Western Gateway Partnership – Severn Estuary Commission

Severn Estuary Tidal Energy & System Integration Study

Final Report

Reference: WGP-REP-001

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Acronyms

Acronym	
CBA	Cost benefit analysis
CfD	Contract for difference
CCUS	Carbon Capture Utilisation and Storage
DA	Day Ahead
ENTSO-E	European Network of Transmission System Operators for Electricity
FES	Future Energy Scenarios
LCOE	Levelised Cost of Energy
NPV	Net present value
UK ETS UK	Emissions Trading Scheme
NESO	National Electricity System Operator
NETA	New Electricity Trading Arrangements
GB	Great Britain
HE Pathway	Hydrogen Evolution Pathway
WGP	Western Gateway Partnership
GHG	Greenhouse Gas
WY	Weather Year

Executive Summary

The UK's greenhouse gas reduction target of net zero by 2050 requires a significant transformation for the GB power sector towards low carbon generation technologies. Tidal range technology offers the potential to be a significant part of the low carbon generation mix. The Severn Estuary, because of its high tidal range and large basin, offers a rich potential for tidal range generation outputs. However, to date, the impact and evidence of this potential has not been fully explored. To address this, the Western Gateway Partnership (WGP) commissioned four reports into the environmental, economic, funding & financing and the system integration impacts of the tidal electricity generation assets in the Severn Estuary.

This report covers an assessment of integration of Severn Estuary tidal assets on the GB power system and its role in meeting the UK's net zero targets. To undertake this assessment Arup used both qualitative and quantitative methods. Qualitatively, Arup reviewed the literature on tidal assets, explored the licencing requirements, reviewed tidal range technologies and assessed the costs of connection in the Severn Estuary.

Arup undertook an extensive modelling exercise to explore the system integration impacts of varying capacities and types of Severn Estuary tidal range generation assets. The integration impacts are assessed as the potential costs and benefits to consumers (and society) of adding tidal assets through GB wholesale power prices, transmission constraint costs, existing CfD policy costs and system resilience. These have significant impacts on the cost of the GB power system, costs which are ultimately paid for by the consumer. In particular, the cost of transmission constraints has grown rapidly and is forecast to cost up to £3bn per annum by the early 2030s. The location of generation assets relative to the transmission system is the main driver of these constraint costs. This is the first study to assess how well situated the Severn Estuary is for tidal range assets in terms of these transmission constraint costs.

Arup used its GB Power System model to simulate and quantify the impacts of various tidal range asset scenarios. The simulation inherently requires the use of assumptions about the development and location of future energy supply, demand and the transmission network. Arup used the NESO's Future Energy Scenarios and the 'Beyond 2030' network design assumptions as the basis for this work. Sensitivities on battery storage capabilities and extreme weather events were applied to test the robustness of the results. The results were, where possible, quantified and aggregated into a monetary cost-benefit analysis to provide comparators impacts of tidal assets against other types of generation assets.

A range of target case scenarios were compared against a counterfactual scenario in which there was no tidal range generation capacity assumed on the electricity network. The scenarios were developed to cover a range of technologies, commission dates and generation capabilities. For these target scenarios Arup used its tidal energy generation tool to create generation profiles for each of the generating assets used in the target scenarios. To enable consistency with NESO spatial inputs, all scenarios were based on using locational FES data and projections, and the Hydrogen Evolution pathway.

<table>
<tr><th colspan="2">Target cases used in this study</th><th>Strategic reasons for running the target case</th></tr>
<tr><td colspan="2">Target Case 1:
8.6 GW of Tidal Capacity Severn Estuary
Operating Mode: Ebb and Flood
Rest of GB: 0.7 GW
COD: 2040</td><td>Large Tidal Barrage in the Severn Estuary
Understanding of large costs and impact associated with grid upgrade requirements for massive energy generation in the South-West
Slow to be fully operational due to significant Consenting/Planning challenges but brought forward from 2047 on assumption that there is government ambition and support</td></tr>
<tr><td>Target Case 2a:
4.8 GW of Tidal Capacity Severn Estuary</td><td>Target Case 2b:
4.8 GW of Tidal Capacity Severn Estuary</td><td>2No. Lagoons located in the Severn Estuary
Lagoons will still have a significant installed capacity so will provide better understanding of the extent of grid upgrades required.</td></tr>
</table>

Target cases used in this study		Strategic reasons for running the target case
Rest of GB: 0.7 GW Operating Mode: Ebb and Flood **COD: 2035**	Rest of GB: 0.7 GW Operating Mode: Ebb, Flood and Pump **COD: 2035**	With and without pumping considered as pumping will lead to increased power demand within region Two lagoons to be constructed and delivered at same time, so longer time frame to being operational than Target Case 3
Target Case 3a: 3 GW of Tidal Capacity Severn Estuary Rest of GB: 0.7 GW Operating Mode: Ebb, Flood and Pump **COD: 2032**	**Target Case 3b:** 3 GW of Tidal Capacity Severn Estuary Rest of GB: 0.7 GW Operating Mode: Ebb, Flood **COD: 2032**	1No. Lagoon located in the Severn Estuary Lagoon will have reasonable installed capacity and could be delivered within shorter time frame to maximise benefits of increased capacity. With and without pumping considered as pumping will lead to increased power demand within region Provides sensitivity analysis of installed capacity compared to Target Case 4
Target Case 4: 1 GW of Tidal Capacity Severn Estuary Rest of GB: 0.7 GW Operating Mode: Ebb **COD: 2035**		Smaller Tidal Barrage. Brought online earlier than the 8.6GW barrage but as it's a barrage, expect longer Consenting/Planning compared to a lagoon Smaller installed capacity should limit the impact on the existing grid and limit upgrade costs
Target Case 5: 0.3 GW of Tidal Capacity Severn Estuary Rest of GB: 0.7 GW Operating Mode: Ebb, Flood and Pump **COD: 2032**		1No. Small tidal range lagoon Limited installed capacity should minimise impact on the existing grid and upgrade costs

The target case scenarios were run in Arup's GB power system model to forecast the potential impact of Severn Estuary tidal assets on whole market power prices, constraint costs, existing CfD policy costs and system resilience requirements. These were compared against the counterfactual projections.

Results

Wholesale power prices: The larger generation capacity scenarios (T1 and T2) were found to significantly reduce the wholesale power price over the study period. The scenarios with less capacity only had a modest impact compared to the counterfactual.

Impacts on constraints costs: The modelling projections suggest that the smaller target case scenarios tidal assets in the Severn Estuary do not increase constraints costs compared to the counterfactual in the study period. These suggest that the Estuary is a benign location for smaller assets (below 4.8GW).

However, the larger target case scenarios suggest that capacities above 4.8GW could increase constraint costs payments. There is the potential for network development to reduce the cost impact of the larger capacity scenarios.

Impacts on the costs of existing renewables through the CfD: Similar to the impact on wholesale power prices, the target cases with the highest tidal generation capacity (T1 and T2A/B) have the most significant effect.

These scenarios marginally increase the costs of existing renewables through the CfD, while all other target cases result in costs that remain on par with the counterfactual case.

System resilience: The modelling indicates that tidal generation assets would likely have a positive impact on system stability by providing increased system 'inertia' and reducing the need for the NESO to procure frequency response services. This benefit has not been quantified but is expected to be much smaller in magnitude to the other impacts given the relative current impacts compared to wholesale prices and constraint costs. The larger the tidal capacity modelled the greater the benefit through more system inertia and the reduced need for spendings on frequency support by the NESO.

The battery sensitivity: The sensitivity was run with a co-located 4-hour duration battery of 6.8GW peak capacity as a sensitivity to the target case scenario 1. It is recognised that this is an unrealistic scenario, but was run to illustrate the potential impact of adding battery capabilities. This sensitivity suggested that the additional flexibility improves the integration of tidal assets by reducing the negative constraints costs. The reason being, although tidal energy benefits from a high degree of predictability—since tidal patterns can be calculated far in advance—it is not dispatchable in the same way as flexible generation technologies. Power output is largely constrained by the timing and magnitude of the tides, limiting the ability to adjust generation outside these natural cycles to fit real-time grid needs. Adding a co-located battery to a tidal generator led to the creation of a hybrid generation asset which is better suited to cater for real-time grid needs due to higher degree of flexibility.

A cost-benefits analysis (CBA) using the analysis from this this study was used to combine all the quantified results in a single calculation. The CBA aggregates each element of the quantified results into a single figure Net Present Value (NPV) figure that covers the period of assets coming online to 2050. Given the differences in commissioning dates for the representative tidal projects across target case scenarios, the CBA results are presented in three separate figures, each covering a distinct time period.

- **2040-2050:** This period includes all target case scenarios, as all tidal projects are fully operational by 2040.
- **2035-2050:** This period includes all target case scenarios except for T1, which comes online only in 2040.
- **2032-2050:** This period includes only target case scenarios 3A/B and 5, as these are the only scenarios that begin in 2032.

The CBA results are broadly positive across the range of CBA time periods:

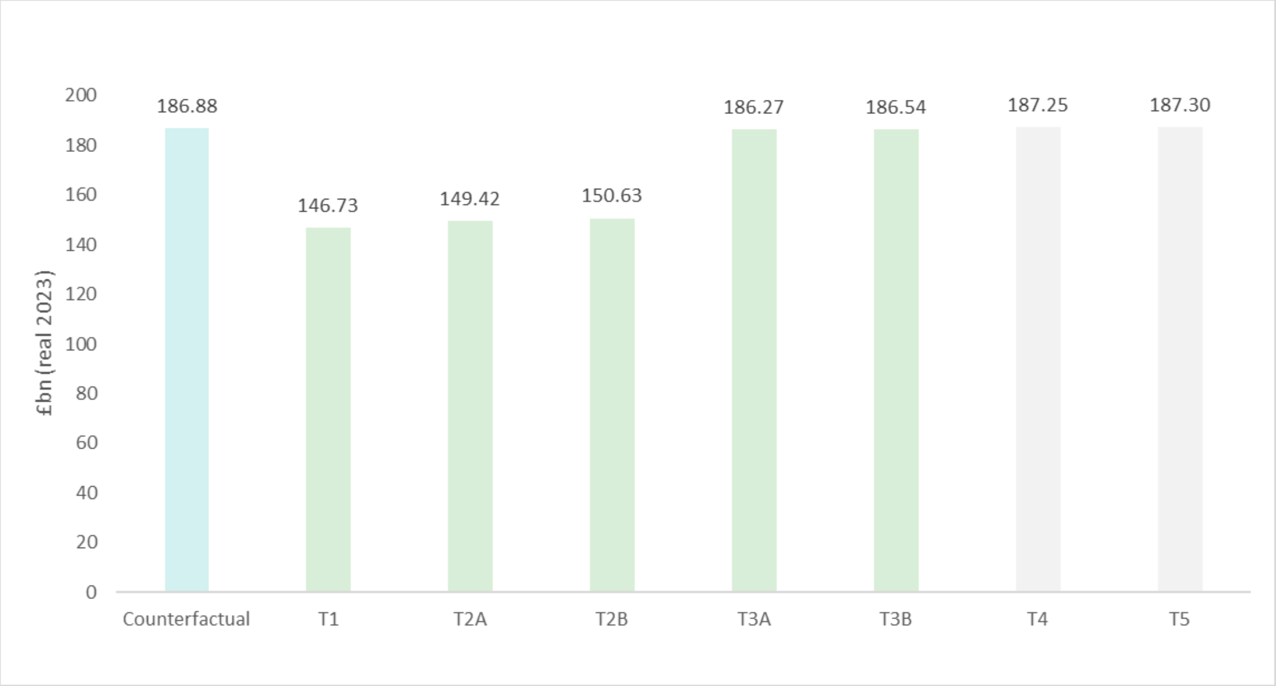
In the period 2040-50, the scenarios are all positive except cases T4 and T5 which are only marginally negative. The larger capacity scenarios offer significantly more positive CBA results through lower NPV costs compared to the counterfactual. This is driven by the larger tidal capacity reducing the wholesale costs, providing significant benefit.

For the period 2035-50 – the targets case T2(A&B) costs are significantly lower than the counterfactual, again driven by reductions in the wholesale power price.

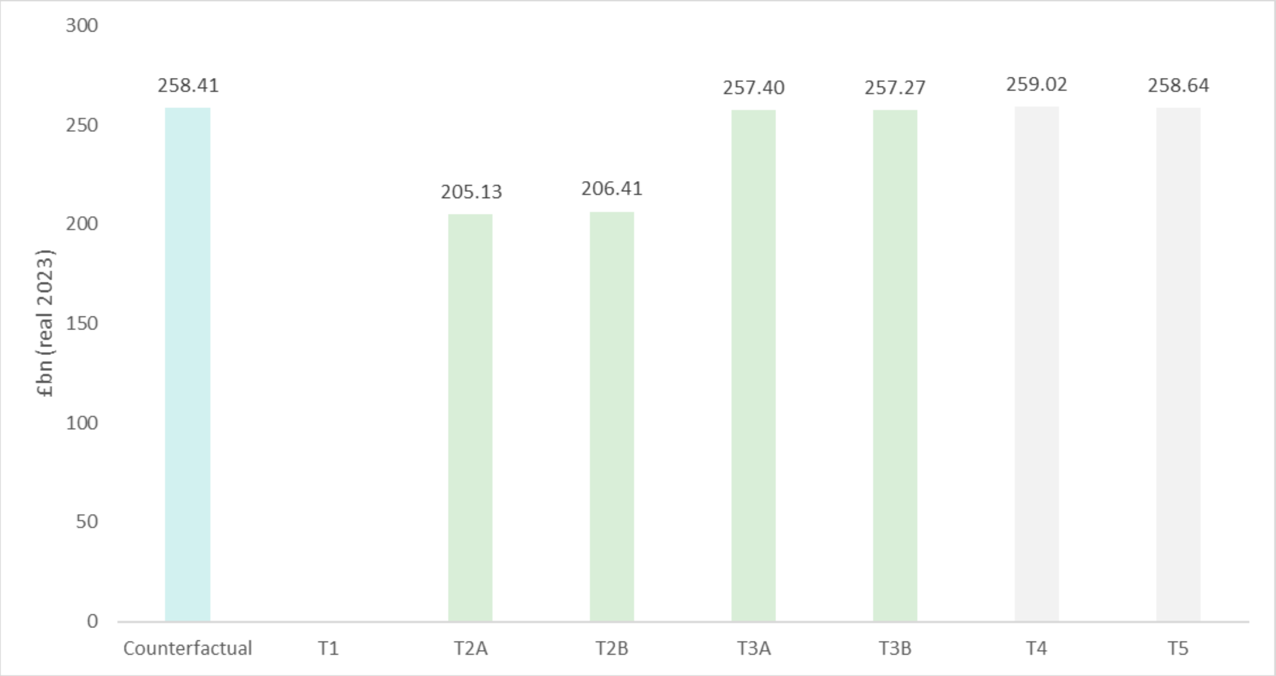
In the period 2032-2050 – the available target cases T3 (A&B) and 5 are all marginally positive (costs less) than the counterfactual scenario.

The results suggest that the earlier the date allowed in the definition of each target case scenario, the economic case is strengthened for each target case with the exception of target case 4. This remains marginally more expensive than the counterfactual case even with a start date in 2035.

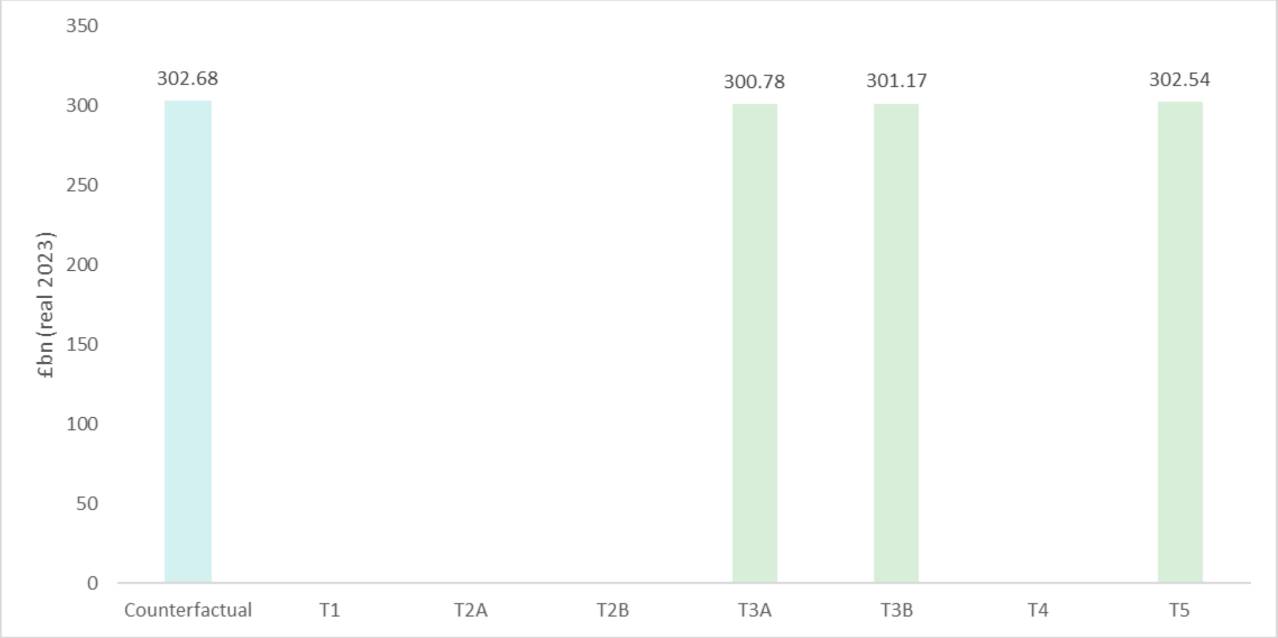
Analysing the breakdown of the CBA results suggest the results are predominantly driven by changes in the wholesale price (see CBA section for the breakdown).



2040-2050 GB Consumer Cost NPV

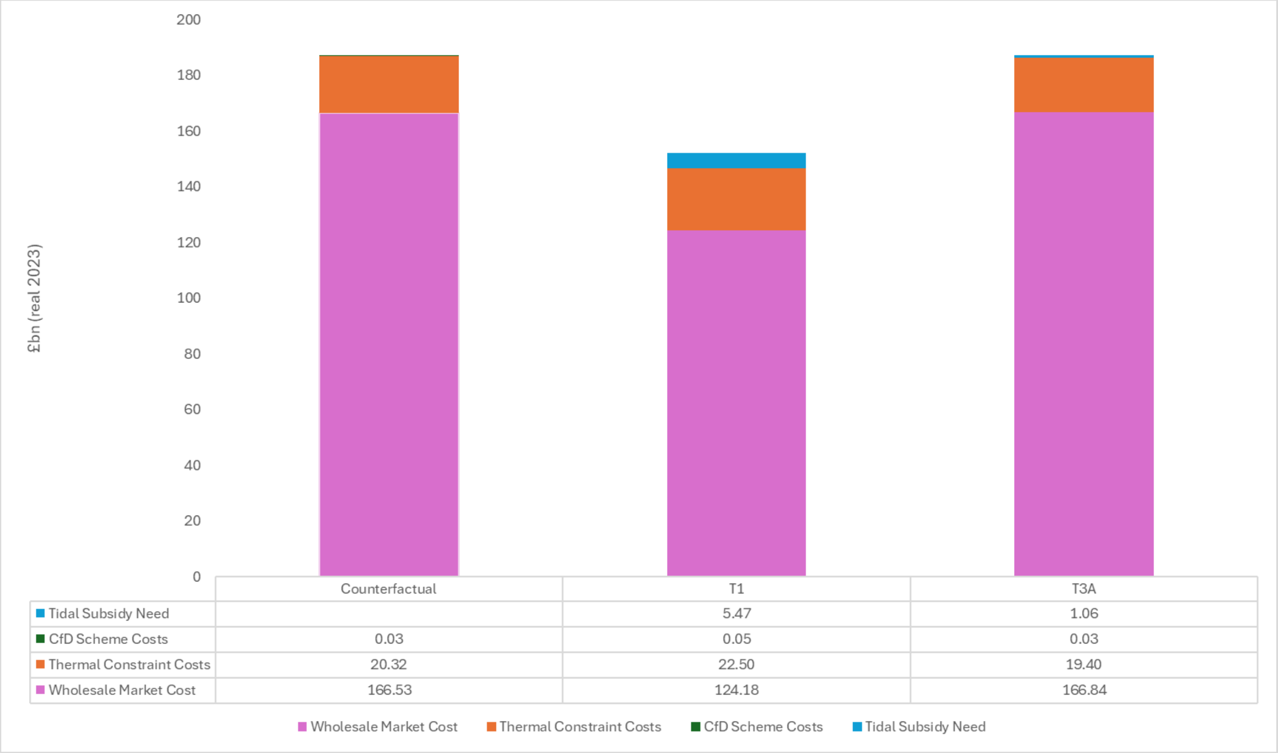


2035-2050 GB Consumer Cost NPV



2032-2050 GB Consumer Cost NPV

A further cost-benefit analysis was conducted using Arup’s outputs combined with Agilia’s data on capital and operational costs, which were not included in Arup’s core CBA (key results presented above). Agilia had been commissioned by WGP to explore funding and financing costs of tidal assets. Using Agilia’s cost requirement estimate of £100 per MWh for tidal assets, together with Arup’s revenue estimates, we calculated the subsidy needed for the target case T1. We then used a value of £75 per MWh for the target case 3A. This figure was then combined with the CBA analysis to provide estimates for the net present value cost including any implied subsidy. It was only available for the target case scenarios T1 and T3A. The results suggest that even when considering these subsidies, the T1 target case scenario would still deliver savings to GB consumers. However, the target case scenario T3A is marginal when the subsidy need of tidal is included in the CBA as demonstrated by the figure below.



	Counterfactual	T1	T3A
■ Tidal Subsidy Need		5.47	1.06
■ CfD Scheme Costs	0.03	0.05	0.03
■ Thermal Constraint Costs	20.32	22.50	19.40
■ Wholesale Market Cost	166.53	124.18	166.84

CBA Comparison on NPV Costs including implied Tidal subsidy costs

Cost of connections. A review of the cost breakdowns from the 2010 Severn Tidal Power Grid Study was carried out, specifically examining the costs associated with the B3 Cardiff to Weston Barrage configuration. The independent desktop connection cost estimates are summarised below considering a 1GW and 8.6GW tidal range asset respectively.

For 1GW, the capex cost estimate for the grid connection is c. £200m. This is based on:

- A 400kV GIS substation located (outdoors) on the barrage or tidal lagoon,
- 6km of cable installed in a cable tunnel in the structure, and
- 25km of cable to the connecting a National Grid substation.

For 8.6GW, the CAPEX cost estimate for the grid connection is c. £1,600m to £2,000m. This is based on:

- A minimum of 5-6 substation 400kV GIS substations, assumed to be located on the barrage,
- Each substation has a 400kV busbar, and
- Each substation has an export cable comprising of 6km installed in a tunnel on the structure and 25km connecting to the National Grid network.

Licencing Arup also undertook an assessment of the licencing the potential licensing requirements in GB. There are a complex set of licensing requirements for tidal assets in GB. These comprise marine, environmental generation and other permitting requirements. Thes requirements are highly project specific and need to be clearly understood for project specific cost estimation. The existing framework is likely to create challenges for merchant project developers as it increases project risk.

Conclusions

Large capacities of tidal generation (i.e. over 4GW) can put downward pressure on wholesale power prices which would benefit the consumer. However, this needs to be considered against the full subsidy cost required to give a balanced assessment. In addition, larger tidal capacities located in the Severn estuary have the potential to increase system constraint costs.

Smaller tidal asset capacities have relatively benign, and in some case positive, impact on constraint costs. This may suggest that the Severn Estuary is a good location for smaller tidal assets in terms of impacts on GB transmission network. The later projects come online the more likely the positive impact on constraints cost payments.

