submitted. The DCO may take 18 months before being awarded and involves an examination of the proposals in public by a panel of inspectors. In parallel, or after the DCO has been awarded, other licences are required to permit operations in a marine environment and to secure sea-bed leases. Further agreements are necessary to enable sale of the electricity produced and to secure investment for construction. A decommissioning

[7] https://infrastructure.planninginspectorate.gov.uk/

plan is also required to determine what happens to the constructed infrastructure once it no longer operates, which may be 120 years or more after it is built.

What are the main challenges for the delivery of a tidal power project?
As a tidal power plant changes the natural water level regime, the natural environment is affected as detailed elsewhere in this Report. Legislation is in place to protect the environment, and if located in specific protection zones, a project needs to be recognised as being in the over-riding public interest[8] and with no alternative before it can be developed. Compensation and mitigation measures are required, including the construction of new inter-tidal habitats to replace any loss caused by the operation of a tidal project.

Funding is another challenge. Such large and long-term projects cannot be sensibly funded or financed in the same way as other renewable technologies. This is covered separately in this report.

Can you build two or more tidal power projects in the Severn Estuary?
In principle, yes, but the different sizes and locations of the candidate projects must be considered as not all will be compatible. The various projects that have, historically, been proposed in the Severn Estuary are shown in Figure 22 but the majority of these are alternative options rather than capable of being co-developed.

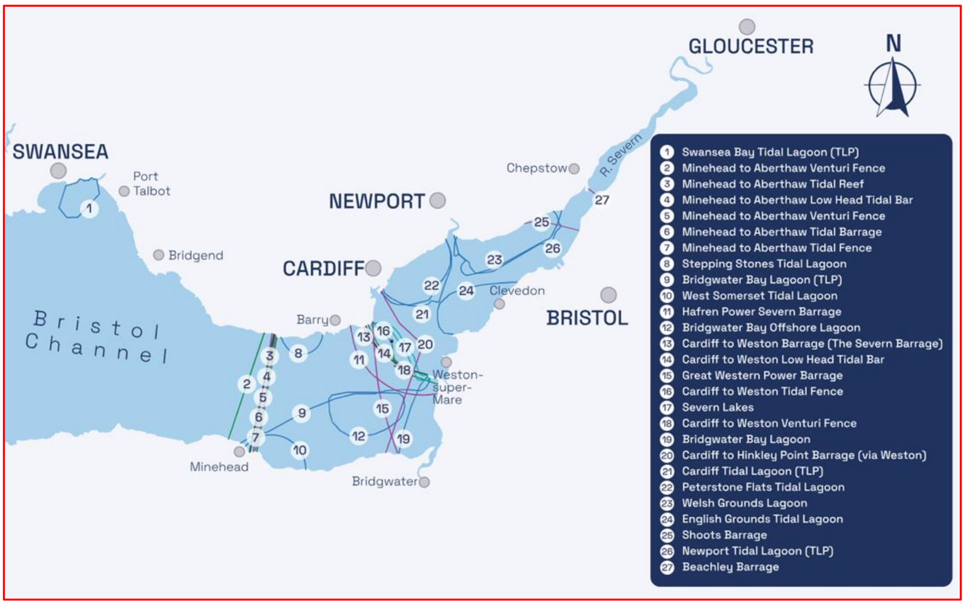


Figure 22: *Projects that have been proposed in the Severn Estuary*

However, a series of projects could be co-developed if their size and location were carefully considered. Specific combinations would require extensive modelling to confirm energy outputs and acceptable cumulative effects. Such modelling is reasonably well established and has been performed for some of the potential combinations[9], although, of course, no full-scale validation has been undertaken. Other different proposals for the Severn Estuary may of course also come forward in the coming years.

[8] IROPI – Imperative Reasons of Overiding Public Interest

[9] Sensitivity of tidal lagoon and barrage hydrodynamic impacts and energy outputs to operational characteristics,

In Summary, what does a tidal power plant produce?

Its contribution to a future clean power network is set out as follows:

i) Generation of low carbon energy for up to 16 hours per day, every day of the year.

ii) Tidal range power projects have more predictable output resources compared with most other forms of renewable energy, reducing demand for long duration energy storage and other forms of back-up generation.

iii) In the Severn Estuary they will be located close to centres of electricity demand with the benefit or shorter transmission links compared with more remote marine energy projects.

iv) If the bulb[10] turbines are synchronised to the grid, they contribute spinning inertia that helps stabilise the grid's frequency response. In addition, they can be brought online very quickly enabling them to be used to meet short-term peaks in the same way as pumped storage plants – as the tides are predictable, any forecast in increased demand that is coincident with a suitable tide state (67% of the time) can be met in this way.