Tidal assets are likely to have beneficial impact on system stability and reduce the costs to the consumer of frequency response services being procured.

The cost-benefit analysis suggests that tidal asset in the Severn estuary could be broadly cost positive for the consumer. However, this would need to be compared to alternative options and costs.

The subsidy required for Severn estuary tidal assets appears to be relatively low – noting that this based on price projections from one FES pathway with significant uncertainty.

Recommendations

The results of this analysis need to be considered in conjunction with the findings from the other reports commissioned by the WGP. Any specific project assessment would need to consider the specific local environmental costs.

The analysis suggests that smaller tidal range asset scenarios in the Severn Estuary could offer positive benefits, subject to any additional local environmental costs and considerations. However, larger-scale capacities may require further scrutiny by the WGP to assess their feasibility and potential impacts.

The Severn Estuary appears a relatively good place for tidal assets in terms of the planned network design and future demand and supply connections. However, this needs further assessment relative to other potential locations and pathways.

Furthermore, tidal assets located Severn Estuary could provide additional benefits from 2050 onwards and these assets are expected to have long operational lifetimes (~100years). These additional benefits should be further considered. In addition, new network design options could increase the benefits of Severn Estuary located tidal range assets by enabling more flows from West to the high demand centres in East.

Arup recommends that the WGP uses this report to initiate discussion with DESNZ and the NESO on Tidal projects in the Severn Estuary,

1. Introduction

1.1 Project context

The UK has legally binding greenhouse gas emissions reduction target of being net zero by 2050. This will require both the decarbonisation of the power sector as well as the electrification of other sectors of the economy. This will drive the need for significant amounts of low carbon generation to be built and connected to the GB power system. Different generation technologies in different locations in GB will have significantly variable costs implications for the GB power system and what consumers pay for it. There is currently limited evidence on the impact of integrating Severn estuary tidal assets on the GB power system. The Western Gateway Partnership have commissioned Arup to address the gaps in evidence with this study.

The Western Gateway Partnership (WGP) comprises 28 Local Authorities, one Mayoral Combined Authority in England, and two Corporate Joint Committees in Wales, representing over 4.8 million people. The Severn Estuary sits at the heart of Western Gateway's geography and has long been recognised for its potential to generate renewable electricity. The Partnership launched the Severn Estuary Commission to consider the feasibility of developing tidal range energy. Chaired by Dr Andrew Garrad CBE FREng, the Commission comprises experts in science, engineering, finance, sustainable development, and environmental disciplines.

The WGP commissioned WSP/ HJA/ Agilia/ Arup to consider four aspects of tidal range potential:

- Environmental
- Socio-Economic
- Funding and Finance
- Tidal asset energy system integration and potential role in net zero.

The Severn Estuary is one of the most extensively studied sites for tidal range energy due to its high tidal range and large basin, which are conducive to energy generation. However, little is known about the potential impacts of integrating Severn estuary tidal assets to the GB power system and their role in achieving the net zero targets. This report is aimed at exploring the potential impacts on the GB electricity network of integrating tidal energy generation assets in the Severn Estuary. The study uses both qualitative and quantitative research to inform the conclusions.

The impacts of tidal assets on the electricity system are key to understand whether tidal generation offers a cost-effective generation solution for GB consumers. For this study the cost of integrating tidal generation have been broken down into the following components:

- Impact on **transmission constraints costs**[1] – the location of generation assets is becoming an increasingly important issue for policy makers and system planners. The National Energy System Operators (NESO) is currently spending about £1.5billion a year to manage transmission constraints. This is forecast to increase significantly, up to £4bn a year, in the late 2020s and 2030s as the NESO has managed increasing amounts of renewables on a limited transmission network. These costs are borne by GB consumers, and the NESO is increasingly trying to mitigate these costs. The location of generation assets is of increasing importance given the NESO's role in planning the system.
- Impact on **wholesale market prices** – tidal range assets are understood to have low marginal costs and are likely to have a downward effect on the overall market price in GB. These impacts are currently not well understood but could have significant implications for GB consumers.

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[1] Thermal constraint costs are extra expenses that arise when electricity flows must be adjusted after the day-ahead market schedule is set. Although the day-ahead market decides who will generate power and when, real conditions can mean certain transmission lines risk overloading. At that point, the National Electricity System Operator (NESO) must re-dispatch—paying some generators to lower output and others to raise it—so the grid does not exceed safe limits and maintain the balance between demand and supply of electricity. The cost of making these last-minute adjustments is referred to as thermal constraint costs.

- Impact on **grid stability and system resilience** – as the UK moves away from fossil fuels, the resilience of the GB power network is affected because of the loss of thermal generation which offers an inherent resilience through the 'inertia' provided by spinning. Thermal generation has residual kinetic energy that helps guard against sudden outages and losses. Tidal generation assets offer a potential counterbalance because the turbines will have a similar spinning affect to thermal generation. This has the potential to reduce the costs of maintaining system stability for the system operator. This is likely to offer a potential benefit albeit the scale of these impacts is in the millions and not the billions associated with constraint costs.

- **Revenues made and subsidy required** – It is highly unlikely that tidal assets will be developed purely on merchant basis given the 'first of its kind' technology and risks to investors involved. Therefore, it is widely expected that some form of subsidy would be required to bring the assets to the market. This study aims to help understand this further by estimating potential revenues that a tidal asset could make. This can then be combined with the estimated costs of capital and operational costs of tidal assets to make an estimate of how much subsidy is required to make the assets economically viable. For this study, Arup used the outputs of the Agilia study to help generate an estimate subsidy required for the assets.

This study uses Arup's tidal energy generation modelling tool to provide electricity generation power outputs from potential assets in the Severn Estuary and sets them out in scenario 'target cases'. The assets considered are 'generic' tidal assets, as in they are not specific development projects providing a realistic view of the generation profiles and asset capabilities. However, to make the study as realistic as possible they have been informed by previous considerations of and the recent research into tidal generation technology. A range of potential scenarios have been used to consider wide and illustrative range of energy generation performance. In addition, the potential for tidal assets to be combined battery technology is also considered in a sensitivity.

The outputs from Arup's tidal modelling are then used in Arup's Power System Model to provide estimates of the impacts on the GB power system market prices, CfD subsidy cost, and constraint costs. The modelling uses the latest FES assumptions on the GB power system network development as set out in the NESO's Beyond 2030 document. This is broken down into GB transmission boundaries, to provide the latest outlook for transmission constraints costs and localised geographical level. We use the latest assumptions and network design assumptions. However, it is highly likely that there will be future network developments which would impact the results.

These modelling elements are aggregated to provide a cost benefit analysis (CBA) of the potential tidal assets in the Severn Estuary in terms of system costs. This CBA aggregates the constraints cost impact, the wholesale price impact and the cost of the existing CfD subsidy scheme in the target case scenarios with varying degrees of tidal capacity and capabilities. A net present value figure is generated to cover the period when the asset comes online in the target case and the 2050 target using Greenbook accounting techniques. The tidal scenario target cases are then compared to a counterfactual scenario. This enables a comparison of how tidal generation compares to other technologies incorporated in the counterfactual. The CBA analysis is conducted under a range of time periods to account for the differing dates when assets come online. A further CBA is performed using the outputs from the Agilia report into the funding and financing of tidal assets to take account of any potential subsidy required.

To inform the modelling and conclusions additional, qualitative evidence was also reviewed:

- **Evidence base review:** analysed previous work on the tidal generation potential of the Severn Estuary, building on past tidal energy initiatives.

- **Tidal energy project evaluation**: assess various tidal energy projects, such as barrages and lagoons, across different scales and configurations, including hypothetical projects informed by project examples.

- **New technology assessment**: identified and evaluated the feasibility of innovative technologies, including bi-directional and low-head turbines, and examine potential infrastructure improvements for cost and performance benefits.

- **Grid connection challenges**: consider the cost and feasibility of connecting tidal energy projects to the grid, considering connections to both the Welsh and English sides of the estuary

The following are not included in this study:

- Optimising a tidal range asset's performance at a specific site. As such, focusing on optimising the performance of a single project will have a negligible impact on the conclusions which can be drawn.
- Similarly, the purpose of this study is not to identify a specific preferred site for a tidal range project but to provide a range of generation capacities to understand the implication of the size of a tidal range project on the GB power network.
- The environmental implications of a tidal range lagoon being introduced into the estuary are not within the scope of this study.
- Where multiple assets are included in a target case, they have been modelled individually. Where two projects are modelled (Target Cases T2A/B), cumulative effects are not taken into account - energy outputs are likely to be lower so, for grid impact purposes, ignoring cumulative effects provides the worst case.

The report aims to inform the debate on the efficacy of Severn Estuary tidal in GB by considering its impact on the GB power system and its costs and benefits to GB consumers. This is expected to be of interest to policy makers at DESNZ, Ofgem and the NESO. The report is expected to be of particular interest to the NESO given its consideration of constraint costs and its new role delivering strategic spatial energy plan. As such the modelling approach and assumptions have been discussed and agreed with the NESO.

The report is structured as follows:

- The reminder of the introduction defines tidal range technology.
- Chapter 2 sets out the target cases and counterfactual. This includes a discussion of the various generation technologies in the scenarios.
- Chapter 3 sets out the CBA analysis.
- Chapter 4 covers the output from Arup's Tidal Tool (ATT) and power market modelling.
- Chapter 5 covers cost of Connection for Severn estuary tidal assets; and
- Chapter 6 cover licencing requirements.

1.2 Tidal energy definition

Tidal range energy is a form of hydropower that converts the energy obtained from tides into electricity or other forms of power. It harnesses the movement of water due to gravitational interactions between the Earth, moon, and sun. Unlike wind or solar power, tidal energy is highly predictable, as tidal cycles follow regular and known patterns. This predictability makes tidal energy a reliable source of renewable energy. The movement of water, whether in the form of rising and falling tides or underwater currents, can be harnessed through specialized technologies, making it an essential component of future renewable energy systems.

Tidal energy remains a relatively untapped resource globally, with only a few large-scale operational projects. It contributes a small percentage to the global energy mix, but its potential is significant, especially in regions with high tidal ranges. For instance, countries like France, South Korea, and the UK have been exploring and implementing tidal range power projects, with France being home to the world's first large-scale tidal power plant at La Rance.

In the UK, tidal energy holds promise due to the geography of its coastline, especially in areas like the Severn Estuary and Pentland Firth. The UK has one of the largest marine energy resources in Europe, with tidal energy seen as a strategic opportunity to diversify the country's renewable energy portfolio. The focus in this study is on tidal range and not tidal stream technology

Tidal energy is especially pertinent in locations with large tidal ranges, such as the Severn Estuary between South Wales and Southwest England, which records one of the highest tidal ranges globally, reaching up to 14 meters during the spring tides. Given this potential, the Severn Estuary has been identified as a prime site for tidal energy development. A range of proposed projects in this region, including the Cardiff–Weston Barrage, Fleming Lagoon, and Shoots Barrage, highlights the potential of the tidal range energy to contribute to the

UK's Net Zero targets. The UK's approach reflects a growing global interest in tidal energy, particularly as countries strive to diversify their energy portfolios to balance growing demand, economic stability, and environmental protection.

1.3 Tidal energy technological overview

1.3.1 Tidal range technologies

Several key technologies are used to harness tidal energy, each suitable for different marine environments and tidal conditions. The focus of this study is tidal **range** energy generation, and so no reference is made to tidal **stream** technology. Tidal range energy generation relies on controlling the flow of water into and out of the impounded area, creating a head difference across the structure which can then be used to generate electricity through turbines. There are several variations on tidal range generators, as described. For project examples, please see Table 0-1

Barrages

A tidal barrage is a dam-like structure built across a tidal basin or estuary, typically crossing from one bank to the other.

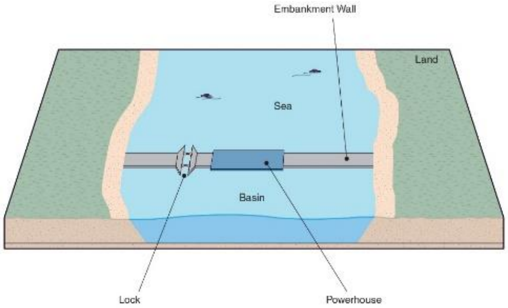

Figure 1-1: Tidal barrage. Source: Arup

Onshore tidal lagoons

Onshore tidal lagoons function similarly to barrages but enclose a small body of water, typically on the same side of the water body.

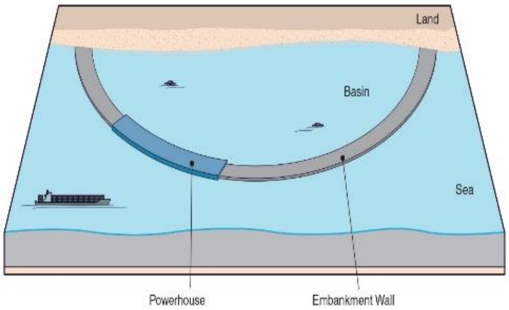

Figure 1-2: On-shore lagoon (also known as coastal lagoon). Source: Arup

Offshore tidal lagoons

Offshore lagoons would impound an area of water entirely offshore but otherwise function similarly to onshore lagoons.

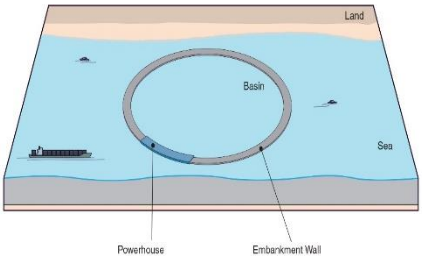

Figure 1-3: Off-shore lagoon. Source: Arup

These technologies collectively demonstrate tidal energy's versatility and adaptability, offering a range of solutions for harnessing this renewable resource in various geographic and environmental settings. However, tidal energy still faces challenges, particularly related to capital cost, environmental impact, and technological maturity, but ongoing projects continue to improve its feasibility and efficiency (IRENA, 2023).

1.3.2 Modes of operation

Tidal range technology can generate energy in three operating modes: ebb generation, flood generation and two-way generation, as described below.

Ebb generation

On a falling (ebb) tide, sluices in the barrage or lagoon are closed to retain water and are released under controlled conditions to allow water to flow through the turbine channel(s). On a rising tide, turbines are disabled and sluices are open, allowing water to freely enter the basin, or impoundment.

Flood generation

This mode operates in reverse to ebb generation and energy is captured using the rising, rather than the falling tide.

Two-way generation

Two-way generation can be used to extend the generation window of tidal energy with a combination of ebb and flood generation, hence improving the load factor. Where ebb or flood generation would generate power twice in a 24-hour period, two-way generation could allow generation four times in the same period. The efficiency of generation for each tidal phase is slightly lower for two-way generation, owing, in part, to the particular design of the turbines and the time required to maximise the head before the start of the next phase of generation. Overall, however, net production is typically increased with two-way operation and will improve the economics of a project.

Pumping

Turbines can be used to provide pumping, which is a method of boosting generating output from tidal range by pumping water out of or into the basin during periods when there is little difference in the height of water either side of the embankment wall.

For tidal lagoons, it can be done at the end of each generation period to continue the flow of water after the turbines have stopped generating and further increase or reduce the final lagoon level achieved at high and low tides respectively or can be used in flood direction only. This increases the total volume of water that can pass through the lagoon or barrage, increase the net difference between internal and external levels and hence the amount of energy that can be produced (even when the energy usage of the pumping is considered). It can reduce the loss of any intertidal area within the basin by more closely matching the natural tidal range.

2. Representative Projects and Target Cases

Using the Evidence Base, Arup identified a selection of example tidal range projects in the Severn Estuary. The purpose of this section is to develop the Modified Representative Projects (MRP) which will be taken forward for further analysis and modelling in the project.

2.1 Representative projects

WGP has put forward a list of tidal range projects that are to be considered as part of this project. A summary of these projects is given in Table 2-1 and the locations are shown in Figure 2-1. These provide an indication of the locations and types of schemes that have been proposed in the region. A number of other proposed tidal range projects have been suggested in the past for the Severn Estuary such as Flemings Lagoon, Bridgewater Bay Lagoon and Beachley Barrage.

For the purposes of this study, consideration of further lagoon types, locations and configurations is not seen to add value to the overall objectives. The six schemes provide a wide range of installed capacities which will enable the study to draw broad conclusions about the impact that different sized tidal generation schemes have on the regional and national power network, as well as different operating modes.

Table 2-1: Summary of Representative Projects

Project	Installed Capacity (GW)	Energy Generated (TWh/yr)	Description
Cardiff–Weston Barrage	Up to 8.6	16.7	One of the largest proposed tidal range projects globally, spanning from Cardiff to Weston-Super-Mare. This project is the largest of the schemes considered in the estuary and would have the largest impact on grid infrastructure [1].
Shoots Barrage	1	2.8	A smaller proposed barrage located upstream of the Severn Bridge.
Cardiff Lagoon	1.8	5.5	A proposed tidal range onshore lagoon with its 25km breakwater extending from Cardiff Docks to the River Usk.
West Somerset Lagoon	2.5	6.5	A proposed onshore lagoon with 14km breakwater located between Minehead and Watchet on the southern coast of the Bristol Channel [2].
Stepping Stones	0.8	1.2	A smaller proposed onshore lagoon located on the rock formation between Aberthaw and Barry in South Wales, close to Aberthaw Power Station. This lagoon would avoid the main shipping channels and most sensitive areas of the Severn Estuary [3].
Swansea Bay Lagoon	0.3	0.520	A relatively small proposed onshore lagoon, located in Swansea Bay on the South Wales coast with a 9.5km long breakwater [4].

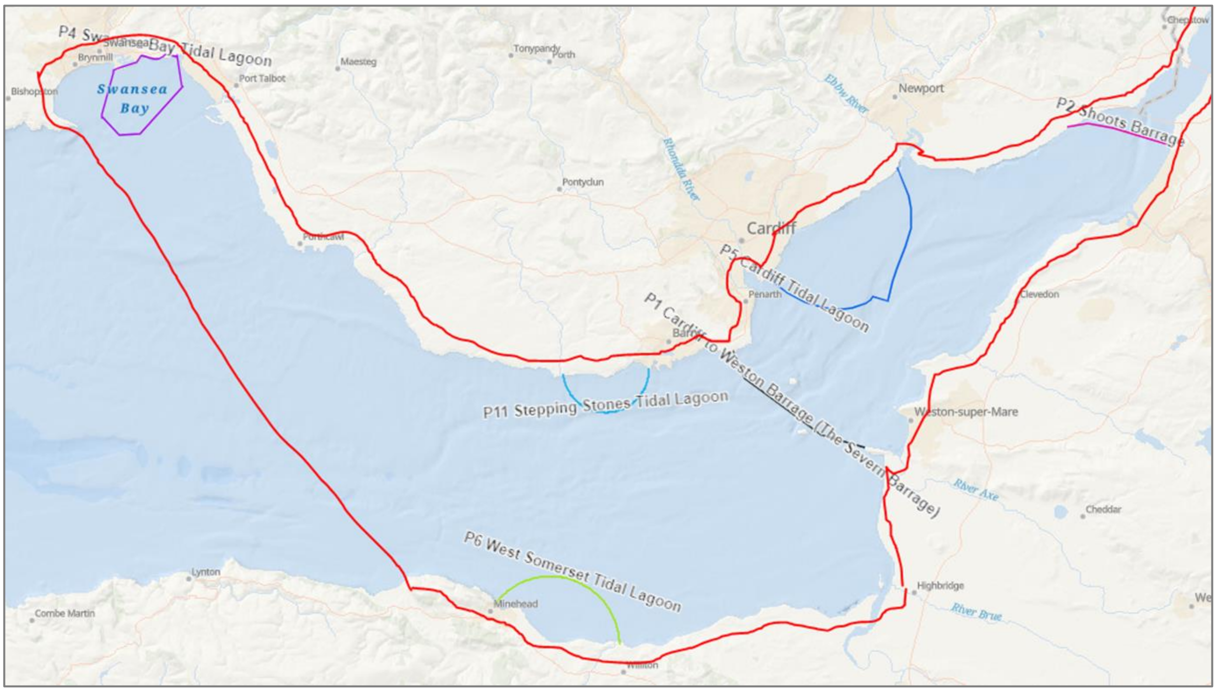

Figure 2-1: Representative tidal range projects

2.2 Modified Representative Projects (MRP) and Target Cases

The Representative Projects provide a sufficient range of installed capacities to be able to develop a number of scenarios, or ‘Target Cases’ which will be used to model energy generation profiles and assess the impact of these assets on the GB energy network. To develop the target cases, the representative projects have been further developed to form a list of modified representative projects (MRPs). This means that specific proposed projects within the Estuary have not been modelled, but instead information from the representative projects has been used to identify reasonable target cases to model.

In addition to the consideration of the schemes in the Severn Estuary, it was also agreed that a further project outside of the region should be considered as part of the power market modelling to reflect the possibility of additional tidal generation as part of the UK power network within the next 25 years, and in line with FES Scenario. It was decided that this tidal range project should be based in North-West England as the tidal range in this area is sufficient to make a scheme credible and there are already proposals for projects in this region.

The MRPs are modelled to use conventional bulb turbines, operating in the modes illustrated in Table 2-2. Turbine technologies are discussed briefly in Section 1.3. The large tidal ranges in the Severn mean that low head turbines are unlikely to be required, and sufficient data is available on bulb turbines to allow them to be accurately modelled.

Table 2-2: Modified Representative Projects for analysis

Tidal Range Project	Installed Capacity	Operating Modes Considered
Large Barrage	8.6 GW	Ebb/Flood
Small Barrage	1 GW	Ebb only
Lagoon 1	3 GW	Ebb / Flood Ebb / Flood with Pumping
Lagoon 2	1.8 GW	Ebb / Flood Ebb / Flood with Pumping
Lagoon 3	1 GW	Ebb / Flood with Pumping
Barrage based in North-West England	0.7 GW	Ebb / Flood Ebb / Flood with Pumping

The Target Cases that will therefore be modelled in this study are shown in Table 2-3 below alongside a rationale for why consideration of the case is considered relevant.

Table 2-3: Target cases for energy market analysis

<table>
<tr><th colspan="2">Target cases used in this study</th><th>Strategic reasons for running the target case</th></tr>
<tr><td colspan="2">**Target Case 1:**
8.6 GW of Tidal Capacity Severn Estuary
Operating Mode: Ebb and Flood
Rest of GB: 0.7 GW
COD: 2040</td><td>Large Tidal Barrage in the Severn Estuary
Understanding of large costs and impact associated with grid upgrade requirements for massive energy generation in the South-West
Slow to be fully operational due to significant Consenting/Planning challenges but brought forward from 2047 on assumption that there is government ambition and support</td></tr>
<tr><td>**Target Case 2a:**
4.8 GW of Tidal Capacity Severn Estuary
Rest of GB: 0.7 GW
Operating Mode: Ebb and Flood
COD: 2035</td><td>**Target Case 2b:**
4.8 GW of Tidal Capacity Severn Estuary
Rest of GB: 0.7 GW
Operating Mode: Ebb, Flood and Pump
COD: 2035</td><td>2No. Lagoons located in the Severn Estuary
Lagoons will still have a significant installed capacity so will provide better understanding of the extent of grid upgrades required.
With and without pumping considered as pumping will lead to increased power demand within region
Two lagoons to be constructed and delivered at same time, so longer time frame to being operational than Target Case 3</td></tr>
<tr><td>**Target Case 3a:**
3 GW of Tidal Capacity Severn Estuary
Rest of GB: 0.7 GW
Operating Mode: Ebb, Flood and Pump
COD: 2032</td><td>**Target Case 3b:**
3 GW of Tidal Capacity Severn Estuary
Rest of GB: 0.7 GW
Operating Mode: Ebb, Flood
COD: 2032</td><td>1No. Lagoon located in the Severn Estuary
Lagoon will have reasonable installed capacity and could be delivered within shorter time frame to maximise benefits of increased capacity.
With and without pumping considered as pumping will lead to increased power demand within region
Provides sensitivity analysis of installed capacity compared to Target Case 4</td></tr>
<tr><td colspan="2">**Target Case 4:**
1 GW of Tidal Capacity Severn Estuary
Rest of GB: 0.7 GW
Operating Mode: Ebb
COD: 2035</td><td>Smaller Tidal Barrage. Brought online earlier than the 8.6GW barrage but as it's a barrage, expect longer Consenting/Planning compared to a lagoon
Smaller installed capacity should limit the impact on the existing grid and limit upgrade costs</td></tr>
<tr><td colspan="2">**Target Case 5:**
0.3 GW of Tidal Capacity Severn Estuary
Rest of GB: 0.7 GW
Operating Mode: Ebb, Flood and Pump
COD: 2032</td><td>1No. Small tidal range lagoon
Limited installed capacity should minimise impact on the existing grid and upgrade costs</td></tr>
</table>

2.3 Counterfactual Cases and Target Cases Capacity Mixes

Figure 2-2 represents the capacity mix replacing tidal capacity in the FES Hydrogen Evolution. Therefore, Figure 2-3 does not represent the pure FES Hydrogen Evolution capacity mix. The replacement capacity mix was designed with two key aspects in mind, first and foremost ensuring that that the security of supply was maintained and secondly that the replacement capacity represented a diverse range of technologies as to avoid concerns of potential design bias in favour of tidal energy. This modelling approach and assumptions were discussed and agreed with the NESO during a workshop.