Athanasios Angeloudis, Roger A. Falconer
Hydro-environmental Research Centre, School of Engineering, Cardiff University, The Parade, Cardiff, UK

10 The turbines used are often called "bulb turbines" as a result of their bulb- shaped casings.

4 APPENDICES

A. Cost Assumptions

B. Energy Assumptions

C. Appendix C from Government's Energy NPS Consultation Response

A Cost Assumptions

Estimating the costs of marine walls is complex and published cost data varies across a significant range with costs being influenced by the length of the marine wall, its form of construction, its service requirements and its context. Offshore sea walls for flood defences are generally very expensive because they require high mobilisation costs and are often very short in length which converts to a relatively high unit cost per metre length.

The primary cost database for tidal power is the only published cost build-up which was undertaken by Cost Consultants Corderoy between 2008 and 2010 for the Severn Tidal Power Feasibility Study (STPFS). This is more relevant than the Environment Agency's Cost Database for offshore structures (2015) which focuses mainly on short structures or landside coastal defences or the Scottish Natural Heritage equivalent which dates back to 2000. The STPFS cost database has therefore been used as the baseline data source for costs but benchmarked against the Peel Energy study on the Mersey and the published preferred bidder costs for the Swansea Bay Tidal Lagoon. The unit costs included in the STPFS have been reviewed and updated to a 2023 cost base.

Whilst the analyses of the individual projects largely use STPFS estimates, some proposals are based on developer's own estimates. These have been carried forward by the study and carried forward after indexation up to a 2023 cost base. Where developer's data has been used, this has been compared with the equivalent STPFS empirical data to assess whether cost estimates are under or over-estimated. This is then used to comment on the likely accuracy of the cost estimates in the project database.

Inflation

As there is little recent contemporary evidence, it is necessary to update historic costs to a March 2023 cost basis. It should be noted that DESNZ evaluate renewable energy costs under the Contracts for Difference (CfD) mechanism to a 2012 cost base so this should be born in mind when comparing data with external sources.

The inflation factors used in the toolkit are based on the Bank of England Inflation Calculator which is based on Costs and derived from the Office of National Statistics. Inflation from 2010 to 2021 averaged 2% per annum. 2022 is significantly higher in the range of 8 to 12%. (Note energy retail prices have historically risen at a faster rate than construction costs and thus the value attributed per unit of energy should be inflated using specific energy indices).

Inflation Adjustment to March 2023 Cost Basis	
£1 in 2010	1.44 (2023)
£1 in 2012	1.34 (2023)
£1 in 2015	1.29 (2023)
£1 in 2016	1.28 (2023)

Empirical Cost Data

The empirical cost data used in reviewing project data estimates has been derived as set out below the relevant data sources. It is presented in two primary sections – Mechanical and Electrical Costs and Civil Engineering Costs.

Mechanical and Electrical Engineering Costs

These cover all the mechanical and electrical elements from the turbines and sluice gates through to the switch gear, control systems, cabling and grid connection. They are presented as a global figure on a per MW basis synthesised from previous study data, as per the table below:

Data Source and Detail	**Summary (@ 2023 cost basis) £m/MW**	
	Central Ebb and Flood Unit Cost	*Ebb Only Unit Cost*
Severn Tidal Power Feasibility Study (2010) - *p238 (of 403) from the SEA ODR V3 Volume 2 Report (https://www.gov.uk/government/collections/severn-tidal-power-feasibility-study-conclusions):* (£7,081m for 8640MW ebb only Cardiff Weston Barrage (£0.819m/MW) to £8,765m for 8,640MW ebb and flood Cardiff Weston Barrage (£1.014m/MW) including grid connection and all M&E requirements. Lagoon estimates were based on ebb and flood performance and resulted in a unit costs of £3,697m for 3,600MW ebb and flood Bridgwater Bay Lagoon (£1.027m/MW)	1.5	1.2
Swansea Bay Tidal Lagoon Published Data (2016) - *https://www.parliament.uk/globalassets/documents/commons-committees/business-energy-and-industrial-strategy/Correspondence/Swansea-Appendices-B1-D3-17-19.pdf* 320MW GE-Andritz tendered cost at 2016 prices of £316m or £0.99m/MW	1.26	1.16

Civil Engineering Works and Services

The civil engineering works cover the main elements of the project and the M&E costs above are also reproduced here on the basis that the Civil Engineering Contractor would be Prime and all other suppliers acting as Sub (nominated or otherwise). The table below shows the cost breakdowns per major contract and also by component to provide two perspectives.