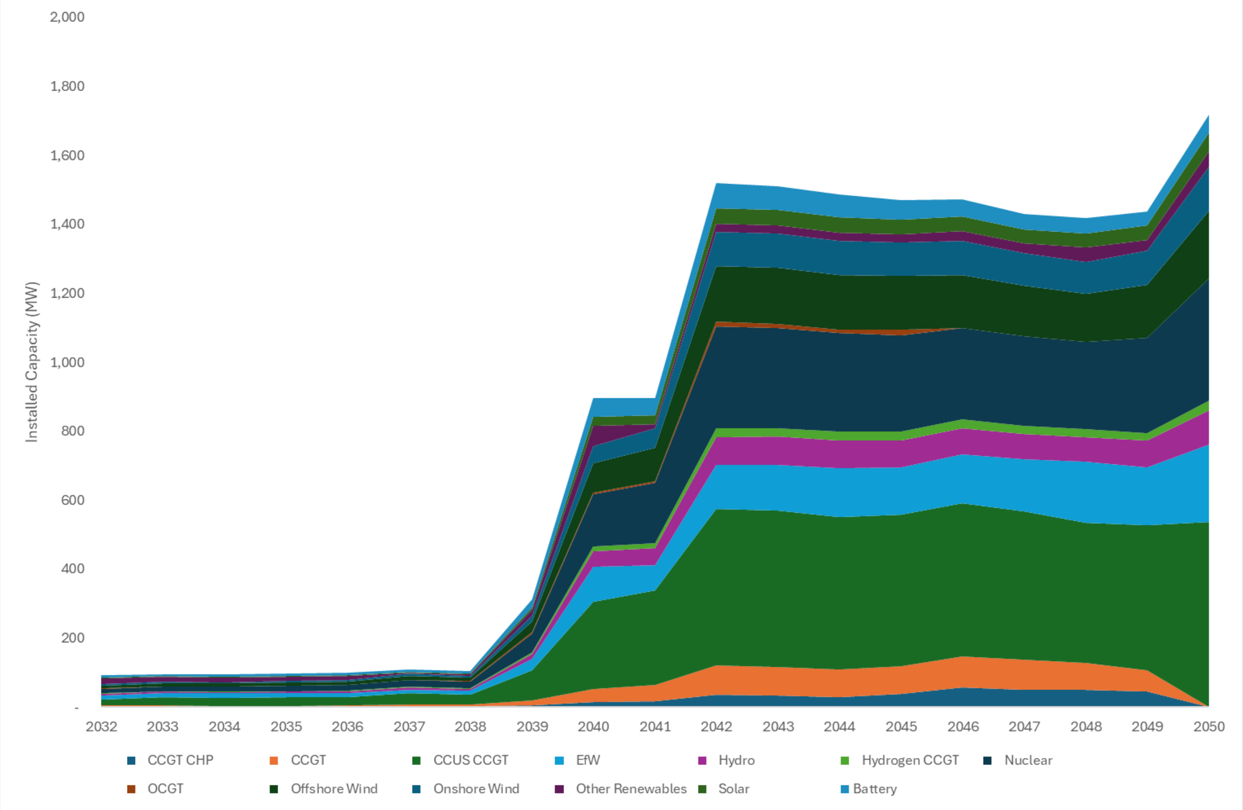

Figure 2-2: Tidal Replacement Capacity Mix for the Counterfactual

The following charts illustrate the capacity mix that fills the gap left by the shortfall in tidal capacity compared to the levels assumed in the FES Hydrogen Evolution (HE) Pathway for the target cases, where the tidal capacity does not reach the level assumed in the pathway, resulting in a capacity gap that is filled by additional generators. This gap is filled by other generation technologies to maintain the security of supply level required in the system. Target cases with tidal capacity equal to or exceeding the FES HE Pathway level required no adjustments, as agreed upon with NESO.

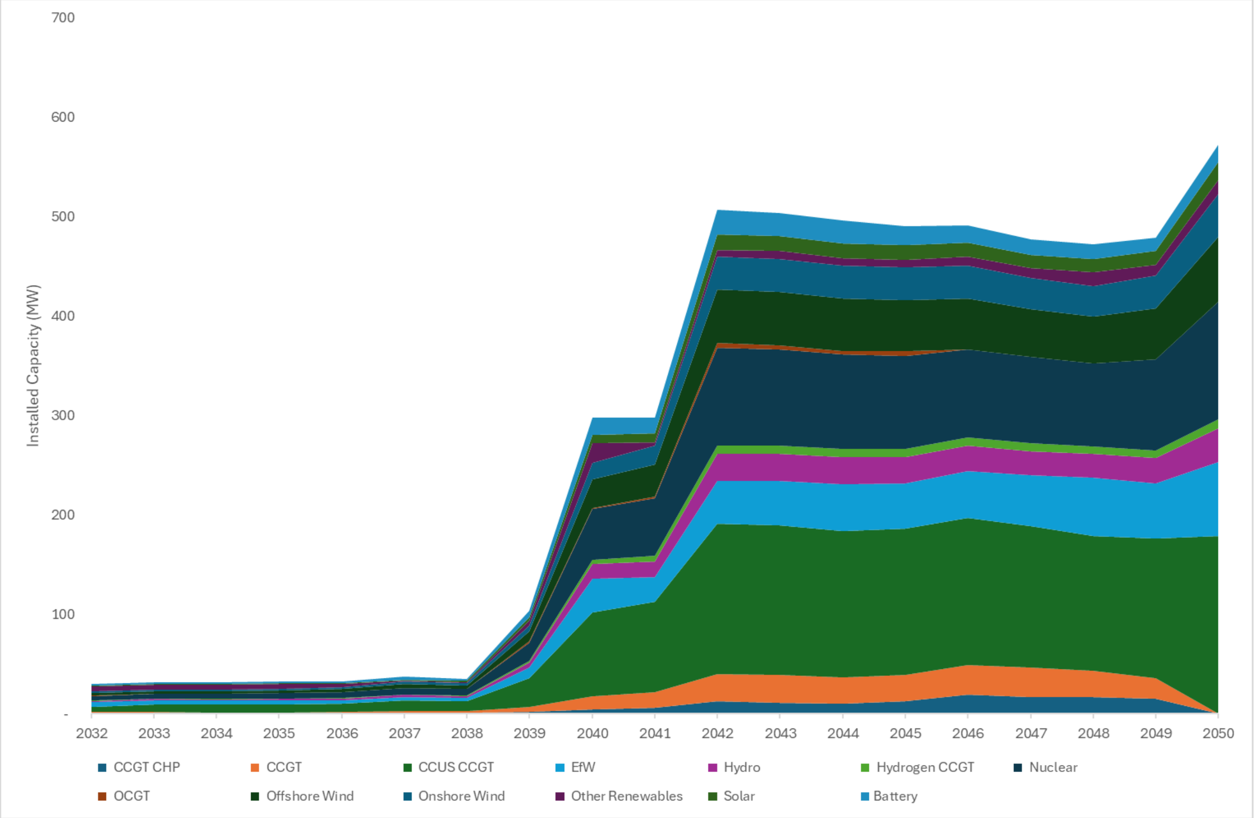

Figure 2-3: Tidal Replacement Capacity Mix for the Target Case 3A & 3B

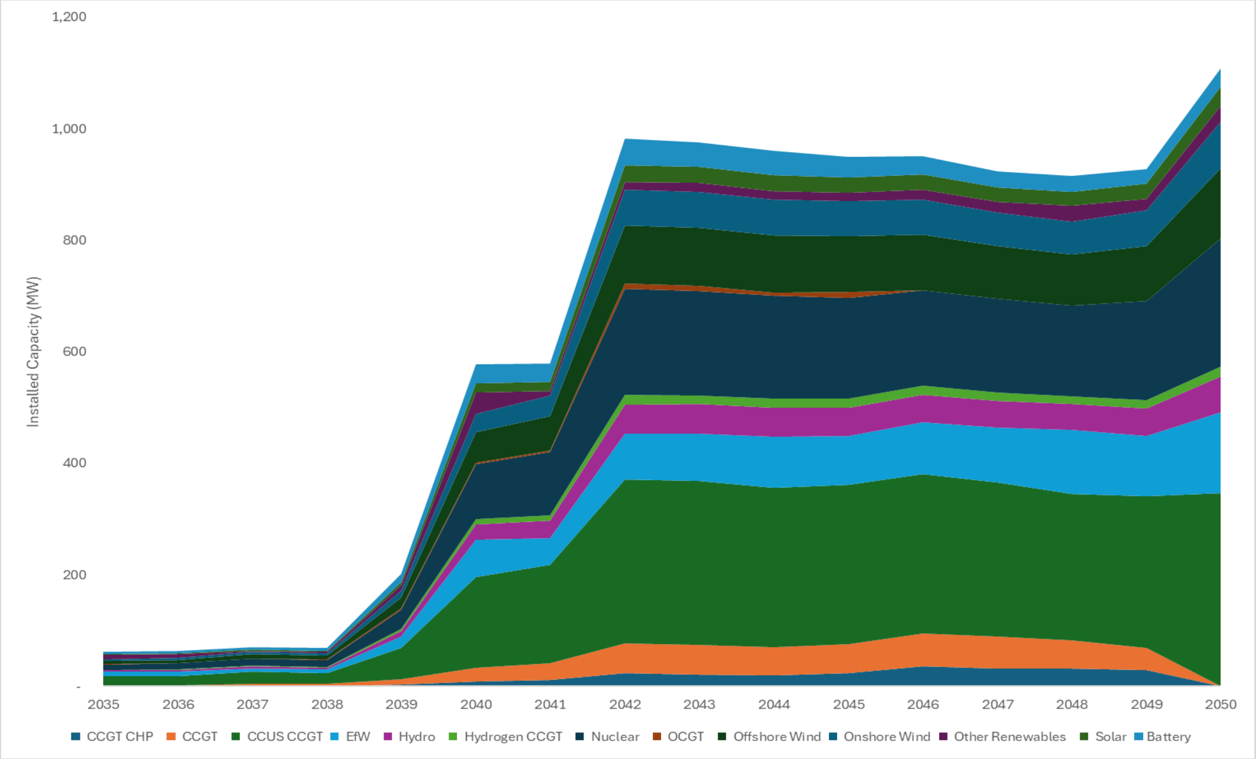

Figure 2-4: Tidal Replacement Capacity Mix for the Target Case 4

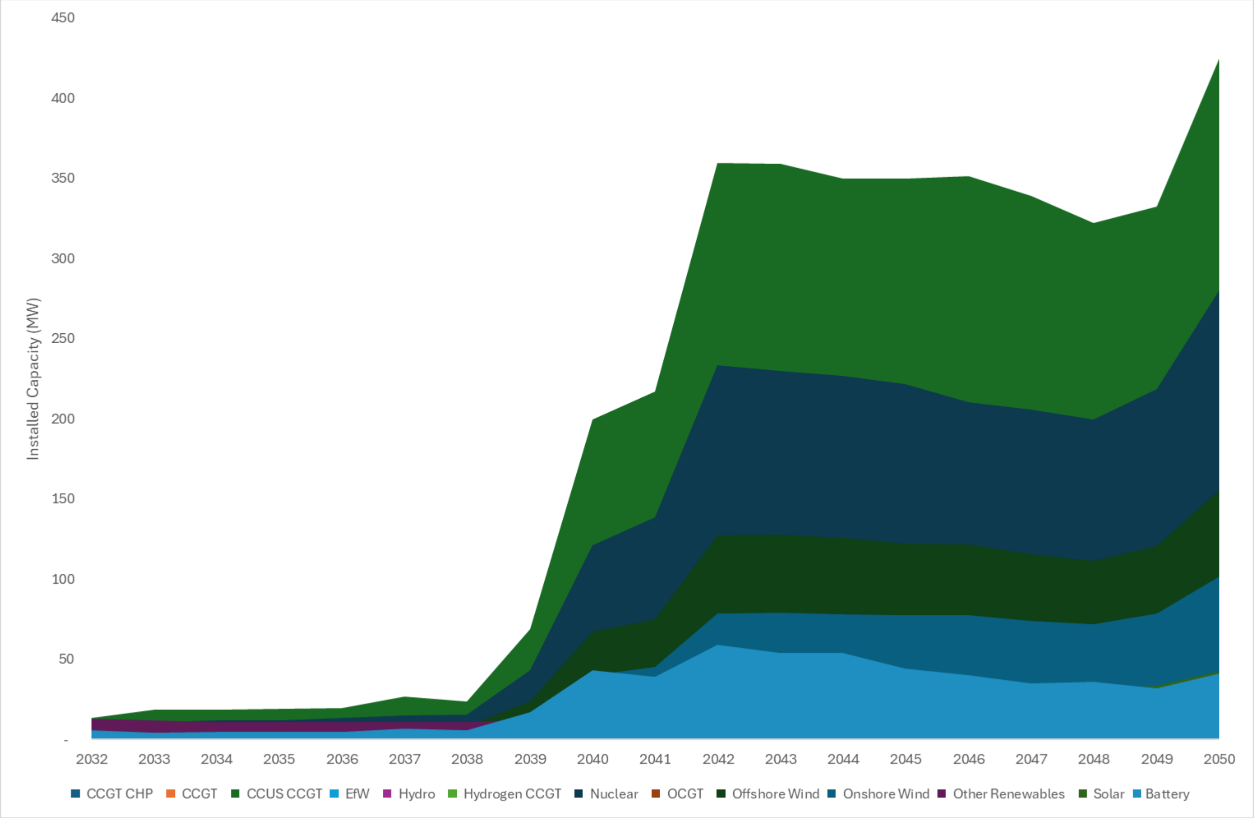

Figure 2-5: Tidal Replacement Capacity Mix for the Target Case 5

3. Impact of Tidal on GB Consumer: CBA Analysis

3.1 Approach and Definition of the GB Consumer Cost

The following section sets out the CBA analysis conducted for this study. The purpose of the CBA is to bring together the results of the modelling analysis into a single Net Present Value (NPV) figure. This enables the target case scenarios to be compared to one another and against the counterfactual. A comparison can also be made on a consistent basis accounting for the differing start dates in the scenarios. As all scenarios, including the counterfactual scenario, will have the cost for the consumer.The tidal asset scenarios are deemed to be beneficial when this cost is lower than the counterfactual. The analysis uses HMT Greenbook accounting guidance, with the costs and benefits discounted at 3.5% from the start of asset operations. The study period looks at impacts up to 2050.

The NPV is comprised of the following quantifiable impacts on:

Wholesale market - tidal assets have the potential to affect the GB wholesale power price. The modelling forecasts the possible power price in the contractual and in the target cases scenarios. If tidal assets result in lower power price compared to the counterfactual this can be a significant benefit to consumers. The modelling uses The Day-Ahead wholesale electricity price, estimated hourly across the study period. The cost of carbon set by the UK Emissions Trading Scheme (UK ETS), meaning generators factor the carbon price into their bids, influences the overall market price.

Constraints costs – The NESO has spent millions of pounds each year manging constraints on the network where there is insufficient transmission capacity to get supply to meet demand. This is forecast to be between £500-3bn by the early 2030s. The constraint costs are driven by the location of generation assets relative to transmission capacity and electricity demand. The modelling estimates how much NESO will have to pay to this annually in the target case with generartion assets in the Severn Estuary and counterfactual scenario, thereby estimating what impact Severn estuary tidal assets could have on constraint costs.

***Existing CfD Policy costs* –** the costs of the existing CfD schemes are affected by the market price and the dynamic of the generation supply mix. This is not linked to the financing of the tidal generators under consideration in this study. Instead, this cost component captures the ripple on effects of tidal generation on the generators who have a CfD contract by affecting the wholesale market price. The modelling compares the potential of the scheme in the counterfactual and target case scenarios.

The GB Consumer outputs from the power market modelling (using PLEXOS) are fed into the CBA, this in turn uses the tidal energy modelling (conducted with Arup Tidal Tool) as input into in the power market modelling as illustrated in the figure below.

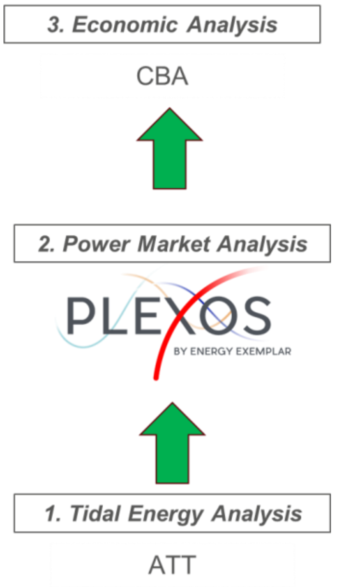

Figure 3-1: Step-by-Step Input flow logic of the study

The GB consumer cost is made up of three distinct components as illustrated in the figure below:

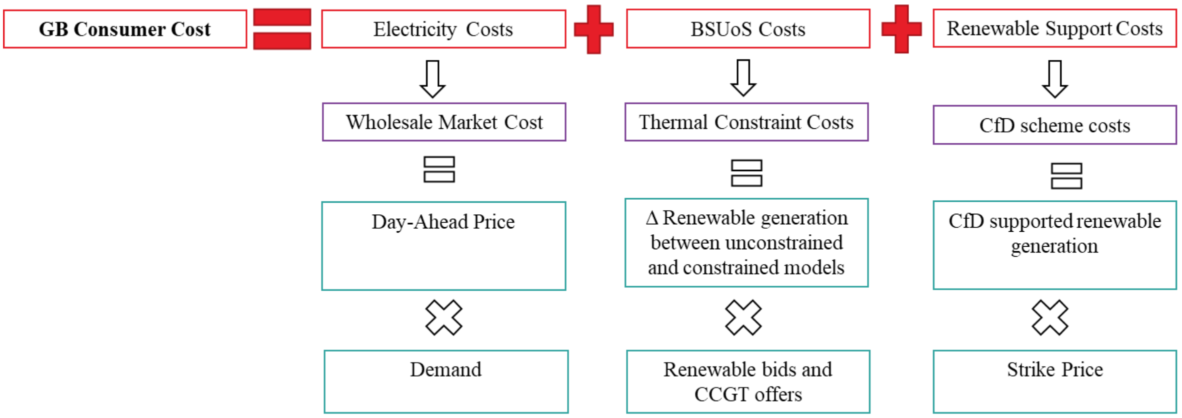

Figure 3-2: GB Consumer Cost Definition[2]

The analysis also presents results of the battery and extreme weather year sensitivities. The following caveats to the analysis should be noted.

FES Pathway – The market price impacts are modelled on **one** FES pathway. This is also adjusted to allow for assessment of tidal impacts. Therefore, the price impacts should be taken as indicative and only a sign of the potential price impacts.

Network design assumptions – the modelling uses the latest assumptions on the network design. However, these will undoubtedly change on the way to 2050. This is likely to lead to changes to our network design that will significantly affect constraints cost. This would affect both the counterfactual and target cases scenarios.

Study time period – the study time period goes up to 2050 as the focus on the of tidal for UK's GHG targets. Tidal assets are known to have long asset lives approximately 100 years. This means significant potential for future costs and benefits to be realised. This is outside the scope of this study.

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[2] Balancing Services Use of System (BSUoS) charges. The BSUoS charge recovers the cost of day-to-day operational cost of constraints including the cost of balancing the electricity transmission system. CCGT stands for Combined Cycle Gas Turbine Power Plant. CfD stands for contract for difference.

Project specific costs – including local environmental impacts are not included in the CBA.

3.2 CBA Results

The following goes through the high-level results of the CBA analysis. This is considered in two different cases. The first cases explore the CBA for consumers assuming no potential subsidy costs. Later in the section the results explore the CBA including the potential subsidy. This requires comparing the revenue generated by these tidal generators with the Levelized Cost of Energy (LCOE) calculated by Agila, the financial advisor of WGP. This enables an indicative figure for any subsidy required to be estimated and used in the CBA.

3.3 The CBA results

As discussed, target cases do not all start in 2032. Therefore, the figure below focuses on the common time range between the counterfactual and all target cases for ease of comparison. In other words, the figure below can be interpreted *as if* all cases started in 2040. The view is presented to facilitate the comparison between the various target cases on an equal basis.

Each bar represents the net present value (NPV) of the cost borne by the GB consumer for each case. The lower the height of the bar respective to the counterfactual case, the higher the GB consumer cost savings and therefore the better for GB consumer welfare.

Figure 3-3: 2040-2050 GB Consumer Cost NPV

The key insight from Figure 3-3 above is that out of the seven target cases, five are delivering a saving to the GB consumer (green bars) when considering the period 2040-2050 in the NPV calculation. Equally important, the two remaining cases (grey bars T4 and T5) are only marginally above the cost to GB consumer in the counterfactual case.

The following figure below provides further explanations of Figure 3-3 by breaking down the GB Consumer cost into its individual components:

	Counterfactual	T1	T2A	T2B	T3A	T3B	T4	T5
CfD Scheme Costs	0.03	0.05	0.05	0.05	0.03	0.03	0.03	0.03
Thermal Constraint Costs	20.32	22.50	22.33	22.38	19.40	20.28	20.25	20.29
Wholesale Market Cost	166.53	124.18	127.04	128.21	166.84	166.23	166.97	166.98

Figure 3-4: 2040-2050 GB Consumer Cost NPV – Broken by cost components

The Figure above, explains why for example, the target case 1 leads to a GB consumer cost saving with respect to the counterfactual despite having higher thermal constraint costs *and* higher CfD scheme costs. These two higher costs are offset by the decrease in the wholesale market cost. Target cases 2A and B follow a similar trend where the increased thermal constraints costs *and* CfD scheme costs are more than offset by the decrease in the wholesale market cost, resulting into a lower overall cost for the GB consumer.

Target cases 3A and 3B differ marginally from each other due to the different operating mode of the same tidal generator. Target cases 4 and 5 have similar impact on the GB consumer cost components with a marginal increase on the wholesale market cost and a marginal decrease on the thermal constraint costs and the CfD scheme costs.

Now, if we expand the range of the NPV calculations to 2035-2050 for the target cases it applies to: namely 2A, 2B, 3A, 3B, 4 and 5. Comparing the Figure 3-5 below, with the Figure 3-3 offers a consistent picture as target cases 2A, 2B, 3A and 3B continue to deliver savings the GB consumer whilst target cases 4 and 5 continues to be marginally above the counterfactual case. This means that the GB consumers have a vested interest in having a start date for the cases in 2035 rather than 2040.

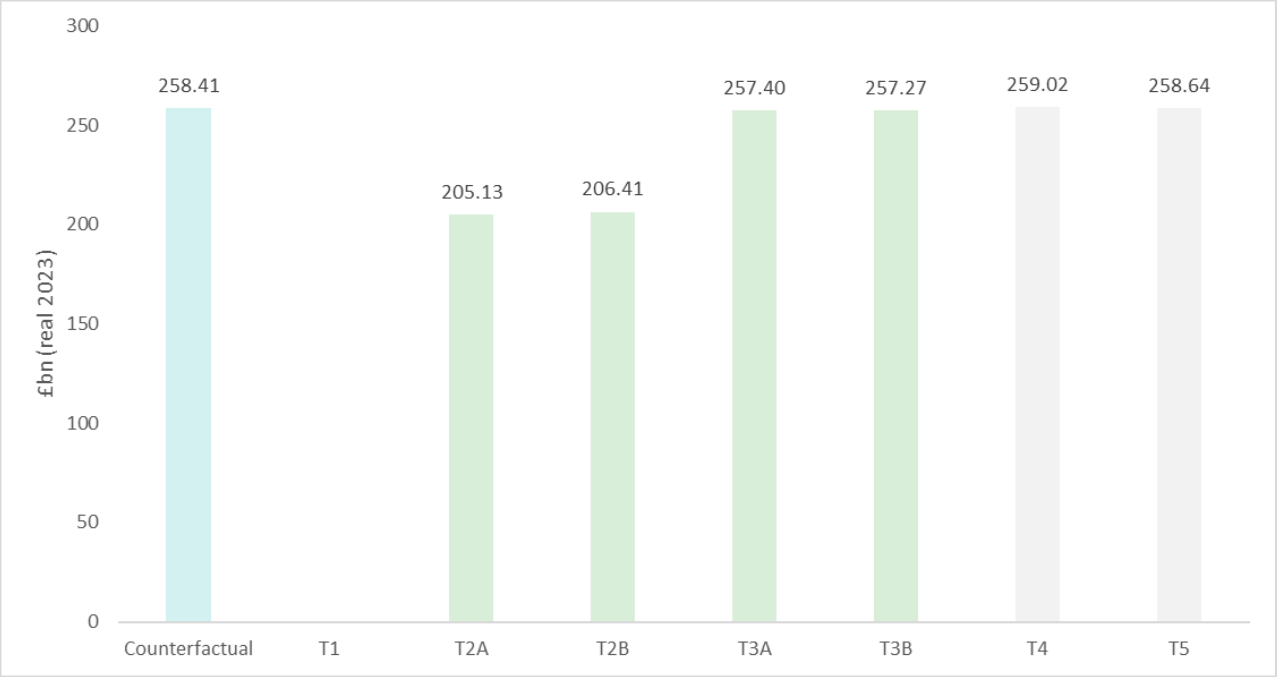

Figure 3-5: 2035-2050 Consumer Cost NPV

Following the same logical thread, we expand the range of the NPV calculations to 2032-2050 for the target cases it applies to: namely 3A, 3B and 5. Figure 3-6 below demonstrates that target cases 3A and 3B continue to deliver savings to GB consumers, whilst target 5 benefits from a longer operational time window with an NPV value now delivering a marginal saving to GB consumers.

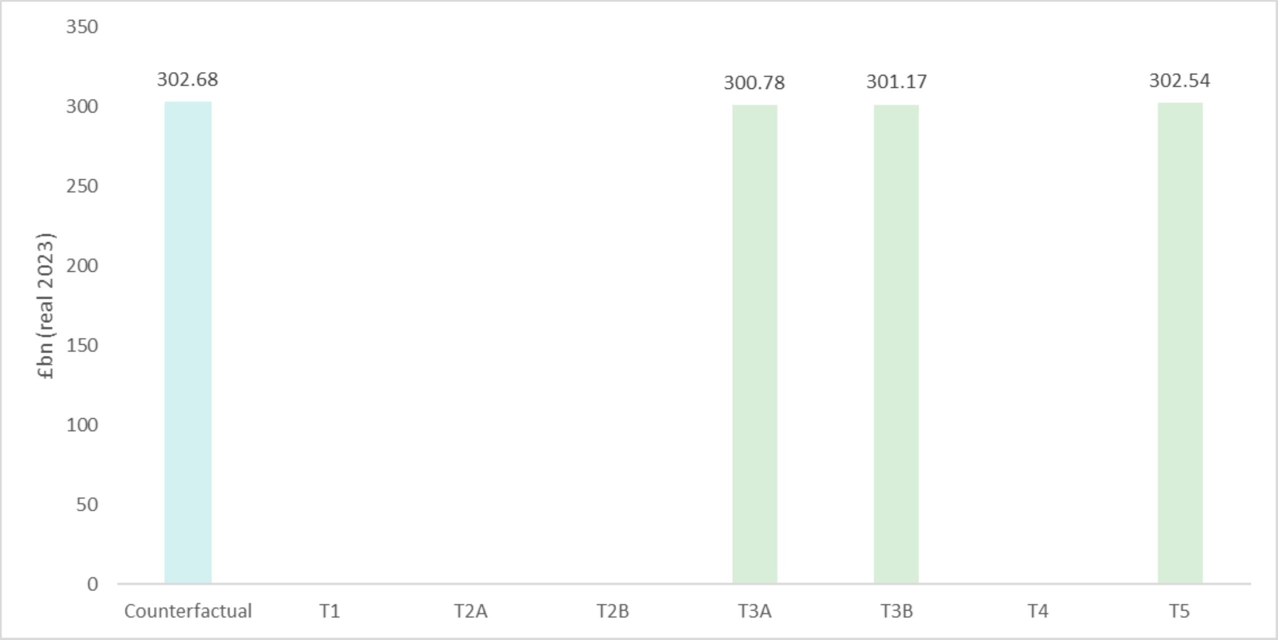

Figure 3-6: 2032-2050 Consumer Cost NPV

Key insight: When one compares the results of Figure 3-3, Figure 3-5 and Figure 3-6, the trend is that when one uses the earliest date allowed in the definition of each target case, the economic case is strengthened for each target case, with the exception of target case 4 which remains marginally more expensive than the counterfactual case even with a start date in 2035. This means that target cases 3A, 3B and to a lesser extent target case 5 are projects that would benefits the GB consumers if started as early as 2032.

3.4 Extended CBA analysis including tidal subsidy need

Figure 3-7 below builds on Figure 3-4 by providing an estimate of the tidal subsidy needed on top of the other GB consumer cost components shown in Figure 3-3. These figures should be treated as indicative. The underlying tidal cost assumptions (i.e., £100/MWh in target case 1 and £75/MWh in target case 3A, both in real 2023 terms) are sourced from Figure 1 of Agila's report. The subsidy need of tidal was calculated using the following steps:

- Tidal Capture Price[3] (£/MWh) = Tidal Generator Gross Revenue (£) / Tidal Generation Output (MWh)
- Subsidy Need (£) = [Tidal Cost (£/MWh) - Tidal Capture Price (£/MWh)] × Tidal Generation Output (MWh)

When calculating the total NPV, three main consumer cost components—Wholesale Market costs, Thermal Constraint costs, and CfD Scheme costs—are combined, with the tidal subsidy need added on top. Even with this additional cost component included, target case 1 yields around a 19 percent cost saving (i.e., £152.19 billion) versus the counterfactual (£186.88 billion). Meanwhile, target case 3A's total NPV is effectively the same as the counterfactual, being only about 0.2 percent higher. Hence, excluding any

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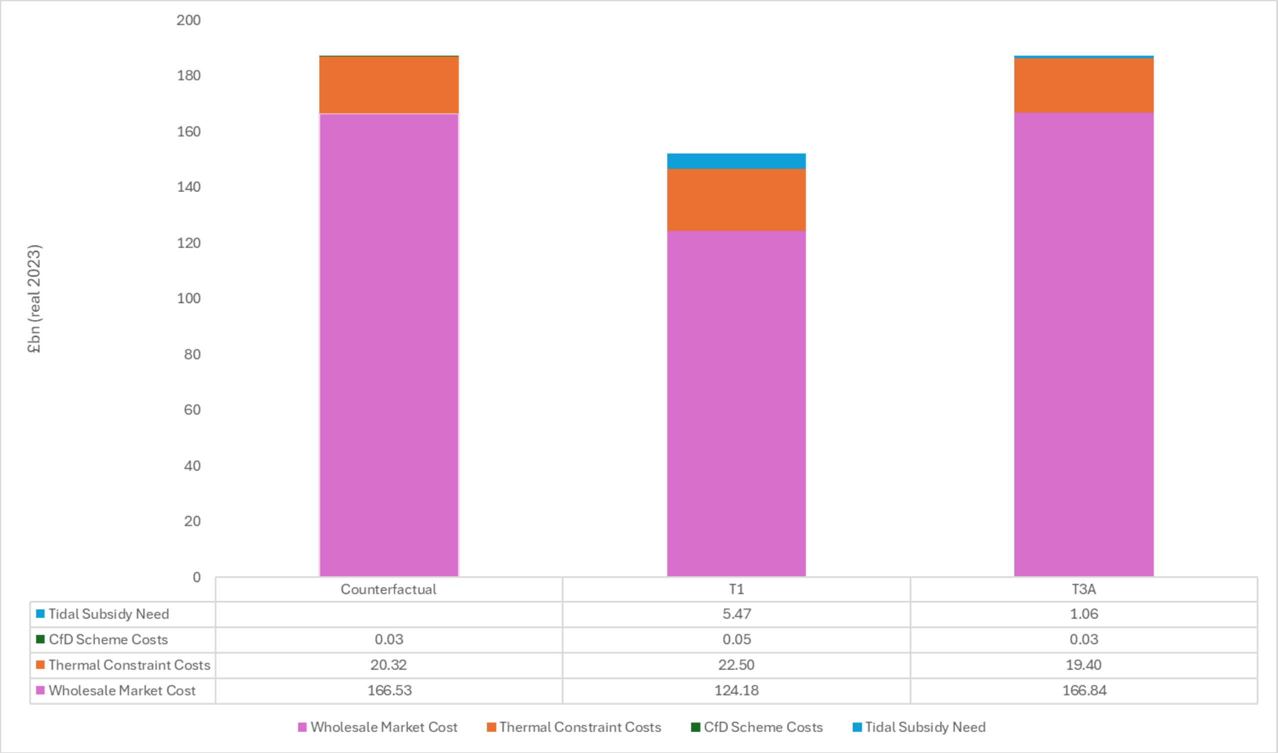
[3] Tidal capture price is defined as the day-ahead electricity wholesale price at time of tidal generation.

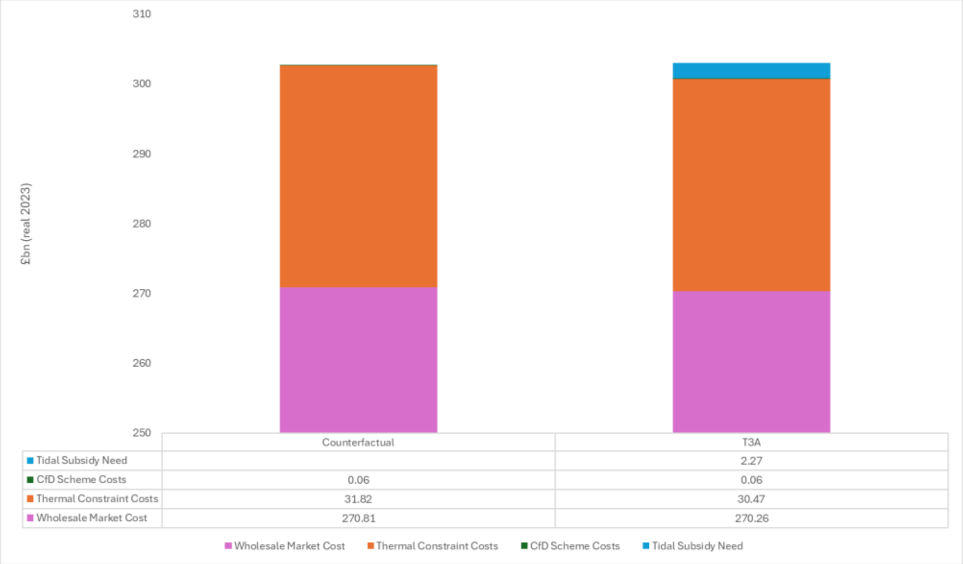
monetisation of environmental benefits, target case 1 represents a net saving to GB consumers, while target case 3A can be regarded as cost neutral.



	Counterfactual	T1	T3A
■ Tidal Subsidy Need		5.47	1.06
■ CfD Scheme Costs	0.03	0.05	0.03
■ Thermal Constraint Costs	20.32	22.50	19.40
■ Wholesale Market Cost	166.53	124.18	166.84

Figure 3-7: 2040-2050 GB Consumer Cost NPV with Tidal Subsidy Need Included

Figure 3-8 below examines the potential impact of initiating target case 3A from the earliest permitted start date in its definition—2032. The results indicate that target case 3A remains nearly cost-neutral compared to the counterfactual scenario. Specifically, the total GB consumer cost in T3A is only 0.1% higher than the counterfactual. This suggests that even with an earlier start date, the overall financial impact on GB consumers does not significantly deviate from the counterfactual GB consumer cost, reinforcing the insight that target case 3A can be regarded as quasi cost neutral for the GB consumer.



	Counterfactual	T3A
■ Tidal Subsidy Need		2.27
■ CfD Scheme Costs	0.06	0.06
■ Thermal Constraint Costs	31.82	30.47
■ Wholesale Market Cost	270.81	270.26

Figure 3-8: 2032-2050 GB Consumer Cost NPV with Tidal Subsidy Need Included

3.5 CBA results conclusions.

The following conclusions have been drawn from the CBA results:

- The CBA are broadly positive across the range of time periods for tidal asset compared to the counterfactual. This suggests tidal assets in the Severn Estuary compare well to the other forms of generation in terms of system integration.
- In the period 2040-50, the scenarios are all positive except cases T4 and T5 which are only marginally negative. The larger capacity scenarios offer significantly positive CBA result through lower NPV costs compared to the counterfactual. This is driven by the larger tidal capacity reducing the wholesale costs, which provides a significant benefit.
- For the period 2035-50 – the target cases T2(A&B) costs are significantly lower than the counterfactual, again driven by reductions in the wholesale power price.
- In the period 2032-2050 – the available target cases T3 (A&B) and 5 are all marginally positive (costs less) than the counterfactual scenario.
- The results suggest that the earlier the date allowed, the more strengthened the economic case is for each target case with the exception of target case 4, which remains marginally more expensive than the counterfactual case even with a start date in 2035.
- Analysing the breakdown of the CBA results suggest the results are predominantly driven by changes in the wholesale price.
- The subsidy required for tidal generation assets appears relatively low.

4. Tidal Generation and Power Market Modelling

4.1 Tidal Energy Output Modelling (ATT)

This section summarises the approach adopted to modelling the energy output of the scenarios as well as the outputs of the modelling which will form the basis of further analysis in the power market modelling.

4.1.1 Energy generation modelling methodology

Arup has previously developed a digital tool for modelling offshore tidal range lagoons, the Arup Tidal Tool (ATT), to support early decision making on potential tidal range schemes. The ATT comprises of a lagoon layout and bund volume model, and an energy generation model which provides an understanding of the geometry and energy generation capability for a tidal range project of a certain size and capacity. The energy model is a 0-D tidal power model which simulates energy outputs for the target cases outlined in Section 2.2. The model simulates the flows through the turbines using a time step of one minute, and calculates the associated head, to estimate the power output over that time step.

In order to carry out the energy generation calculations, the tool utilises a number of parameters including:

- A defined lagoon outline
- A defined number of turbines and sluices in operation
- Location-specific tidal data
- Turbine operational data
- And, where applicable, pumping operational data (discussed further in Section 4.1.2)

For the purposes of this study, the primary focus of modelling has been on the energy generation model to provide realistic energy generation profiles and pumping demand profiles to input into the PLEXOS energy system model. The tidal range projects have been set up to provide the agreed installed capacity for each target case as outlined in Section 2.2. As a starting point, GIS shapefiles, provided by the Client for the Representative Projects, were used within ATT and then these have been modified and adapted as required to generate the energy generation profile. The locations of the projects were used to provide realistic tidal data to inform the model. The generalised tidal range projects are summarised in Table 2-2. These five tidal range projects (with the addition of one project outside of the Severn Estuary) provide a range of installed capacity which allows the study to assess the impact of tidal range energy generation on the GB power network and its sensitivity to the introduction of a tidal range asset in the Severn Estuary.

The tides change over an 18-year lunar cycle. For our analysis, an “average” year of 2029 was adopted for modelling the tides. An average year was chosen to provide a mean annual energy production, and this energy generation profile is assumed to repeat year-on-year for the duration of the power market modelling. It was decided that for objectives of this study, modelling a minimum and maximum year would have limited benefit in the wider conclusions which could be drawn.

4.1.2 Application of pumping

Some of the scenarios for this study have used the pumping capability in the ATT. Pumping is used in tidal range schemes to run the turbines in reverse at times of low head differentials between the lagoon and the sea. The low head differential means that a large amount of water can be transferred for a relatively small amount of energy, when compared to optimum generation. The additional water moved during the pumping time provides a greater overall head during the generation phase, meaning that more energy is obtained during that period, than is expended during the pumping period. Figure 4-1 shows the energy generation cycle of a bi-directional tidal range scheme, the area in orange is relative to the energy generation. Figure 4-2 shows a generation cycle with the addition of pumping. As can be seen, the energy expended within the green area, results in a larger generation throughout the generation phase.

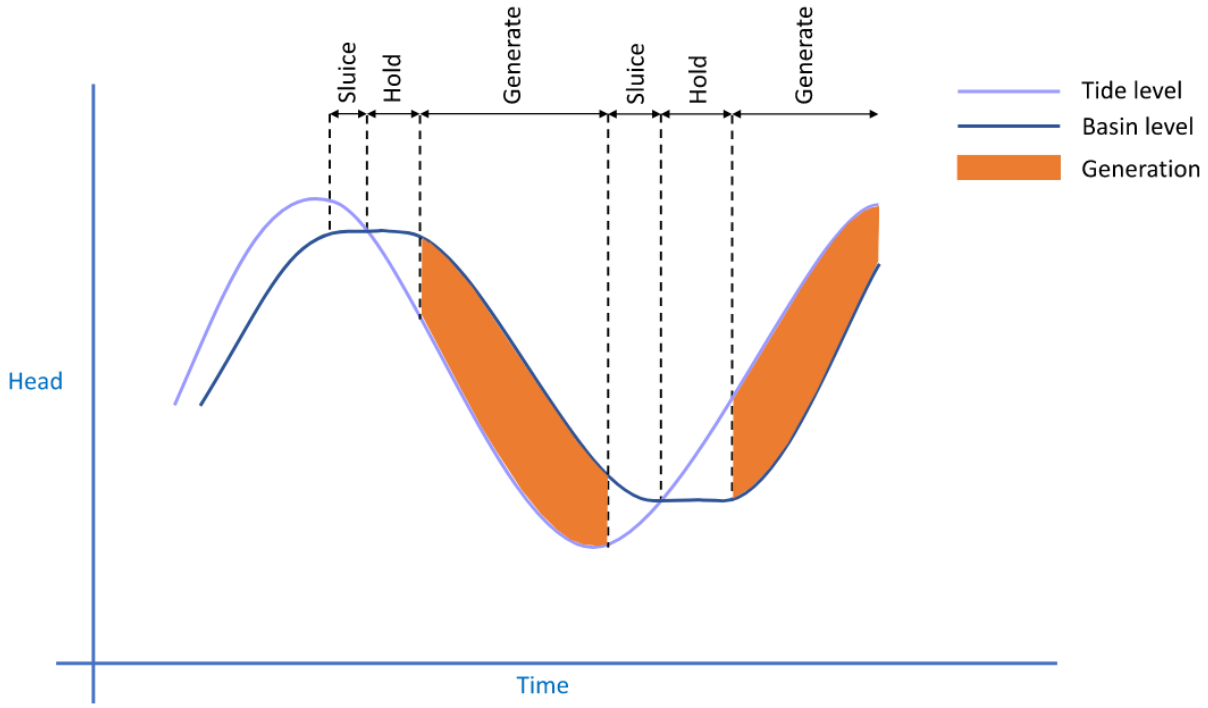


Figure 4-1: Bi-directional generation

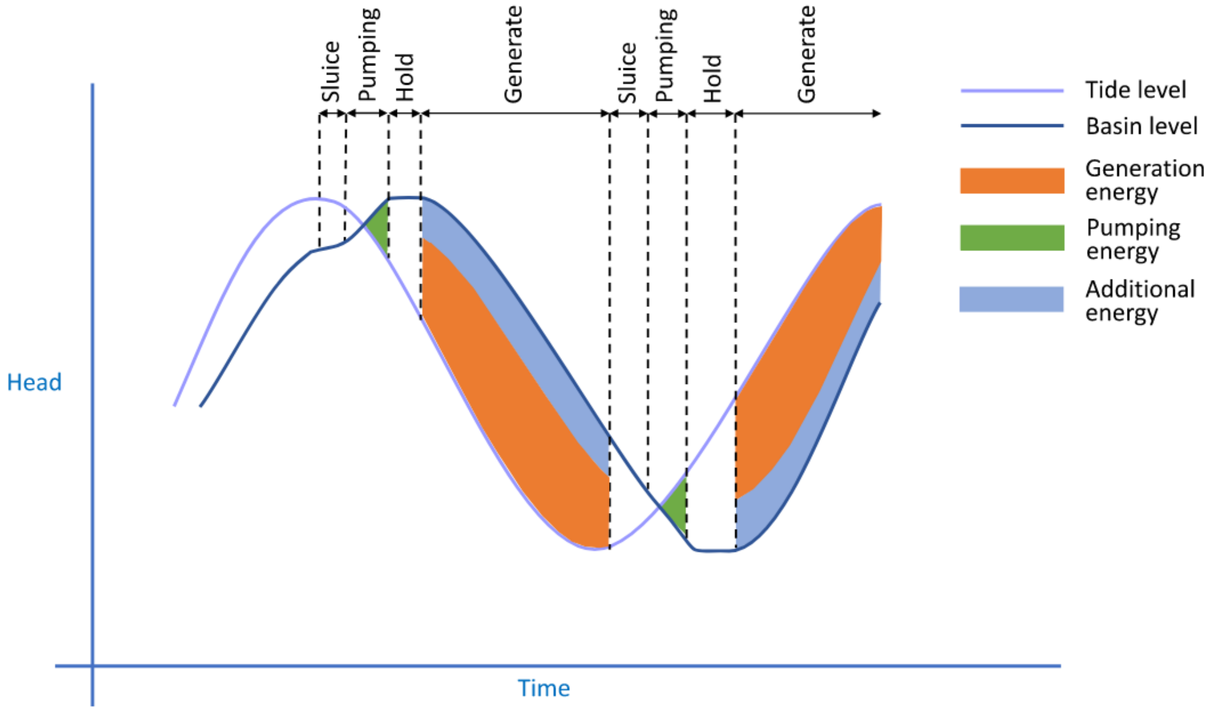


Figure 4-2: Bi-directional generation with pumping

Tidal generators are typically considered to either utilise pumping or rely solely on the natural tidal cycle when generating electricity. There are two types of pumping which are generally applied to tidal lagoons: mitigation pumping and performance pumping. Mitigation pumping aims to replicate the natural tidal cycle within the lagoon or upstream of the barrage, aiming to pump until the maximum or minimum tidal level of the previous cycle has been matched. Performance pumping aims to extract as much energy as possible, and pump to the point at which the energy balance between pumping and generation is optimised. This results in pumping beyond the natural tidal cycle levels.

The runs undertaken as part of this study which include pumping, used the performance pumping mode. There are control parameters within the pumping model that can be further refined on site specific conditions, such as the number of turbines running at a given tide size, or the dynamic start and stop heads. A general model was used for this study, but further optimisation is possible. As such, more energy could be generated with further optimisation. Following comparison with predicted outputs from similar tidal assets, the results were deemed acceptable for use within this study. It also takes into consideration the additional demand of the asset to power the pumps.