Items		Description	Original Unit Cost	Summary (@2023 cost base)	
				Units	*Central Estimate*
Capex Costs by Contract		*These contract figures are derived from equivalent aggregate values from the STPFS (2010) and published tendered values for Swansea Bay. They are presented on a per MW basis (for the advance works and powerhouse contracts) and a per km basis (for the marine wall)*			
1	M&E	*See Details above. Summary figures rounded*		£m/MW	1.5 (ebb and flood) 1.26 (ebb only)
2	Marine Wall	*Swansea Bay received three tenders for their marine wall contract which varied from £340m to £360m with two received from major European marine contractors. The embankments figure for the Bridgwater Bay Lagoon in the STPFS was £638m, 22% of the total Civils Costs of £2.902bn. Adding 22% of the general overhead costs of £617m would give an equivalent marine wall cost of £638m+£135m=£773m for a marine wall length of 13.2km (caissons form the balance of the 16.5km total length).*	Adopting Swansea Bay's higher figure of £360m gives a rate of £40m/km at 2016 cost base. The STPFS Bridgwater Bay example is £54.60m/km . Bridgwater Bay costs are higher because of the very poor ground conditions. A reasonable range of marine wall costs on a per km basis, updated to 2023 cost base is therefore between £55m to £85m.	£m/km	70
3	Powerhouse	*There are four reference points for the civil engineering costs for the Powerhouse. The Swansea Bay figures ranged from £240m (original tender) to £490m (after risk erosion) - £360m is the central value and is for in-situ*	Central estimate of £1.4m/MW applies for ebb and flood schemes although costs may vary from £1.1m/MW to £1.7m/MW depending upon site characteristics, tidal range and other	£m/MW	1.4 (ebb and flood) 1.1 (ebb only)

Items		Description	Original Unit Cost	Summary (@2023 cost base)	
				Units	*Central Estimate*
		construction which incurs additional cofferdam costs. Bridgwater Bay and Cardiff Weston data comes from the STPFS and assume floated in caissons. Peel Energy's Mersey proposals had a cost of £870m for a 700MW turbine installation which was constructed in-situ.	factors. Costs for ebb only projects could be reduced by 20%		
4	Contingency	*For the STPFS in 2010, cost estimates were based on 10% escalation in unit rates plus a 15% contingency giving a total contingency of around 20%. Contingencies in the civil engineering sector can range from 10% for very low risk projects up to 66% for public sector promoted projects incorporating optimism bias.*	Max Optimism bias would skew central estimate so a central figure of 20% has been used.	% of total cost	20%
5	Client Costs excluding navigation and environmental mitigation	*This has been derived from the STPFS and includes all estimated costs outside of the main contracts but excludes navigation and environmental costs which will vary significantly by location.*		% of total cost	3.6%
Capex Costs by Component					
1	Turbine and Sluice Caissons	*As powerhouse analysis above for turbine and sluice caissons.*		£m/MW	1.15 (ebb and flood) 0.95 (ebb only)
2	Rockfill Embankments	*Swansea Bay rate of £53 per cu m (2015) or Bridgwater Bay Lagoon from STPFS which had a cost of £505m for embankments with volume of 11,700,200 cu m which equates to £43.16 per cu m(2010).*	For a 2023 cost basis, the Swansea Bay rate is £67.65 and the STPFS rate is £62. The Swansea Bay rate has been used as it is more recent.	£ per cu m	68.0

Items		Description	Original Unit Cost	Summary (@2023 cost base)	
				Units	*Central Estimate*
3	Plain Caisson Costs	*For plain caissons, WSP's work for The Crown Estate estimate was £55,000 per m of caisson assuming 23m depth, 30 m length and 20 m crest width using 2012 cost basis. This equates to £80,000 per m at 2023 prices. Converting this to a per cu m basis gives a cost of £175 per cu m of caisson volume.*	The crest level of the plain caisson can be close to high water as the structure offers structural protection against overtopping unlike rockfill embankments which require a 5m freeboard to protect against wave damage. A rockfill embankment will be higher than its caisson equivalent but will have a reduced crest width	£ per cu m of caisson volume	175.0
4	Other Civil Engineering Costs	*Other civil engineering costs, excluding navigation locks, are typically for buildings to house the electrical equipment and operating personnel, together with advance works to provide access roads and other site related infrastructure.*	A figure of between £120,000 and £160,000 per MW of installed capacity is proposed. This would equate to a sum of between £40m and £50m for a project the size of Swansea Bay. This compares with their advance works contract value of £34m at 2016 cost base	£/MW	140,000
5	Navigation Locks	*Costs for navigation locks are dependent upon the size of the lock and the STPFS in 2010 estimated costs ranging from £20m for small craft and maintenance dredging vessels through to over £1bn for full scale post Panamax commercial shipping. There are no unit rates for navigation as a consequence.*			
6	Compensatory Habitat	*Compensatory habitat costs were researched extensively for the STPFS. Key issues were the replacement ratio for habitat lost a consequence of changed water levels and their location.*	STPFS used a figure of £45k per hectare for compensatory habitat and a replacement ratio of 2:1. AT 2023 cost levels, this is £65 for every hectare of new habitat or double this figure if measured on the extent of lost habitat.	£/ha of lost habitat	130
7	Other Environmental Mitigation Costs	*Other environmental measures were also included resulting in mitigation costs of between 1% and 5% of the construction costs.*		% of construction cost	3%

Items		Description	Original Unit Cost	Summary (@2023 cost base)	
				Units	*Central Estimate*
8	Decommissioning Costs	*Decommissioning costs need to include, as a minimum, the removal of all mechanical and electrical plant. Removal of the impounding structures may be more challenging as they will have developed their own eco-system communities. However, they will require a fund to help maintain them after closure.*	The range for decommissioning costs ranges from 5% to 50% of the original construction cost depending upon the scale of decommissioning required.	% of construction cost	28%

B Energy Assumptions

Energy assumptions have been tested using two methodologies – one using a capacity factor, the other an empirically derived algorithm based on impounded area and tidal range. These, like the cost assumptions, have been used to assess the appropriateness of developer's own data and to provide a commentary on whether they are over or under optimistic. However, it is the developer's own data that is reproduced and updated to a 2023 base rather than the independent assessment (again echoing the approach used to assess costs). An empirical data assessment is no substitute for a detailed model that simulates the operation of a tidal project to assess energy outputs and the degree of energy modelling undertaken is critical in the assessment of developer's estimates.

Modelling Approaches

Conventionally, a first pass for assessment of annual energy production (AEP) would be undertaken using a 1-D model whereby the water flows through a turbine are modelled against the changing head and tail waters driven by the tidal cycles and the selected operating regime (both mode of operation such as ebb and flood with pumping and the detail of the operating sequence such as the head difference available at the start of generation and the sluicing regime).

Once this had been optimised (for example to confirm the best combination of starting heads for different tidal states, the sluicing regime and the operation mode), more extensive studies would be carried out using a 2-D model. This would model the interference from adjacent turbines and natural currents and what effects this would have on energy output. As a rule of thumb, previous studies have shown that 1-D models over-estimate energy yields by as much as 10% compared with 2-D models.

Another complication is the effectiveness of pumping. In theory, pumping water in or out of the impounding basin when the level difference between the tide and basin is near zero should mean that whatever volume of water is pumped at negligible head could be used to generate more electricity than consumed by pumping if it is released at a higher head. Previous studies have identified energy gains of between 5 and 15%. However, there are at least two practical problems. Firstly, because pumping can only take place over a relatively short period of time, the shape of the impounding basin has a major influence on the potential additional energy. This is because it takes time for water pumped at the powerhouse location to reach the shore. The closer the shoreline, the quicker the lagoon water levels will stabilise (when pumping first starts, the water level will be higher than the water level at the shoreline – simplistically, this results in the pumping head required being double that of the average increase in water level over the entire lagoon area). The net energy gain from pumping is therefore likely to be higher for smaller lagoons than larger ones. The second issue is the cost of pumping. Whilst net energy production may increase, costs for pumping will be variable depending upon the time of day and therefore the increase in energy may be offset in part by the higher costs of pumping.