4.1.3 ATT modelling outputs

A summary of the annual energy generated by lagoons and different operating modes is summarised in Table 4-1. More detailed graphs showing an example 24-hour period output of the modelling for a spring and neap tide are shown in Appendix B for each lagoon.

Table 4-1: ATT Modelling Outputs

Project	Installed Capacity	Operating Mode	Annual Energy Generated (TWh/annum)
Large Barrage	8.6 GW	Ebb/Flood	15.32
Small Barrage	1 GW	Ebb only	1.04
Lagoon 1	3 GW	Ebb / Flood	5.25
		Ebb / Flood with Pumping	5.35
Lagoon 2	1.8 GW	Ebb / Flood	3.38
		Ebb / Flood with Pumping	3.41
Lagoon 3	0.3 GW	Ebb / Flood with Pumping	0.530
North-West Lagoon	0.7 GW	Ebb / Flood	0.840
		Ebb / Flood with Pumping	0.840

The outputs of the energy modelling provide a generation profile over a full year for each lagoon and operating mode. Where pumping forms part of the operating mode, an additional profile is generated which represents the power demand required for the pumps. In order for this to be input into the power market modelling of the energy system, the minute time-steps had to be reduced to hourly intervals over the course of the year.

4.1.4 Summary

In summary, the annual energy generation of the modelled tidal range projects aligns with publicly available information on similarly sized projects. Whilst there are differences, these are likely due to modelling assumptions, consideration of different operating modes and through further optimisation of the operating regimes for a lagoon. For the basis of this study, they provide a sufficiently realistic generation profile to meet the objective of understanding whether the GB power network will benefit from one or more tidal range assets located in the Severn Estuary.

Additionally, the modelling results suggest a nominal increase in overall generation when pumping is in use (circa. 1%). It is likely that, when focusing on optimising the energy output of a specific lagoon, this could be increased.

The modelling also demonstrates that, over a long-time scale (several months or more), the energy produced over any given time period is proportional to that length of time, i.e. there is no difference in energy generation at a given time of day. For example, at peak times of 07.00-09.00 and 17.00-21.00 (totalling six hours), the amount of energy generated is approximately 25% of the total energy generated in a given year. This effect is due to the continuously shifting time patterns of the tide, moving the generation periods later or earlier in the day. When pumping is introduced, the average duration of energy production over a 24-hour period increases.

4.2 GB Power Market Modelling (PLEXOS)

4.2.1 Modelling Assumptions and Approach

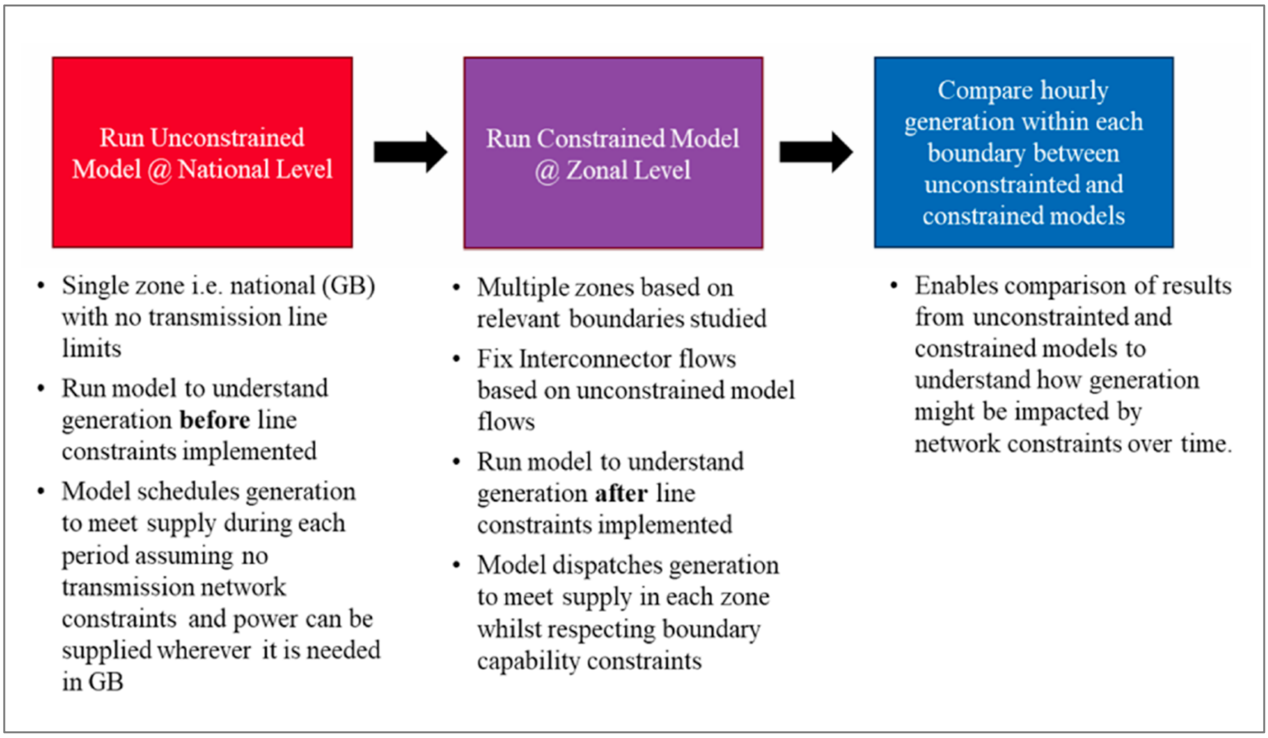
NESO’s Future Energy Scenarios (FES) provide alternative pathways for the UK to meet its 2050 net zero obligations. The pathway selected for this analysis is the Hydrogen Evolution (HE) Pathway which sees the UK’s electricity demand increase from approximately 310TWh/yr today to 720TWh/yr in 2050. The HE Pathway was selected with WGP approval as it contained the higher amount of tidal energy of the four pathways. It is also the same FES pathway which has been selected for the forthcoming NESO Tidal study with the specific intention of making the studies comparable and consistent.

The modelling basis is to compare the energy system market response for the Hydrogen Evolution Pathway with the different tidal range power scenarios, set out in Table 1, against a counterfactual scenario in which the tidal range component is replaced by a mix of technologies. This is to avoid the pitfall of biasing the results with the strengths and weakness of a single replacement technology. The same approach was used for the target cases where the assumed tidal generation capacity was lower than the tidal generation capacity assumed in the FES HE Pathway. This was done to ensure that each case was meeting the required security of supply standard.

Arup has used its Pan-European Power Market Model in PLEXOS to analyse the GB power system, assess constraint costs over the forecasting horizon, and evaluate their impact on the consumer. The GB system model captures the effects of changing boundary capabilities over time as reinforcements are deployed, influencing power flows and generator operations. However, the assumptions for grid development are restricted to the NESO Beyond 2030 assumptions. Whilst this is the very latest set of assumptions, it is highly likely that there would be grid developments beyond 2035/6. These are not considered but would affect the cost of the tidal scenarios and the counterfactual scenario.

Two model runs are required for the counterfactual and each scenario: an unconstrained run, with no network limits, and a constrained 'redispatch' run with transmission constraints. This approach allows the network constraints to be analysed and costed based on assumptions on bids and offers. An average over the last five years has been adopted. It uses the balancing market data from NETA reports to calculate the average accepted bid and offer prices per technology within the GB boundary. These prices are then applied to the volume curtailed to arrive at a counterfactual cost estimate of constraints.

The modelling process is illustrated in Figure 4-3 and the grid topology used to represent the GB transmission grid in the constrained model is illustrated in Figure 4-4.



Run Unconstrained Model @ National Level

- Single zone i.e. national (GB) with no transmission line limits
- Run model to understand generation **before** line constraints implemented
- Model schedules generation to meet supply during each period assuming no transmission network constraints and power can be supplied wherever it is needed in GB

Run Constrained Model @ Zonal Level

- Multiple zones based on relevant boundaries studied
- Fix Interconnector flows based on unconstrained model flows
- Run model to understand generation **after** line constraints implemented
- Model dispatches generation to meet supply in each zone whilst respecting boundary capability constraints

Compare hourly generation within each boundary between unconstrainted and constrained models

- Enables comparison of results from unconstrainted and constrained models to understand how generation might be impacted by network constraints over time.

Figure 4-3: Market Modelling Process

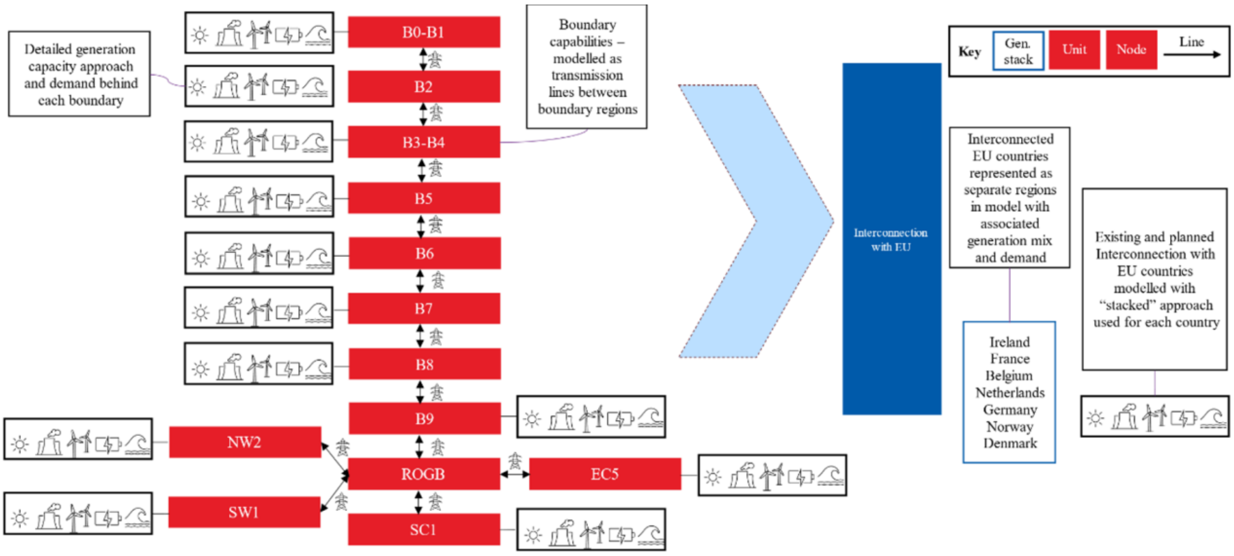


Figure 4-4: GB Transmission Grid Topology

The modelling approach assumes that the Severn Estuary tidal assets connect into the SW1 boundary rather than the other option of connecting into the B13 boundary. This choice was made because the B13 boundary is known to be congested and a tidal range asset connecting to it, would most likely increase constraint costs and unfairly portray tidal generation assets. Whilst it is noted that some of the target cases may connect into B13 (where they are located on the English Shoreline or a barrage which spans the estuary), assuming all assets connect in SW1 enables a comparison of the scenarios and reduces the complexity of the modelling. Arup have been working closely with NESO to agree assumptions given the uncertainties associated with the connection and locational issues.

4.2.2 Key Power Market and System Outcomes

This section presents the principal findings from the power market modelling analysis. Specifically, it examines how introducing tidal energy into the electricity system influences important metrics such as constraint costs, day-ahead wholesale electricity prices, and emissions. By comparing a scenario without tidal power (the "counterfactual") to multiple "target cases" that include different scales and configurations of tidal range projects, we can identify both the benefits and potential challenges of adding tidal energy into the Great Britain (GB) power mix. This analysis underpins the broader cost–benefit assessment and highlights the role tidal projects might play in a future GB power system.

4.2.2.1 Constraint Costs

Constraint costs (also known as Thermal constraint costs) are extra costs to the system and consumers that arise when electricity flows must be adjusted after the day-ahead market schedule is set. Although the day-ahead market decides who will generate power and when, real conditions can mean certain transmission lines risk overloading. At that point, the National Electricity System Operator (NESO) must re-dispatch—paying some generators to lower output and others to raise it—so the grid does not exceed safe limits and maintain the balance between demand and supply of electricity. The cost of making these last-minute adjustments is referred to as thermal constraint costs. Exploring the impact of constraint costs of tidal range energy is a key element of assessing how well tidal range energy can be integrated into the GB power system. If tidal range energy increases constraint costs compared to the counterfactual, it indicates that the integration of tidal range energy could be costly, but similar or lower constraints costs indicate a less costly integration both now and for future network development costs.

The figures below split the results between the target cases displaying predominantly a higher thermal constraint costs profile (Figure 4-5) and those whose thermal constraint profiles gravitate around the counterfactual case level (Figure 4-6).

Figure 4-5: Thermal Constraint Cost Profiles – High Group

Figure 4-5 shows the annual thermal constraint costs of three of the target cases which overall increase the thermal constraint costs of the GB power system. Figure 4-5 demonstrates that the bigger tidal generators have the biggest upward impact on the total thermal constraint costs compared to the counterfactual case. On average the target case 1 displays thermal constraint costs which are 10.6% higher per annum than the counterfactual case, whereas target cases 2A and 2B lead to thermal constraint costs which are respectively 9.6% and 10% higher than the counterfactual per annum.

The counterfactual itself has an upward trajectory due to combined effect of the increase in renewable energy generation over time and the growth trajectory of the GB transmission system. Figure 4-6 below, by contrast, shows that medium and small tidal generators (target cases 3A, 3B, 4 and 5) have less of a noticeable effect on total thermal constraint costs and are having on average a downward impact on thermal constraint costs as demonstrated in Figure 4-6. Target case 3A on average decreases the thermal constraint costs by 3.9% per annum. Target cases 3B, 4 and 5 decrease the thermal constraints cost by an average of 0.2%, 0.4% and 0.01% per annum, respectively.

This finding is echoed in all market outcomes. Bigger tidal generators have the most noticeable impact on the various aspects of the GB power system.

Figure 4-6: Thermal Constraint Cost Profiles – Group Gravitating Around the Counterfactual Level

4.2.2.2 Day-Ahead Wholesale Price

Tidal generation is likely to have some impact on the GB wholesale power prices given it will have different operating costs (marginal cost) to other technologies such as Nuclear, wind solar and CCUS. This has the potential to have significant impacts for GB consumers. In the following we explore the impact on the GB power price using Arup's GB power system model. The day-ahead price is used as the most representative price for consumers (as compared to day prices, week-ahead and month-ahead prices).

Figure 4-7 and Figure 4-8 below split the results between the target cases displaying a more significant downward pressure on the Day-Ahead (DA) wholesale price (high impact group), and those whose Day-Ahead (DA) wholesale price profiles gravitate around the counterfactual case level.

Again, the generators with greater capacity have the biggest downward impact on the electricity day-ahead market as they inject the most zero short-run marginal cost electricity in the GB market.

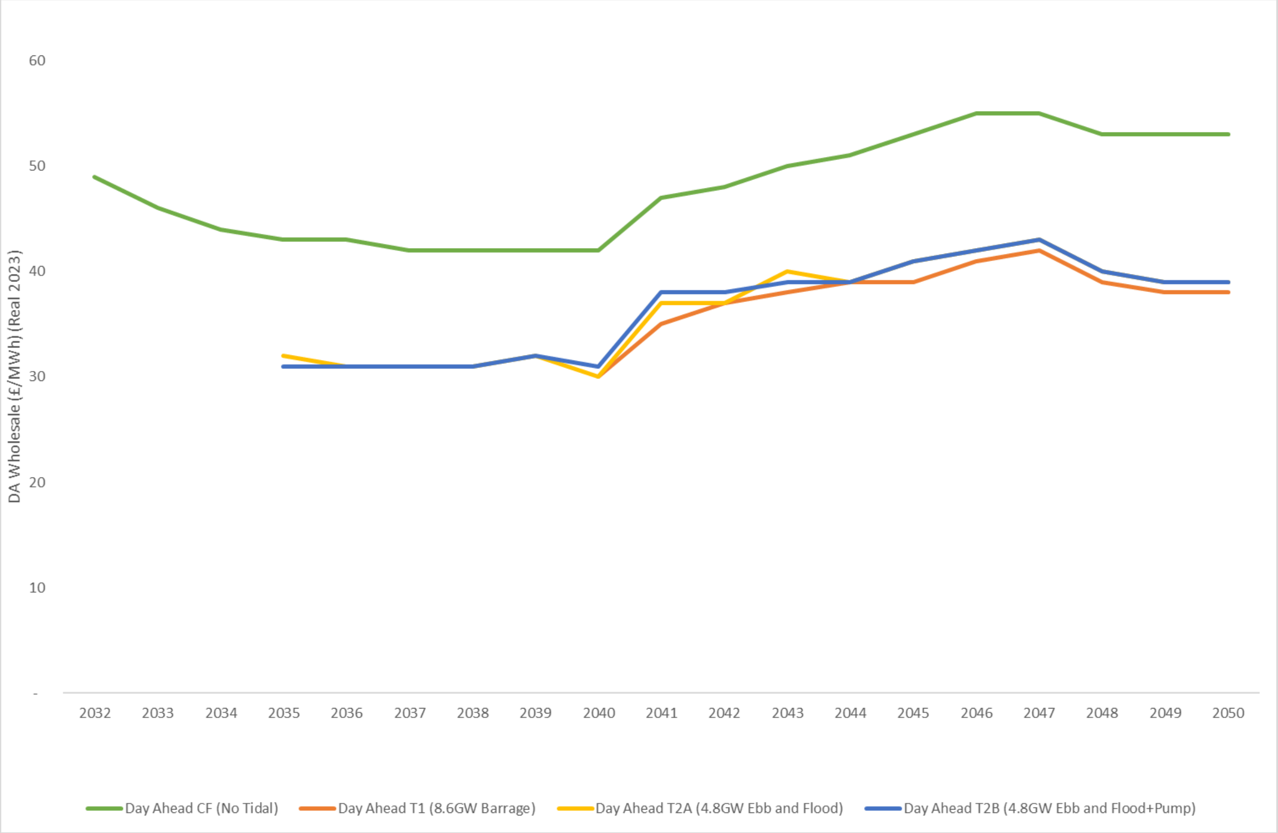


Figure 4-7: Day-Ahead Wholesale Electricity Price - High Impact Group (Downward Pressure)

Figure 4-8 shows that the target cases 3A, 3B, 4 and 5 display a limited deviation from the counterfactual price curve. This is to be expected given that the size of the tidal generators is unlikely to be big enough to significantly drive price movements.

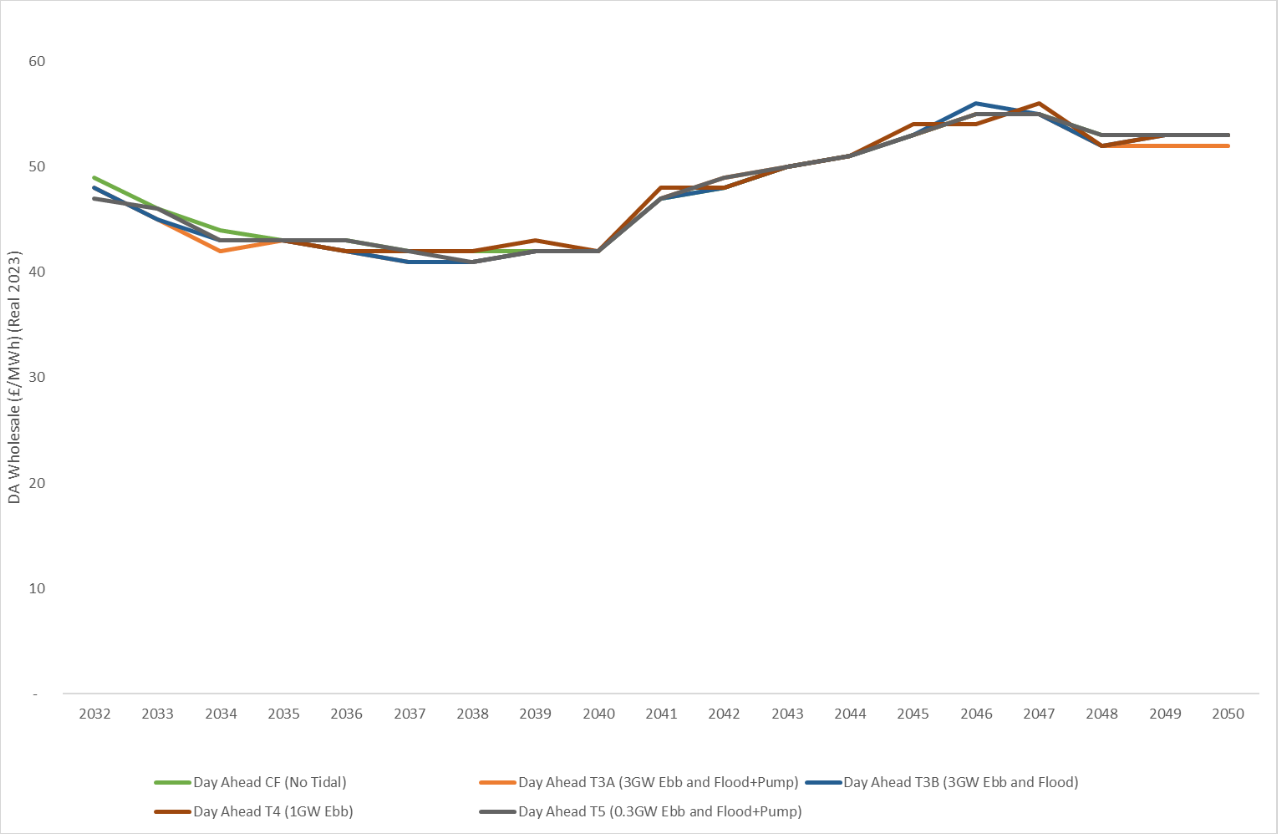


Figure 4-8: Day-Ahead Wholesale Electricity Price - Low Impact Group

4.2.2.3 Emissions Level

The emission level of the GB power system is impacted by varying levels of tidal generation across different target cases. Figure 4-9 displays the yearly difference in emission levels of each target case and the counterfactual cases.

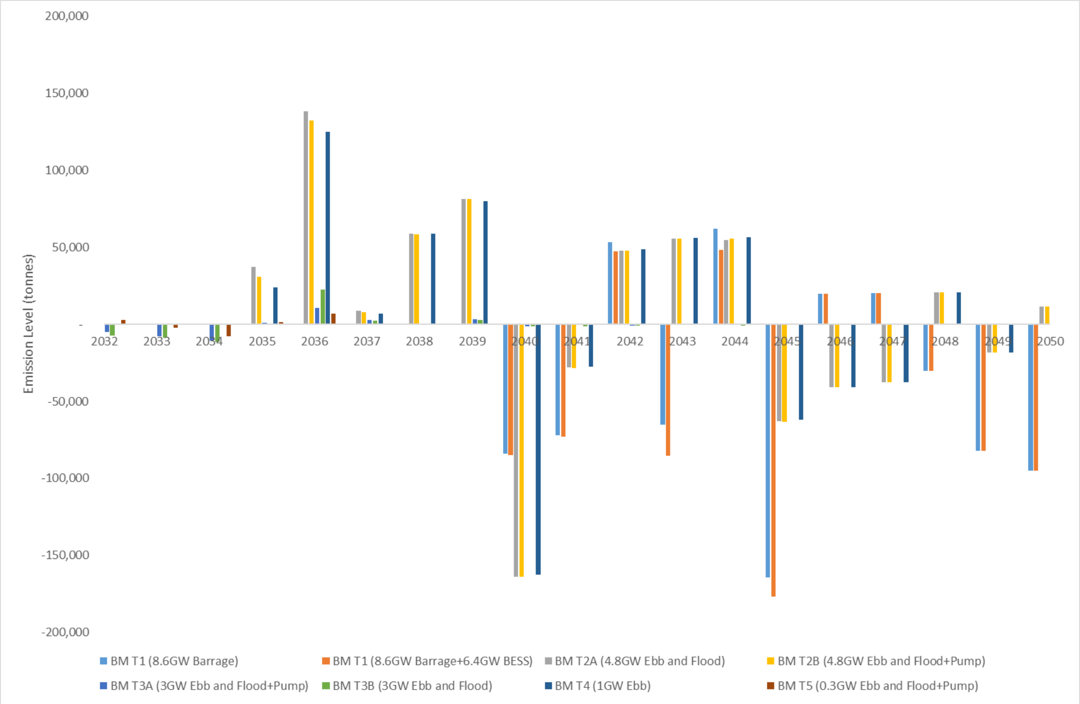


Figure 4-9: Emission Level Differential with the Counterfactual Case

When looking at the period 2040-2050, all target cases deliver lower emissions level compared to the counterfactual case though the difference is very small at the GB power system level. As expected, the biggest reduction in emissions level is achieved by the target case 1 which delivers a lower emissions level of 0.14% compared to the counterfactual case.

4.2.2.4 Tidal Generators Day-Ahead Market Revenue

Figure 4-10 shows the annual revenue level extracted from the day-ahead market by the various tidal generators under consideration in this study. The highest revenue is extracted by the largest tidal generator as expected.

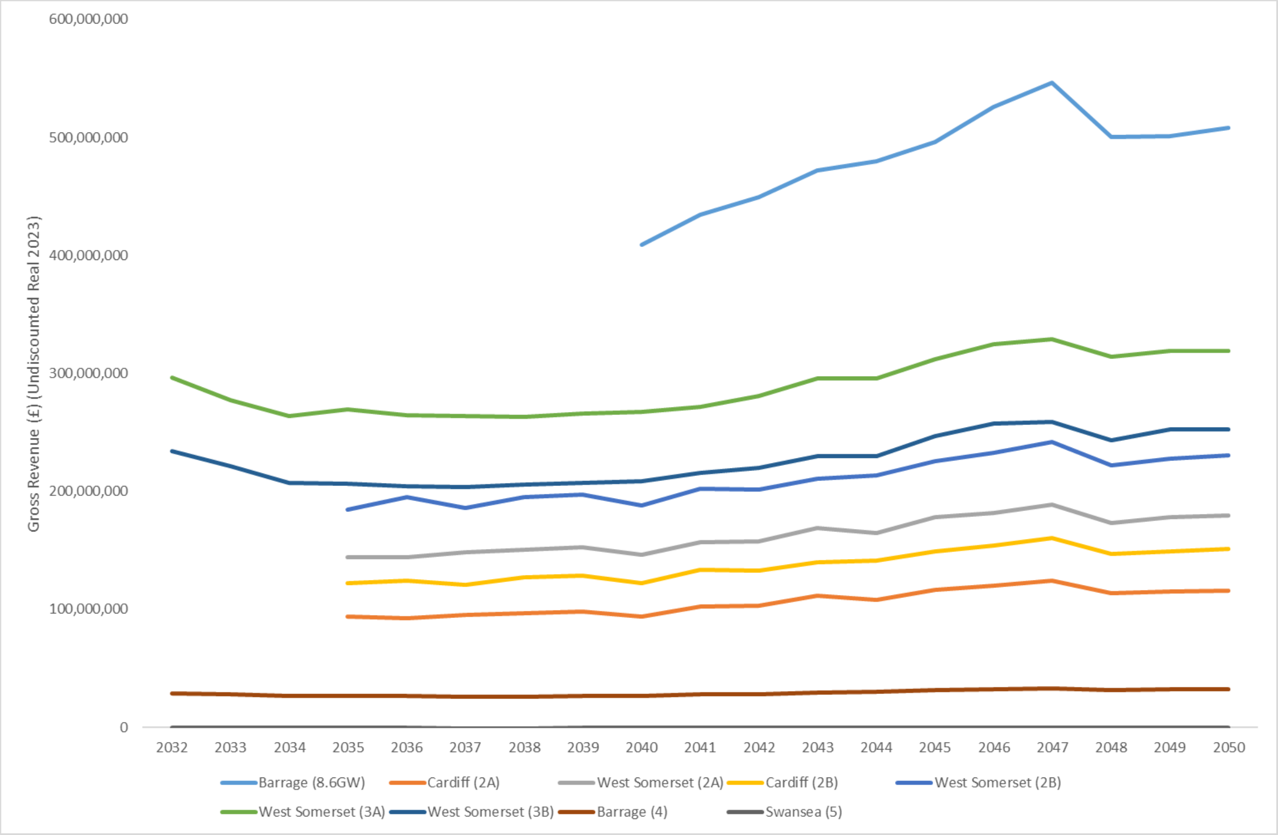


Figure 4-10: Day-Ahead Wholesale Market Tidal Generators Gross Revenue

The day-ahead price curves displayed in the report (Figure 4-7 and Figure 4-8) represent the baseload wholesale price, which is the average price across all hours of the day. The capture price of tidal generators differs from the baseload price because these generators do not produce electricity continuously but only during certain hours. During these generation periods, the wholesale price may deviate significantly from the baseload price.

4.2.3 Sensitivities:

This section explores the impact of a co-located battery with the 8.6GW barrage as well as the impact of extreme weather years on the results of target case 3A.

4.2.3.1 Battery Sensitivity:

The sensitivity was run with a 4-hour duration battery of 6.8GW peak capacity. The results below explore the impact on the GB consumer costs – excluding the subsidy need of tidal and the potential subsidy need of the battery.

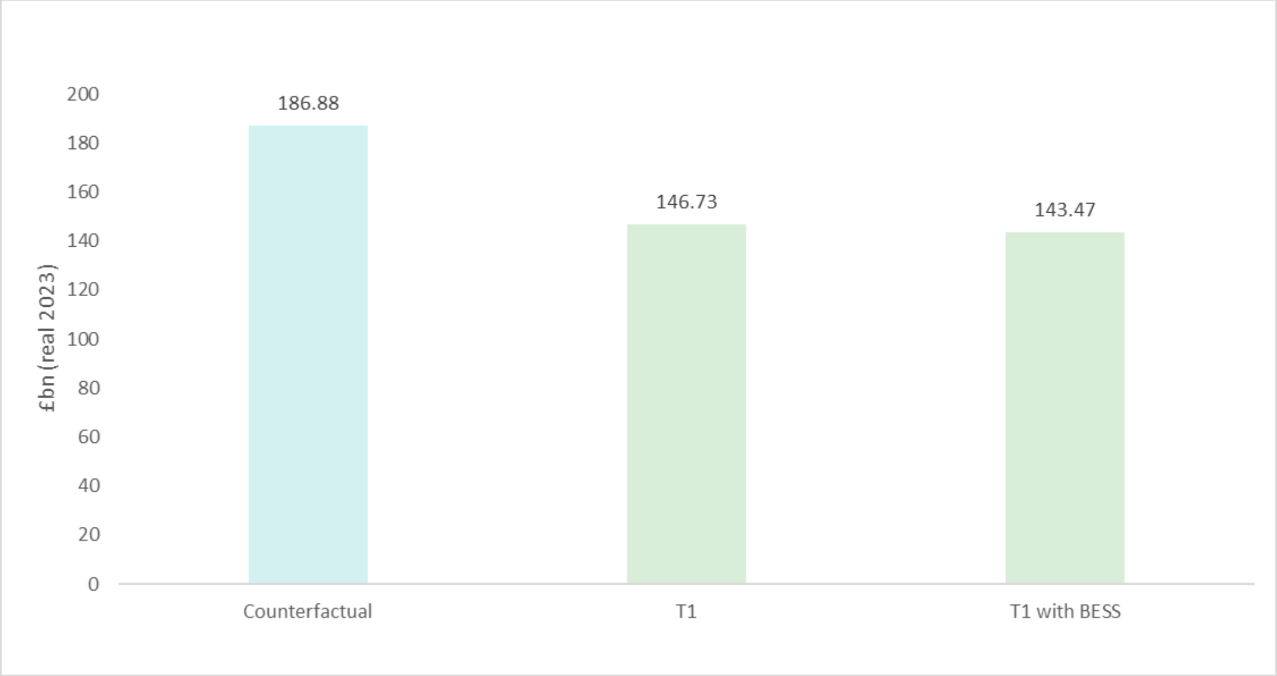
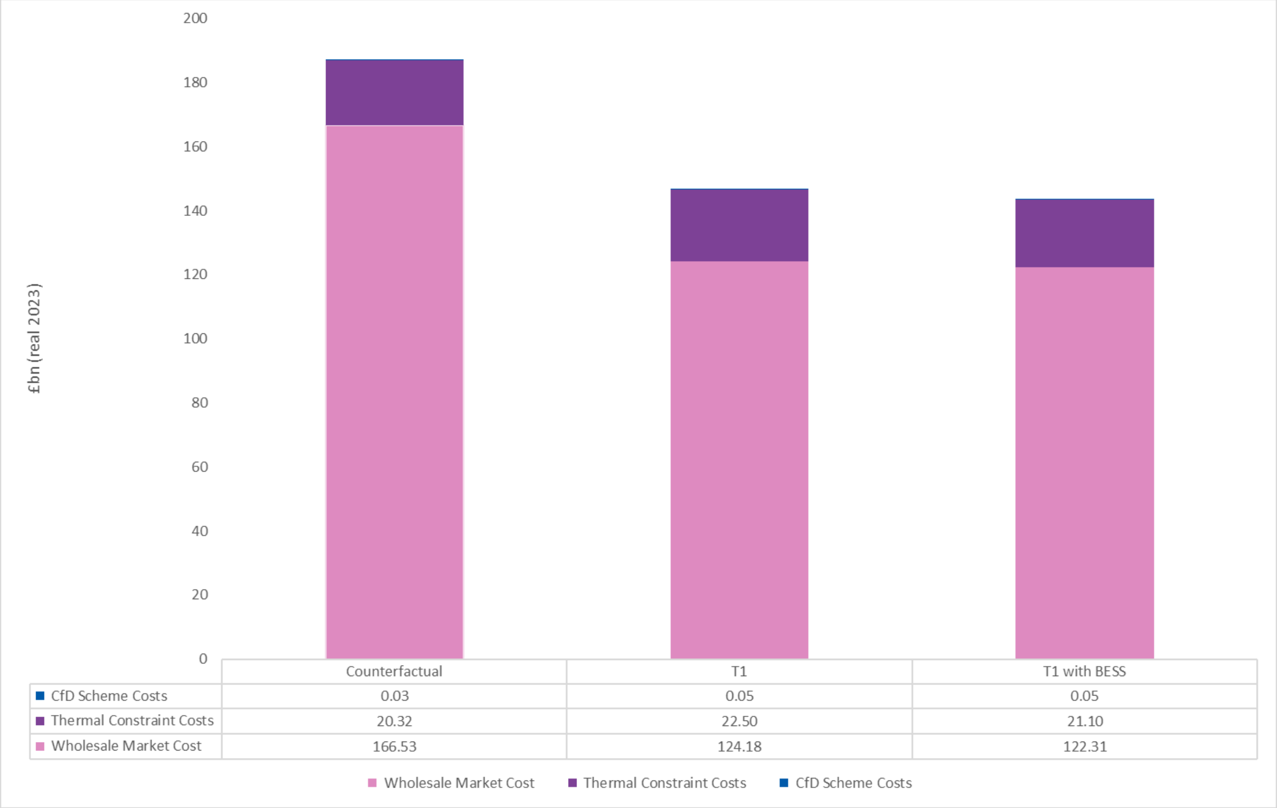


Figure 4-11: Impact of co-located battery on GB Consumer Cost

The Figure 4-11 shows that building a co-located battery alongside the 8.6 GW barrage could lead to up £3.26bn of supplementary cost savings for the GB consumers. The Figure 4-12 shows how this is achieved: the addition of the co-located battery leads to a decrease in thermal constraint costs as well as a decrease in the wholesale market cost. The decrease in thermal constraint costs happens because the battery can store tidal energy which would otherwise lead to thermal constraints on the transmission lines. The decrease in the wholesale market occurs essentially for the same reason by releasing much needed energy during tighter periods in the power market which contributes to lowering the wholesale price.



	Counterfactual	T1	T1 with BESS
■ CfD Scheme Costs	0.03	0.05	0.05
■ Thermal Constraint Costs	20.32	22.50	21.10
■ Wholesale Market Cost	166.53	124.18	122.31

Figure 4-12: Break Down of the Cost Components of the Battery Sensitivity (2040-2050)

4.2.3.2 Extreme weather years: high and lower RES generation years in GB

The modelling methodology used an average weather year to generate results. However, given the potential for more extreme weather Arup tested the results of the study against a stylised version of a Dunkelflaute.

a. A Dunkelflaute is a two-week period of minimal wind and solar output, often accompanied by cold weather, creating a severe stress scenario for power and gas systems. In European adequacy assessments published by European Network of Transmission System Operators for Electricity (ENTSO-E), these events are identified by ranking each year (1987–2016) according to how challenging they would be for meeting electricity demand with wind and solar generation (and associated gas-fired backup).

b. To capture a realistic range of conditions—*high*, *low*, and *average* wind/solar performance—we have selected the following weather years (WY) based on both Great Britain's (GB) wind and solar capacity factors and the European-level Dunkelflaute "stress" ranking:

- **WY1990: High-RES Generation Year**
  – *GB's highest* annual wind/solar capacity factors across the weather years 1987–2016
  – The *4th least stressful* year for Europe's power and gas systems

- **WY2010: Low-RES Generation Year**
  – *GB's lowest* annual wind/solar capacity factors across the weather years 1987–2016
  – The *4th most stressful* year for Europe's power and gas systems

For the avoidance of the doubt the weather year 2007 was used throughout the rest of this study and it displays the following features:

– *GB's average* annual wind/solar capacity factors across the weather years 1987–2016
– The *14h least stressful* year for Europe's power and gas systems out the 30 weather years (1987-2016)

The results of the average RES generation year (2007) are included in the Figure 4-13 and Figure 4-14 below Figure 4-14 as reference points and can be traced back to the other figures in the report.

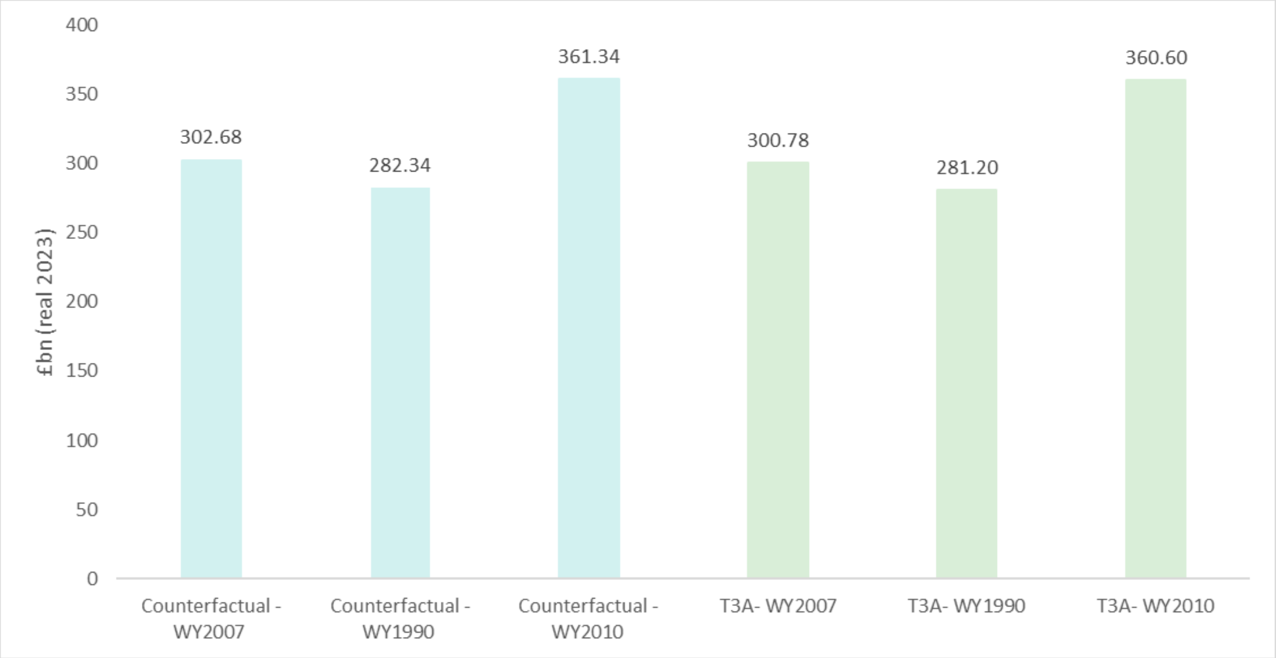


Figure 4-13: Impact of Extreme Weather Years on Target Case 3A (2032-2050)

The Figure 4-13 shows that under the average weather year (2007) and the high-RES generation year (1990), the GB consumer cost remains lower than the counterfactual cases associated with the same weather years. The weather year 2010 (Low-RES generation year) is the only one pushing the GB consumer cost above the counterfactual case associated with the same weather year.

The Figure 4-14 display the impact of the weather years on the various cost components of the GB consumers.

	Counterfactual - WY2007	Counterfactual - WY1990	Counterfactual - WY2010	T3A - WY2007	T3A - WY1990	T3A - WY2010
■ CfD Scheme Costs	0.06	0.06	0.04	0.06	0.06	0.04
■ Thermal Constraint Costs	31.82	31.85	30.39	30.47	31.87	31.84
■ Wholesale Market Cost	270.81	250.42	330.92	270.26	249.27	328.73

Figure 4-14: Cost Breakdown of the Extreme Weather Years Sensitivity (2032-2050)

Key insight: Regardless of the weather used, the target case 3A deliver a cost saving to the GB consumer relative to the counterfactual case.

4.2.4 Inertia and Balancing Services Analysis

Power systems with significant thermal generation benefit from reduced system stability requirements because thermal generators offer ‘inertia’. This means that the turbines continue to spin and produce power even after shutting down, utilising stored kinetic energy that helps slow down the rate of frequency change (Rate of Change of Frequency), when there is a sudden loss of generation or demand. However, as these types of generators come off the system there is a need for the NESO to procure stability services to help guard against sudden losses causing blackouts.

Synchronous AC connection of tidal power plants to the rest of the grid can provide inertia, contributing to more stable and manageable grid operations. Inertia, provided inherently by synchronous generators, helps slow the rate of frequency change following a disturbance, aiding system stability.

As of 2025, NESO has indicated a minimum system inertia requirement of approximately 120 GVA·s, with a target to reduce this further to 102 GVA·s as new frequency response services and grid-forming technologies are deployed (NESO Frequency Risk and Control Report 2025). The forecast of the minimum system inertia requirement over the period 2032-2050 falls outside the scope of this report. For ease of discussion, we will assume that it remains at 120GVA.s

The following table presents the potential inertia contribution of each tidal power plant configuration in this study, assuming a synchronous AC connection and an inertia constant of 5 seconds:

Table 4-2: Inertia Contribution of the various Target Cases

Target Case	Type and Mode	Capacity (GW)	Inertia Contribution [4](GVA·s)
1	Large Barrage	8.6	43
2a	Two Large Lagoons	4.8	24
2b	Two Large Lagoons with Pumping	4.8	24
3a	One Large Lagoon	3	15
3b	One Large Lagoon with Pumping	3	15
4	Small Barrage	1	5
5	Small Lagoon	0.3	1.5

These inertia contributions could represent a significant proportion of the minimum inertia requirement:

- The Large Barrage (8.6 GW) would contribute 43 GVA·s, equating to 42% of the 102 GVA·s target.
- The Two Large Lagoons (4.8 GW) would contribute 24 GVA·s, representing 24% of the target.
- Even the Small Lagoon (0.3 GW), while modest, would still add 1.5 GVA·s, contributing 1.5% of the target.

The potential inertia provision from these tidal power plants could help support grid stability, particularly as more inverter-based renewable generation (e.g., wind and solar) reduces naturally occurring inertia. However, the ability of tidal plants to provide additional balancing services, such as frequency response and reserve, would require operational flexibility.

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[4] Inertia contribution is defined as the nameplate capacity of the generator times the inertia constant.

However, whilst the Large Barrage offers potential benefit, the sheer scale of it would also present some risk to the NESO. A proposed high-capacity tidal plant, such as the Large Barrage (8.6 GW) considered in this study, could significantly influence the volume requirement for frequency response and reserve services. If deployed, this plant would surpass the size of current largest infeed losses, potentially driving an increase in the system-wide requirement for these ancillary services.

The Large Barrage (8.6 GW) could become the new reference contingency size for system operators when planning for infeed losses. This increase would not directly impact the tidal plant's operation or profitability but would likely lead to higher whole-system costs due to the increased demand for balancing services.

The deployment of this high-capacity tidal generator could shift the GB system's largest infeed contingency to levels significantly higher than current norms, increasing the need for frequency response and reserve services, with subsequent implications for overall system costs. These depends on whether they have one or many connection points.

The remainder of this section aims to show the impact of tidal range energy on the overall GB power system inertia and therefore the role that tidal energy plays in maintaining grid stability. This analysis - whilst relying on quantitative outputs of the power market analysis (step 2 of Figure 3-1) - is meant to provide qualitative insights. The impact of tidal energy in terms of inertia has not been monetised and thus did not feed into the CBA analysis (step 3 of Figure 3-1).

The charts below explore how the hourly average inertia profile provided by all other generators (besides tidal generators) compares with the hourly average inertia profile provided by tidal generators. The analysis is based on the premise that if the average hourly profile of tidal inertia coincides with periods of lower system-wide inertia, it positively contributes to maintaining the overall inertia level of the power system.

Key insight: Regardless of which target case one looks at, the average hourly tidal inertia profile comes at a helpful time during the day to support the inertia of the power system.

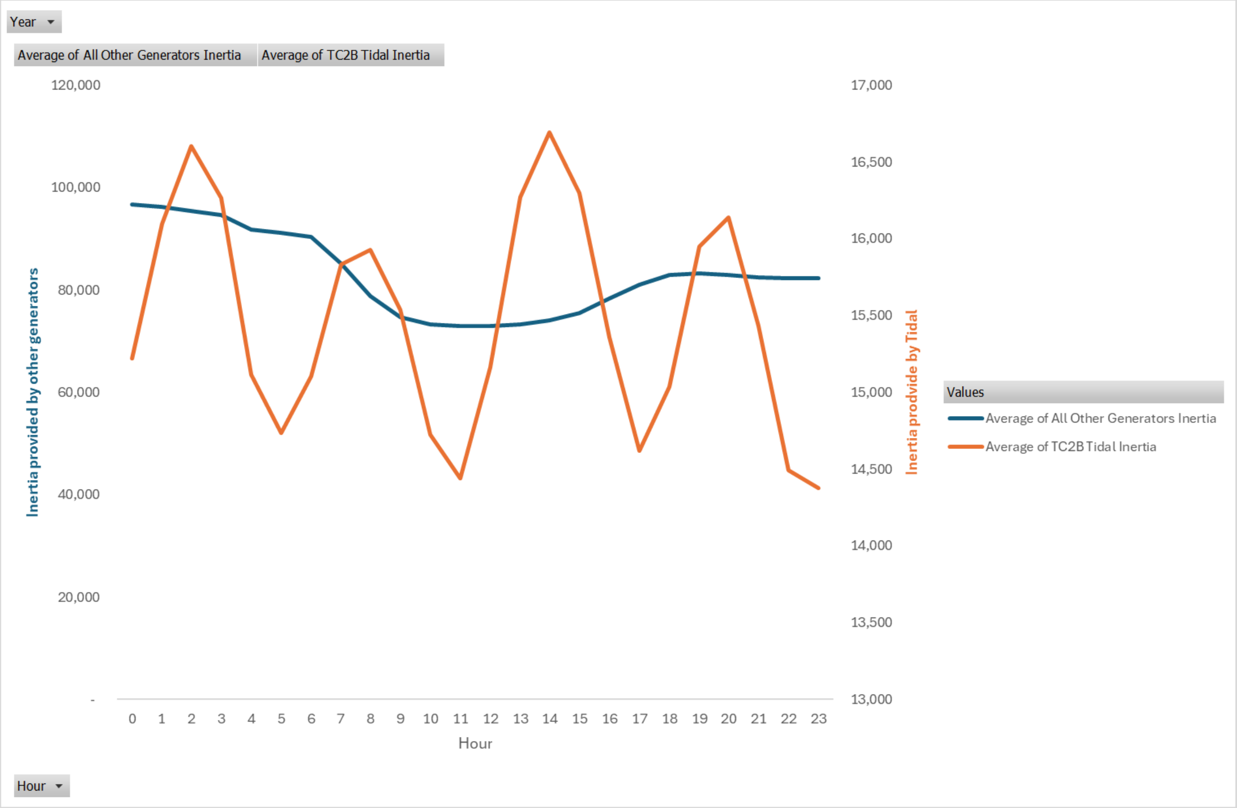

Figure 4-15: Average Hourly Inertia Profiles (2035-2050) – Target Case 2B

Figure 4-15 is based on the average of all the hourly values between 2035 and 2050. This was done to provide a clear representation of the average hourly inertia profile between the inertia provided by non-tidal generators and the inertia provided by tidal generators in the target case 2B. From the figure above, it can be observed that the first three peaks of tidal inertia of the day typically occurs at a moment in the day with the rest of the inertia supply is either going down (first two peaks) or past its lowest point. This means that tidal inertia on average comes at a helpful time to support the inertia of the power system.