There is also a potential issue with fish passage. Using the turbines in pump mode increases turbulence and reduces efficiency and these can have a negative impact on fish passage through the turbines. If pumping is to be used, measures need to be in place to eliminate fish from being able to pass through the turbine passages. In addition, if a developer advocates leisure pursuits in the newly created impoundment, exclusion zones would be required to ensure the public are prevented from being at risk from the increased currents during turbining, sluicing and pumping.

Calculating Energy Outputs: Method 1 – Capacity Factor

This is the simplest method and assumes 20% for ebb and flood operation and 25% for ebb only operation. Previous studies have shown a range of 14% (West Cumbria) to 22% (Bridgwater Bay) for tidal lagoons operating in ebb and flood mode and 23% (Cardiff Weston) to 30% (Shoots – English Stones) for tidal barrages operating in ebb only mode. The Swansea Bay and Cardiff tidal lagoons proposed by Tidal Lagoon Power had similar capacity factors of 18% but a default value of 20% has been used as both Swansea Bay and Cardiff lagoons have higher installed capacities than would typically be expected. The higher the installed capacity, the lower the capacity factor for a given energy output (which is typically governed by the area impounded rather than installed capacity for tidal lagoons).

As can be seen, the equation is simple:

Installed Capacity x Capacity Factor x 24 hrs x 365 days = Gross Annual Power Output

Losses are then deducted. They take two forms:

i) the loss in output from the generator terminals to the grid connection point (default = 5%) and

ii) the loss in output due to lack of availability because of outages (default availability = 98%, therefore losses are 2% of gross output).

For a 300MW project with a 20% capacity factor, the final output is 525GWh/yr reducing to 490GWh/yr after 10GWh losses due to outages and 25GWh losses to the grid connection point.

Calculating Energy Outputs: Method 2 – Impounded Area and Tidal Range

This method applies only to tidal lagoons as it is based on the impounded area. Tidal barrages tend to impound larger areas than they need for energy generation purposes and this method is likely to over-estimate energy output from barrages – consequently, this method is only used for tidal lagoons.

The table below sets out the calculation steps using this method. Essentially, the impounded area and tidal range are used to calculate the annual energy production through correlation of outputs from previous studies. The correlation formula is

*Gross Annual Energy (GWh/yr) per sq km = ((((tidal range-5)/5)*0.04)+0.015)*1000*

The energy output per sq km is then multiplied by the impounded area to produce the Gross AEP before adding pumping net energy gain before applying losses as per Method 1. Using a 300MW example, a tidal range of 8.6m and an impounded area of 12 sq km would give an energy yield of 525 GWh/yr before losses.

C Appendix C from the Government Response to Energy National Policy Statement Consultation

The Government's response to the Energy National Policy Statements Consultation included a checklist that they expect to see for tidal range projects. This is reproduced below. It was simplified in December 2023[11] but is reproduced below as originally published.

Appendix C – Guideline Criteria for a 'Well Developed' Tidal Range Proposal

1.1 This appendix details the kind and quality of evidence that Government expects tidal range developers to provide in order to demonstrate that their project is well developed.

1.2 The criteria set out here are published for indicative purposes only, and do not constitute a definitive or exhaustive list of requirements.

1.3 Moreover, these criteria specify only the minimum level of detail necessary for Government to give initial consideration to a proposed development. Satisfaction of these criteria – either in whole or in part -- will not guarantee the Government's entry into negotiations, whether financial or otherwise.)

1.4 So far as is reasonably practicable, all information supplied to Government in connection with the criteria set out here should be supported by robust evidence and/or verification by independent third parties

Table – Guideline Criteria for a 'Well-Developed' Tidal Range Proposal

Thematic Criterion	Evidence Required
1. Demonstration of Energy System Benefits.	Detailed modelling of energy system costs/benefits, including e.g. any effect on electricity system balancing costs, transmission costs, system inertia, and security of supply.
	Detailed information on the expected generation profile of the station, to be verified by an independent engineer. This should be expressed in terms of a high/low range of outputs, and should be periodised to the smallest useful time-interval. The expected average output plus expected standard deviation should also given.
	Detailed information on the turbines to be used, including likely manufacturer and/or supplier.
	Where the proposal depends on commercially unproven technology, developers should provide:

[11] https://www.gov.uk/government/publications/tidal-range-projects-criteria-and-how-to-submit-a-proposal/criteria-for-a-well-developed-tidal-range-proposal

Appendix C – Guideline Criteria for a 'Well Developed' Tidal Range Proposal		
		1. Evidence of commitment from a turbine manufacturer and any associated information of relevance concerning patents and intellectual property. 2. Evidence of plans to move from concept stage to commercialisation, including in-situ testing. 3. Information from testing, including on a full size prototype in a comparable environment (for example with the range of fish species expected), to inform realistic predictions of turbine operations, including energy output. 4. Detailed summary of lessons on viability and feasibility of the technology gleaned from testing, such as lessons on blade survivability in the marine environment. 5. Evidence of contingency plans for system failing to meet predicted performance after full scale testing.
		Detailed assessment of the whole-life carbon impacts of the project.
	2. Demonstration of Credible Environmental Impact Mitigation Strategy	Evaluation of potential flood impacts throughout the lifecycle of the project. (Impacts should be quantified in absolute terms, and also expressed in terms of impacts on standards of protection and life of existing defences, so as to enable third parties to make judgements on the significance of the impacts.) An environmental scoping and impact report to include the following:
		6. A description of the proposed development, including the physical characteristics, land use requirements and build materials. 7. A specification of the site selection criteria and the main alternatives considered, taking into consideration the potential environmental impacts. 8. Realistic modelling of potential environmental impacts, including detailed assessment of likely impacts on fish populations; habitats and fisheries; birds; and water quality. 9. Assessment of the above impacts, as well as impacts on wider fauna and flora, air, water, soil, climate, heritage, landscape, and any interrelationship between these receptors. 10.Assessment of any pertinent indirect, secondary, and/or cumulative impacts
		In light of the above, detailed plans on how environmental impacts will be avoided, reduced, mitigated and (if required) compensated for, including statement of approach to biodiversity net gain

Appendix C – Guideline Criteria for a 'Well Developed' Tidal Range Proposal

		Evidence of extensive environmental stakeholder engagement, ideally including letters of support from relevant stakeholders.
	3. Demonstration of Value for Money.	Detailed funding strategy including specific information on expected sources of debt and/or equity during the design, construction and operation phases. Ideally to include views and feedback from specific potential investors.
		Where the project depends on commercially unproven technologies, an analysis of how project costs could vary as those technologies move from concept to commercialisation
		Visibility of the project's financial model on an open book basis in order to test all relevant assumptions
		Supply chain management strategy including critical path analysis and information on how inputs have been cost-benefit evaluated and will be secured throughout project life. This should include a construction plan describing in detail the necessary programme of works, associated risks, and timeline for their completion.
		End of asset life strategy, including rationale for leaving infrastructure in situ or costed plans for decommissioning. Where applicable include statement of options for repowering.
		Evidence that relevant data can be made available to enable a value for money assessment to be undertaken, according to the relevant value for money framework.
	4. Demonstration of Socio-Economic Impacts and Benefits.	Substantiation of the project's claimed economic benefit, including e.g. a statement of expected capital and operational spend in the UK, and independently audited net and gross job creation projections.
		A cost-benefit report to include: 11.Analysis of impacts on relevant local industries (such as commercial and recreational fisheries; aggregates). 12.Analysis of impacts on ports and navigation. 13.Plans for any mitigation or compensation required in light of the above.
		Evidence of extensive stakeholder engagement (including with local communities and any affected industries). Letters of support from relevant stakeholders should ideally be included.
		Evidence and accounting of any additional benefits, including e.g. coastal erosion protection, flood defence, recreation, tourism and broader community benefits

Appendix C – Guideline Criteria for a 'Well Developed' Tidal Range Proposal

1.5 Additionally, developers should provide a detailed project delivery plan including the anticipated timetable for securing all necessary leases, consents and grid connections. A post-construction plan for operational monitoring and maintenance should also be given.

1.6 Such a plan should also include documentation of the potential delivery risks and associated mitigation actions, as well as a summary of the project's governance arrangements. A holistic assessment of delivery confidence in the project as a whole should also be given.

Kings Orchard
1 Queen Street
Bristol
BS2 0HQ

wsp.com