The driving factors behind the midday fall in overall GB power system inertia is the increasing prominence of the solar generation in the generation mix. Figure 4-16 below shows a normalised hourly solar generation profile.

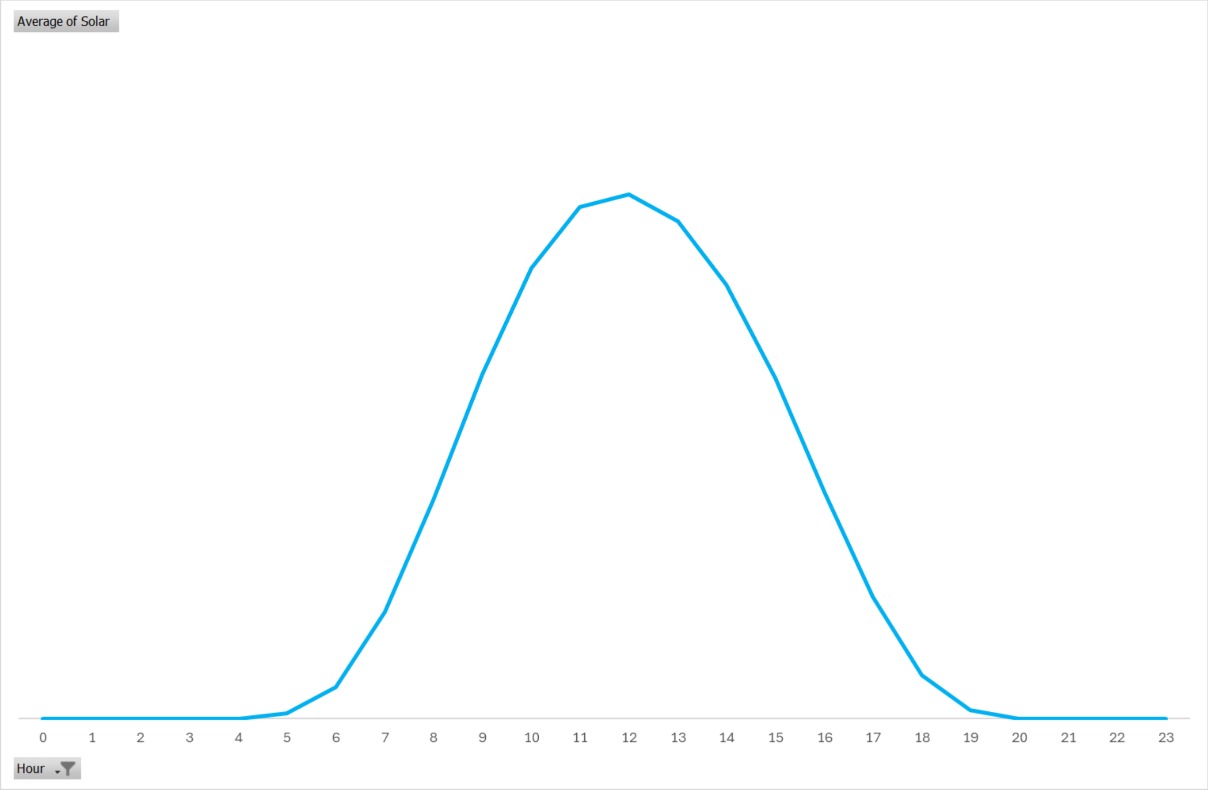

Figure 4-16: Normalised Hourly Solar Generation Profile

The impact of tidal inertia is becoming more pronounced towards the later years in the forecasting horizon under consideration as it can be observed by comparing the right-hand (2050) chart with the left-hand chart (2035) of the Figure 4-17 below. This is directly linked to the footprint of the increasing solar generation in the GB power system towards the back end of the horizon under consideration. Meaning, tidal inertia, on average, comes at a helpful time to support the inertia of the power system even more so in the later years of the horizon under consideration.

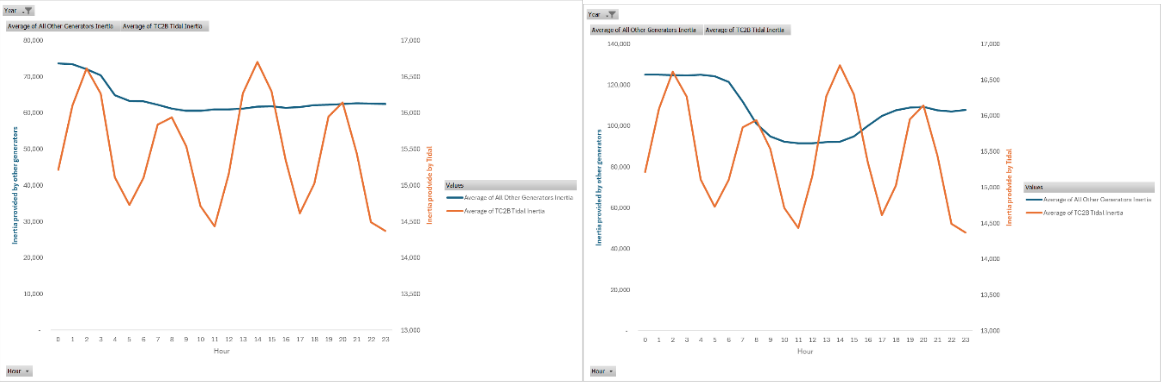

Figure 4-17: Average Hourly Inertia Profiles for 2035 (Left) and 2050 (Right)

The chart below demonstrates that the same conclusion is drawn when considering Target Case 1. For brevity, only the overall period chart is shown – the first and last year charts of each target case like the Figure 4-17 above are omitted. The same findings are observed for the other target cases. The charts for the other target cases are not included in this executive summary but will be included in the final report.

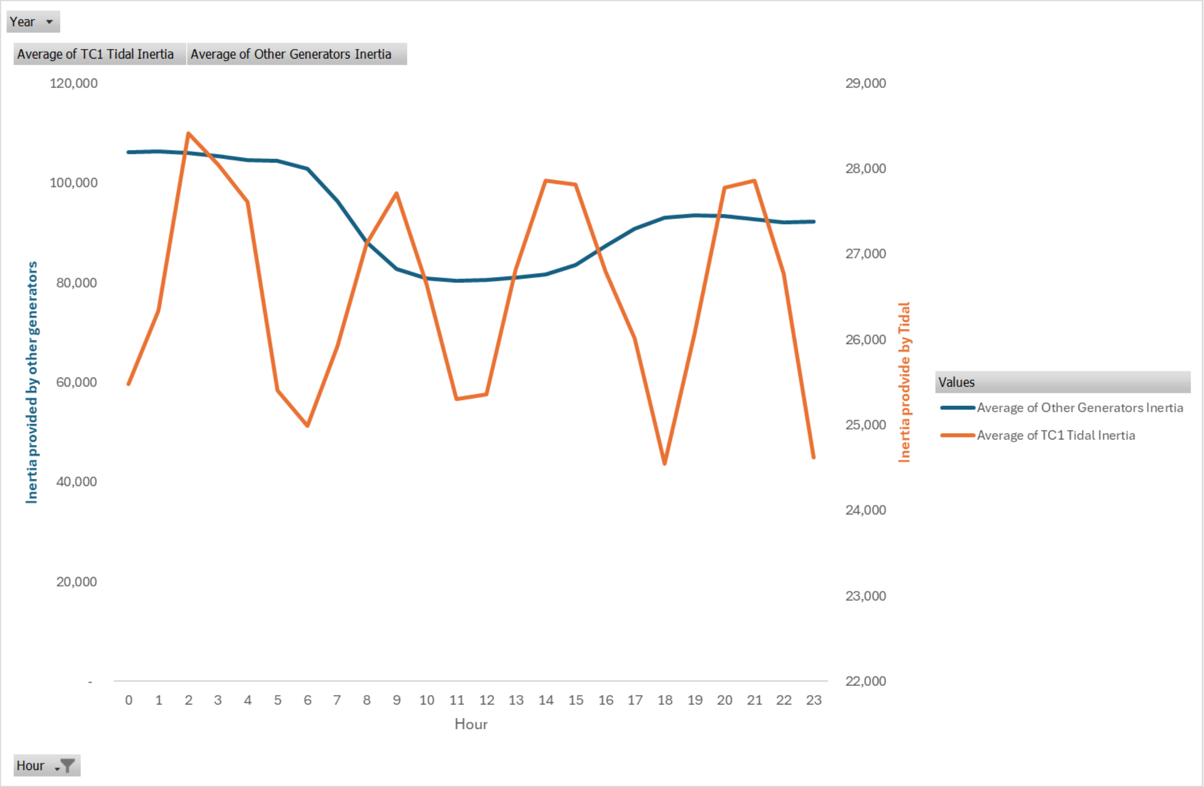

Figure 4-18: Average Hourly Inertia Profiles (2040-2050) – Targe Case 1

5. Cost of Connection Estimation

The cost of a grid connection is driven by the capital cost of connecting generation (or demand) assets to the electricity network. What constitutes a grid connection is the infrastructure between the generation collector system and the point of connection with the local distribution or national transmission network, depending on the size of the generation site. The costs of the collector system i.e. generation equipment (e.g. turbines), array cables etc, do not form part of the grid connection assets.

A connection typically consists of a collector substation where the strings or arrays that connect the generating units are rationalised through a step up in voltage and where some local control and protection is provided. Export circuits then connect the collector substation to the electricity system substation, to a connection point at this substation (e.g. bays and switchgear). The topology of the connection can vary depending on the size of the site, voltage level at the connecting substation and other influencing factors, e.g. an additional substation may be required to step the voltage level up further before connecting to the electricity network.

Capital connection costs will depend on the size of the generator and the voltage level at which it is connecting. These are likely to be in the order of multiple £100m for GW-scale projects connecting to the transmission network. Some of these direct costs will be incurred by the TO to connect the generation into their substation and these are then passed back on to the generation developer.

The GB electricity network is heavily congested in many areas and so large generation projects could trigger wider network reinforcements, depending on their location and connection point. Transmission network upgrade costs are socialised via Transmission Network Use of System Charges (TNUoS) and so these do not form part of the capital cost of a grid connection and have not been considered here.

The need for reinforcement on the network also has an impact on connection timescales, and developers are currently experiencing exceptionally long lead times for connection dates. To address this, and also to meet more strategic energy system ambitions, NESO is currently progressing through a Connections Reform[5]. Under this reform, projects are moving from a first come, first served approach to a first ready, first needed, first connected approach, and connections could be accelerated, with the first connected and operational from 2026. The reform should also remove any inactive projects from the queue, potentially enabling some improvement in connection dates.

For this study, we have provided an overview of the transmission system in the area around the Severn Estuary, noting constraints and required reinforcements in South Wales and the South-West, behind the relevant system boundaries. The overview indicates that there is a substantial volume of generation currently within the offer process in the area, including nuclear, offshore wind and interconnectors in England & Wales. Note that this may shift to an extent following the completion of the connections reform process.

5.1 Transmission Network Overview

As of December 2024, ~152.9 GW of generation is contracted and within the offer process in South Wales and the South West, and 19.6 GW is currently connected [5]. This includes:

- 22.6 GW Battery and Energy Storage Systems (BESS)
- 32.1 GW Solar – including hybrid projects e.g. Solar/BESS
- 18 GW Thermal including Nuclear
- 7.8 GW Interconnectors
- 25.7 GW Offshore Wind

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[5] https://www.neso.energy/industry-information/connections/connections-reform

- 35.5 GW Embedded Generation

The development of all of these generation projects will depend on how they progress through the Connections Reform process and whether the projects can demonstrate readiness to proceed, and indeed whether there is a system need for them.

5.1.1 Transmission Boundary Constraints

There are two transmission system boundaries that are of interest in this study. The following sections provide a summary of these boundaries from the recently published in the Electricity Ten Year Statement (ETYS) 2024.

SW1 (South Wales area) on the Northern side of the Severn Estuary

Within the SW1 boundary, shown in Figure 5-1, is a mixture of generation types, including some renewable generation and fossil fuel sites which are expected to close. Generation within the boundary is consumed by large cities such as Cardiff and Swansea and surrounding industrial developments. Boundary capabilities are currently expected to broadly remain as-is in the near-term and suitable for the requirements for the foreseeable future.

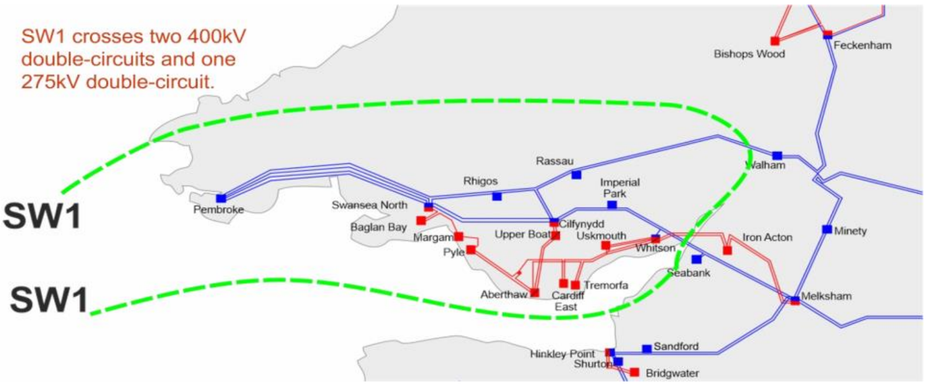

Figure 5-1: Transmission boundary - South Wales area [Error! Reference source not found.**]**

The boundary capability is limited to 3.8GW due to a thermal constraint on the Imperial Park - Melksham 400kV circuit. Within the timeframes of the tidal project (around 2040), plans for medium to long term grid reinforcement become relevant. Figure 5-2 shows the boundary capability (in red) based on the recommendations from the Beyond 2030 optimal path which uses FES 2023 and ETYS data, while the 50%, 90%, Economy RT and Security RT lines are based on Clean Power 2030 pathways.

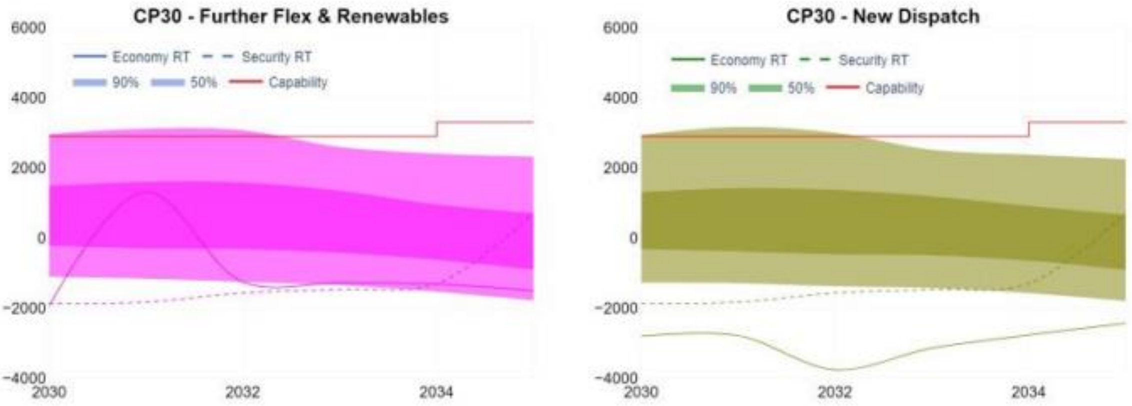

Figure 5-2: Expected SW1 Boundary Capability

B13 (South West England area) on the Southern side of the Severn Estuary

Within the B13 boundary, shown in Figure 5-3, there is a high level of localised generation and demand. It is expected that there will be very little variation in boundary requirements for B13, until new generation or interconnector capacity is required. As it stands, the current importing boundary capability is sufficient to meet the short-term needs.

The significant capacity of potential new generators seeking to connect close to boundary B13 is likely to result in large exports, however, the current network plan raises boundary capability to a sufficient level. Further reinforcements may be required post-2030, following the connection of offshore wind projects in the South West. The NESO's final recommended design for the Celtic Sea could see the connection of up to 1.5GW of offshore wind into South West England, behind B13, by 2035. An additional 4- 10GW could potentially be leased by 2030 and in operation from 2035 to 2040. This could see an acceleration of the system requirements in the South West.

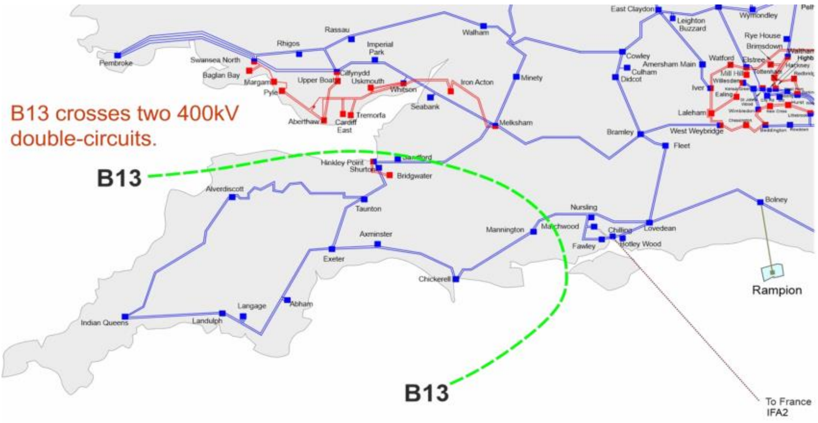

Figure 5-3: Transmission boundary - South West England area

The boundary capability is limited to 3.5GW due to a thermal constraint on the Landulph - Langage 400kV double circuit. Within the timeframes of the tidal project (2040 and beyond), plans for medium to long term grid reinforcement become relevant. Figure 5-4 shows the boundary capability (in red) based on the recommendations from the Beyond 2030 optimal path which uses FES 2023 and ETYS data, while the 50%, 90%, Economy RT and Security RT lines are based on Clean Power 2030 pathways.

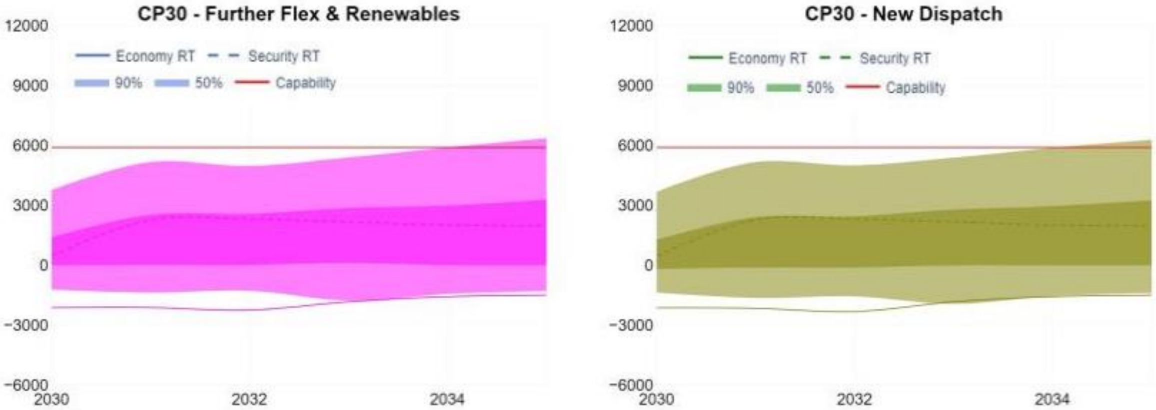

Figure 5-4: Expected B13 Boundary Capability

5.1.2 Regional Developments

New connections in the South-West and South Wales are primarily for generation. NGET is currently re-evaluating the optimal sequencing of works to maximise transmission system capacity for this volume of generation. In the long term, the region requires a new 400kV transmission circuit from the South West towards demand hotspots, likely in West London. Any new generation in the South West and South Wales will be scheduled for 2037+ dates due to the need to wait for these overhead line (OHL) reinforcements.

The Greenlink 500MW interconnector to Ireland became operational in January 2025, which links Pembroke to County Wexford. This link offers bi-directional power flow so excess power in GB could be exported to Ireland. Future international interconnectors with Ireland could also be relevant to the Severn Estuary's location and may influence the cost implications of grid connection for tidal projects in this area.

5.1.3 Grid Reinforcement Costs

The original Severn Tidal Power Feasibility Study discusses the costs associated with grid reinforcement that would be required to connect a new tidal range asset in the Severn Estuary to the electricity transmission network. While grid reinforcements are not included in the grid connection costs being estimated in this section, it is noted that based on provisional estimates, a cost of between £214m and £271m per GW of installed capacity was provided at the time [6], considering two project capacities: 8.64GW and 1.365GW. This translates to between £0.33B and £0.41B[6] per GW today.

Ofgem approved £656m for the Hinkley Point C grid reinforcements in 2020[7], a cost of £190m/GW. This amount covers 49km of new T-pylons, and 8.5km of underground cable between Hinkley and Seabank. The cost also includes a new substation and reconfiguration of two existing substations; however, this isn't the full extent of the wider transmission network reinforcements required for the project.

More recently, a review of NESO's 'Pathway to 2030' report, which assesses the transmission grid reinforcements required to reach 50GW of offshore wind by 2030, suggests that £21.7B needs to be spent on the network by 2030 to meet these ambitions [7]. This estimate suggests that an approximation of £0.6B investment is required per GW of installed capacity.

It is worth noting that supply chain constraints due to increasing demand from decarbonisation are impacting electricity asset costs and delivery times.

5.2 Grid Connection Assets

5.2.1 Grid Connection Assets

As stated above, the cost of a grid connection is driven by the capacity of the development and the characteristics of the local grid to which it will connect. The design of the connection itself is also governed by the capacity of the development, and the configuration of the generating technology e.g. lagoon or barrage. As part of this study, there are several MRPs being investigated, detailed in Section 0. Since it is not possible to provide accurate grid connection costs for the different MRPs without going through a detailed electrical design process, two MRPs have been selected to illustrate how the costs could range according to development size, site configuration and grid connection location (distance to NGET system). The two MRPs selected are shown in Table 5-1.

Table 5-1 MRPs selected for grid connection cost estimate

Project	Installed Capacity	Operating Mode
Large Barrage	8.6 GW	Ebb/Flood
Lagoon	1GW	Ebb/Flood

These MRPs are highlighted in green in Figure 5-5 below.

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[6] cost adjusted for inflation only, based on Consumer Price Index from the National Office for Statistics between 2009 and 2024

[7] https://www.ofgem.gov.uk/press-release/ps60-million-savings-new-hinkley-point-c-grid-link#:~:text=Energy%20regulator%20Ofgem%20has%20confirmed,power%20station%20to%20the%20grid.

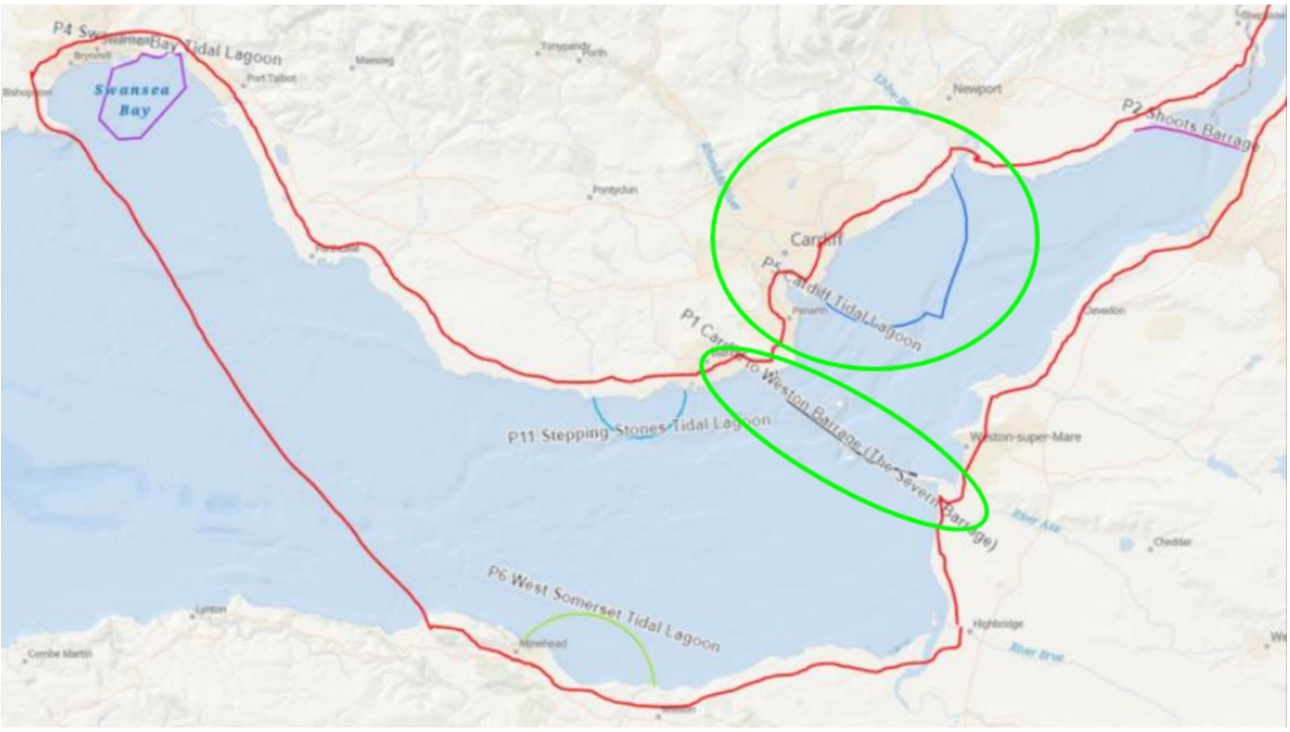
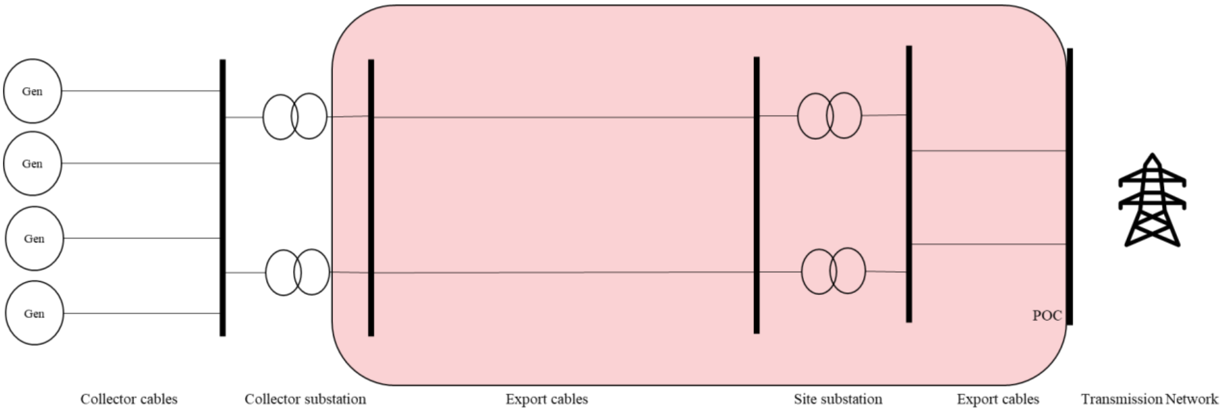


Figure 5-5 Location of MRPs selected for grid connection cost estimate

At a high level, a grid connection has key electrical assets:

- A collector substation, including step up transformer(s) which rationalise lower voltage circuits coming from individual generating units
- Export cable circuits that connect the collector substation either
    - To a site substation to further step up the voltage, or
    - Directly to the transmission system substation
- Site substation (if required), including step up transformer(s)
- Any other equipment required, such as reactive compensation
- Additional export cable circuits (if required) to connect site substation to transmission system substation.

Other costs include communications, protection, control, earthing, enabling civil works, and etc. The assets included in the grid connection costs are highlighted below in pink.



The grid connection assets do not include:

- Tidal turbines
- Electrical circuits (string, array, other configuration) connecting the tidal turbines
- Protection and control equipment associated with the above turbines and circuits
- Any infrastructure past the Point of Connection (POC) to the transmission network

5.2.2 Grid Connection Characteristics for Tidal schemes

The structure of a tidal barrage or lagoon, such as those proposed here, can accommodate transformers, allowing the collector substation(s) (mentioned above) to be located directly on the barrage. As such, the need for a separate collector substation structure (onshore or near to shore separate from the barrage or lagoon structure) is not necessarily required. As such, the cost estimates have assumed no separate collector substation(s). It has also been assumed the voltage level will be stepped up to 400kV at this stage, and so no additional site substation or step in voltage is required. The projects will therefore connect directly to the NGET transmission system via 400kV cables from the barrage or lagoon.

The practicalities of this may have to be investigated further for the large barrage project which will likely require a minimum of 5 x 400kV transformers to be housed on the structure. This would have significant impact on the weight bearing and space requirements.

Additionally, for the large barrage project, there would have to be the consideration that additional NGET transmission substations may also be required to accommodate 8.6GW of capacity.

5.3 Grid Connection Cost Estimates

A review of the cost breakdowns from the 2010 Severn Tidal Power Grid Study has been carried out, specifically examining the costs associated with the B3 Cardiff to Weston Barrage configuration. The independent desktop connection cost estimates are summarised below considering a 1GW and 8.6GW tidal range asset respectively.

For 1GW, the capex cost estimate for the grid connection is c. £200m. This is based on:

- A 400kV GIS substation located (outdoors) on the barrage or tidal lagoon,
- 6km of cable installed in a cable tunnel in the structure, and
- 25km of cable to the connecting a National Grid substation.

The benchmark as-installed asset costs are derived from our database of confidential transmission project costs. These have been adjusted where appropriate to reflect the installation arrangements.

For 8.6GW, the CAPEX cost estimate for the grid connection is c. £1,600m to £2,000m. This is based on:

- A minimum of 5-6 substation 400kV GIS substations, assumed to be located on the barrage,
- Each substation has a 400kV busbar, and
- Each substation has an export cable comprising of 6km installed in a tunnel on the structure and 25km connecting to the National Grid network.

Multiple substations, busbars and cables are necessary to remain compliant with SQSS requirements (loss of a generator no larger than 1.32GW[8] but may increase in future). Alternatively, there could be fewer

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[8] Normal Infeed Loss Risk: This is the maximum loss of power infeed that the system must be able to withstand without significant frequency deviation. The limit is 1320 MW.

substations, but these would need to have more busbars (per substation) and other equipment, and so there would be a larger footprint which may be limiting on the barrage.

Please note that recent supply chain pressures across the electricity industry have increased supply delivery times and costs.

6. Licensing

Tidal range projects require a comprehensive understanding of licensing types to ensure regulatory compliance and operational efficiency. The purpose of this section is to examine the licensing categories relevant to both generator and energy storage components of tidal range projects, focusing on the UK context.

6.1 Infrastructure consent licencing

In the UK, tidal energy projects that exceed specific capacity thresholds—50 MW onshore or 100 MW offshore—typically require a Development Consent Order (DCO) under the Planning Act 2008. This designation as a Nationally Significant Infrastructure Project (NSIP) streamlines the process by consolidating multiple permissions, including environmental assessments and public consultations, into a single application overseen by the Planning Inspectorate. Projects below these thresholds may instead seek Section 36 consent under the Electricity Act 1989, along with a Marine Licence. A DCO can also incorporate a "Deemed Marine Licence," simplifying regulatory approvals for complex projects (Rankl, 2024).

6.1.1 Marine Licence

The Marine Licence is necessary for activities in marine environments, covering construction, deposit of substances or articles, alteration, and operational activities in waters adjacent to the UK, ensuring minimal impact on marine biodiversity and water quality. The Marine Management Organisation (MMO) in England, Marine Scotland in Scotland, and Natural Resources Wales in Wales oversee the Marine Licence process.

Large-scale tidal projects require several assessments to secure a Marine Licence and ensure both environmental and navigational safety. An Environmental Impact Assessment (EIA) evaluates the project’s effects on ecosystems, water quality, and coastal processes, with public consultations used to inform mitigation strategies (Marine Management Organisation, 2021). If protected habitats or species might be impacted, a Habitat Regulations Assessment (HRA) is conducted to ensure compliance with conservation laws, focusing on Special Areas of Conservation (SACs) and Special Protection Areas (SPAs). Additionally, a Navigational Risk Assessment (NRA) identifies potential hazards to maritime traffic in high-traffic areas, proposing measures to ensure safe navigation. These assessments collectively help to ensure tidal projects are sustainable and safe.

6.1.2 Environmental Permits

For tidal energy projects, an environmental permit is typically required due to potential impacts on marine ecosystems and water quality. Large-scale projects, especially those located in ecologically sensitive areas (Severn Estuary), undergo rigorous assessments, including Environmental Impact Assessments (EIA) and compliance checks under the Conservation of Habitats and Species Regulations. These permits, overseen by agencies like the Environment Agency and Natural Resources Wales, ensure that tidal projects adhere to environmental standards and minimize ecological disruption, aligning with UK conservation objectives [8].

Table 6-1: Environmental licences

License	Description	Regulatory Body	Key Requirements	Relevant Assessments
Section 36 Consent	Required for generating stations above specific capacities (50 MW onshore, 1 MW offshore) under the Electricity Act 1989	Department for Energy Security and Net Zero	EIA, public consultation, and grid compliance.	Environmental Impact Assessment (EIA)

License	Description	Regulatory Body	Key Requirements	Relevant Assessments
Marine Licence	Necessary for marine construction and operations to ensure minimal impact on marine ecosystems.	Marine Management Organisation (MMO), Marine Scotland, Natural Resources Wales	Includes multiple assessments to evaluate impact on marine ecosystems and navigational safety.	Environmental Impact Assessment (EIA), Habitat Regulations Assessment (HRA), Navigational Risk Assessment (NRA
Development Consent Order (DCO)	Required for projects classified as Nationally Significant Infrastructure Projects (NSIPs), typically exceeding 50 MW onshore or 100 MW offshore.	Planning Inspectorate	Consolidates permissions into a single application, incorporating environmental assessments and public consultations for NSIPs.	May include a Deemed Marine Licence, Environmental Impact Assessment (EIA)

6.2 Generator licencing

6.2.1 Section 36 Consent

Section 36 of the Electricity Act 1989 mandates that any electricity generating station with a capacity exceeding 50 MW onshore or 1 MW offshore must obtain Section 36 Consent. This consent ensures that large-scale energy projects meet regulatory standards and environmental protections [9].

Requirements: Projects must conduct a detailed Environmental Impact Assessment (EIA) to assess and mitigate environmental impacts, especially on marine ecosystems. The consent process also mandates public consultations to incorporate community and stakeholder feedback. Compliance with grid connection standards is required, ensuring that the generated energy can be effectively integrated into the national grid.

Regulatory Body: Applications for Section 36 Consent are reviewed by the Department for Energy Security and Net Zero in collaboration with other relevant government agencies.

6.2.2 Planning Permission

Local planning authorities may require planning permission for the construction and operation of energy storage facilities. This process involves assessing the project’s impact on the local environment and community (Local Government Association, 2021).

6.3 Energy storage licencing

Energy storage facilities, which play a crucial role in balancing supply and demand, require an Electricity Storage Licence issued by Ofgem. This licence ensures that storage operators comply with regulatory standards and maintain operational safety (Ofgem, 2020).

Table 6-2: Energy storage licencing

License	Description	Regulatory Body	Key Requirements	Relevant Assessments
Electricity Generation Licence	Required for electricity generators connected to the GB transmission network.	Ofgem	.	Environmental assessments if significant storage infrastructure is involved. Requirement to sign up to the Balancing and Settlement Code.
Planning Permission	May be required by local planning authorities for construction and operational activities,	Local Planning Authorities	Assesses impact on the local community and environment, ensuring alignment with	Environmental assessments as part of the planning application

License	Description	Regulatory Body	Key Requirements	Relevant Assessments
	particularly for energy storage components.		regional planning requirements	

6.4 Additional licenses

Table 6-3: Additional licencing

License	Description	Regulatory Body	Key Requirements	Relevant Assessments
Environmental Permits	Required to manage environmental impacts, such as emissions and waste, for projects in ecologically sensitive areas, including the Severn Estuary	Environment Agency, Natural Resources Wales	Compliance with Conservation of Habitats and Species Regulations, including environmental and habitat conservation standards	Environmental Impact Assessment (EIA), Habitat Regulations Assessment (HRA
Water Abstraction License	Required for any project that involves the abstraction of water from natural sources.	Environment Agency, Natural Resources Wales	Ensures sustainable water use and minimal impact on water resources.	Environmental Impact Assessment (EIA), Water Framework Directive (WFD) Assessment
Flood Risk Activity Permit	Necessary for activities that could affect flood risk management structures or watercourses	Environment Agency, Natural Resources Wales	Ensures that flood risk is managed and mitigated.	Flood Risk Assessment (FRA), Environmental Impact Assessment (EIA)
Coastal Erosion Management Permit	Required for projects in areas prone to coastal erosion	Local Planning Authorities, Environment Agency	Ensures that coastal erosion is managed and mitigated.	Coastal Erosion Risk Assessment, Environmental Impact Assessment (EIA
Navigational Safety Consent	Ensures that the project does not interfere with navigational safety.	Maritime and Coastguard Agency (MCA)	Includes assessments of navigational risks and safety measures.	Navigational Risk Assessment (NRA)

Location-specific permits, such as Coastal Erosion Management Permits and Flood Risk Activity Permits, may be required based on the project’s geographic and environmental context.

The licencing regime for any potential tidal project is complex and highly project specific. This can add delays, risks and costs to projects. Any specific project models will need a clear and early view of which licensing route it would need to take and understand the costs associated with their specific obligations.

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Appendix A

Literature Review

A.1 Review of the Evidence Base

In preparation for the launch of this program of work, an initial assessment of the current tidal range literature was conducted by WSP for WGP. Building upon this foundational analysis and framework ("The Evidence Base"), Arup have undertaken a comprehensive review to examine the energy system considerations of tidal energy. This section synthesizes existing literature and previous research, providing key insights into the methodologies, findings, and knowledge gaps related to tidal energy's role in the future energy system.

The purpose of this review is to collate and critically analyse relevant work to identify actionable insights and gaps. By doing so, we aim to enhance the understanding of tidal energy's implications on the broader energy system and establish a robust evidence base for future considerations signpost the fact that we provide a rapid historical background of tidal energy, then summarise the existing tidal generators in the world.

A.1.1 Historical background

19th-20th Century Exploration: As early as the 19th century, engineers began exploring the feasibility of electricity generation from tidal sources. However, due to technological and economic limitations, large-scale tidal power was not realized until much later [10].

Post-War Period and Modern Developments: A significant milestone was the opening of the La Rance Tidal Power Station in France in 1966. This first large-scale tidal power project demonstrated tidal energy's reliability, providing an industrial case study that informed global understanding of tidal power generation [11].

1970s-1980s - UK Feasibility Studies: Following the oil crises of the 1970s, the UK government undertook extensive studies on renewable energy, identifying tidal energy as a promising source. The Severn Estuary was highlighted due to its high tidal range, though costs and environmental concerns delayed full-scale deployment [12].

Renewed Interest and Technological Advancements (2000s-2010s): With the onset of the 21st century, advances in turbine technology, such as horizontal-axis designs, increased the efficiency of tidal energy systems (Fraenkel, 2002). This period saw the UK emerge as a leader in tidal energy research, supported by government funding initiatives, such as the Marine Renewable Deployment Fund [13].

Severn Estuary: The Severn Estuary has been the subject of numerous studies due to its tidal capacity, though significant environmental concerns remain [6].

Recent Developments and Ongoing Projects: Recent years have seen a shift towards balancing tidal energy output with ecological considerations, with researchers advocating for tidal lagoons and smaller-scale arrays to minimize disruption [14]. Additionally, international projects in Canada's Bay of Fundy and South Korea's Sihwa Lake have expanded the understanding of tidal power's adaptability to various coastal regions.

A.1.2 Review of the existing tidal generation sites in the world

The table below provides an overview of currently operational tidal range power stations worldwide with a capacity above 1 MW. These projects, such as Sihwa Lake in South Korea and La Rance in France, highlight the potential for tidal range technologies to contribute to renewable energy generation, while also showcasing advancements and challenges in design, operation, and environmental integration.

Table 0-1: Existing tidal generators world-wide above 1MW (excluding tidal stream schemes)

Project Name	Location	Status	Capacity	Annual Energy Output	Technology	Proposed / Completion Date	Description
Sihwa Lake Tidal Power Station	South Korea	Operational	254 MW	552 GWh	Tidal barrage	Operational since 2011	Originally constructed for flood control, it was later adapted to generate power. The project exemplifies how multi-functional infrastructure can address both energy and environmental goals. Comprises 10 submerged bulb turbines, each with a capacity of 25.4 MW. The tidal power station, adapted from a flood control barrage, helped mitigate water quality issues caused by the original barrage, improving seawater circulation, reducing chemical oxygen levels, and restoring local ecosystems [15]. However, these improvements are relative to post-barrage conditions rather than an enhancement over the original environment.
La Rance Tidal Power Plant	France	Operational	240 MW	500 GWh	Tidal barrage	Operational since 1966	The world's first large-scale tidal power plant, La Rance recovered the costs in the first 20 years, showcase tidal energy's commercial viability with low operating costs, high reliability, and 27,600 GWd generated to date, sustaining its role in France's energy system. [16] The project highlights the feasibility of long-term tidal power but also illustrates challenges, including sediment accumulation and ecological impacts on marine habitats.
Jiangxia Tidal Power Station	China	Operational	3.2 MW	6.5 GWh	Tidal barrage	Initial Operation: 1986. Technological Upgrades: 2009.	Technological advancements, including automation upgrades in 2009, enhanced safety and operational efficiency. The plant minimizes environmental impact through effective site selection and supports eco-friendly practices like aquaculture and reservoir reclamation. It serves as a model for integrating tidal energy with environmental and economic sustainability [17].
Kislaya Guba Tidal Power Station	Russia	Operational	1.7 MW	2.4 GWh	Tidal barrage	Initial Operation: Since 1968. (not continuously in operation)	The station is the world's 4th largest tidal power plant in operation since the Annapolis Royal Generating Station ceased operation. Station began operating in 1968 but was later shut down for 10 years until December 2004, when funding resumed.

The next table below summarises notable suspended or decommissioned tidal power projects. These examples illustrate the economic, technical, and environmental challenges that can arise during the lifecycle of tidal energy projects, offering valuable lessons for future developments in this field.

Table 0-2: Suspended or decommissioned tidal generators world-wide (excluding tidal stream schemes)

Project Name	Location	Status	Capacity	Annual Energy Output	Technology	Proposed / Completion Date	Description
Swansea Bay Tidal Lagoon	United Kingdom	Suspended	320 MW	~520 GWh	Tidal Lagoon	Development consent: 2015; Suspension: 2018.	This project is significant as it emphasizes modular construction and environmental adaptability, allowing tidal energy to be generated with a smaller environmental footprint compared to traditional barrages [18]. The project was awarded a Development Consent Order in 2015 but was suspended in June 2018 following concerns about value for money from the UK government.
Annapolis Royal Tidal Generating Station	Canada	Decommissioned	20 MW	~ 50 GWh	Tidal barrage	Operated 1984-2019	The Station was shut down in January 2019 due to an equipment failure. Additionally, the project faced significant environmental challenges, including sediment release, bank erosion, and disruptions to flood flow management. The barrage's raised water levels interfered with agriculture, accelerated erosion, and posed risks to anadromous fish passage and marine life [19]

A.1.3 Summary of literature review: Tidal energy and its role in the energy system

Table 0-3: Summary of literature review

Title	Reference	Key Findings
The Role of Tidal Lagoons	[20]	The study was commissioned by the UK Government to evaluate the strategic potential of tidal lagoon energy within the UK's energy mix. It explores whether tidal lagoons can provide cost-effective, low-carbon electricity while delivering broader economic, environmental, and industrial benefits. The review concludes that tidal lagoons offer a unique opportunity to harness the UK's vast tidal range potential, contributing to energy security, decarbonization targets, and regional regeneration. With a proposed operating lifespan exceeding 120 years, lagoons represent a long-term, sustainable energy solution. The report emphasizes the predictability and reliability of tidal energy compared to other renewables, despite its limited dispatchability. Economic modelling suggests that while initial projects, like the Swansea Bay Tidal Lagoon, may require higher upfront costs, subsequent projects could achieve significant cost reductions through economies of scale and innovation. The review highlights ancillary benefits, including flood protection, habitat creation, and job creation, particularly within the UK supply chain. Environmental concerns, including impacts on marine ecosystems and sedimentation, require careful monitoring and adaptive management. The report advocates for a strategic, government-led approach to tidal lagoon development, starting with a pathfinder project like Swansea Bay, to pave the way for a broader tidal energy program. The study underscores the importance of tidal lagoons as a national infrastructure investment, balancing energy needs with long-term economic and environmental benefits.
Current Trends and Prospects of Tidal Energy Technology	[21]	In the context of the global energy transition, the demand for renewable energy sources has surged to mitigate climate change and reduce reliance on fossil fuels. Among these, ocean renewable energy, which includes tidal energy, contributes up to 7% of the global electricity mix. However, the status of marine power is still classified as "not on track" due to its significant shortfall in meeting the requirements of the Sustainable Development Scenario (SDS), which demands an annual growth rate of 23% until 2030. While tidal energy is not yet a mainstream commercial renewable energy source, it holds significant potential due to its predictability, reliability, and minimal pollution compared to other renewables. Research and development (R&D) in this sector has primarily focused on tidal barriers and turbines, particularly in tidal range systems. For instance, the La Rance Tidal Power Plant in France, with an installed capacity of 240 MW, has demonstrated the viability of tidal range technology by generating 480 GWh annually since 1967. This highlights the potential for tidal energy to evolve into a profitable and sustainable energy source in the near future. Despite its promise, tidal energy faces significant challenges. The high cost of electricity production compared to conventional sources remains a major barrier, along with concerns about environmental impacts, such as effects on marine ecosystems and sediment flow. Nonetheless, extensive plans for tidal barrage projects in countries such as Russia, Korea, India, and the UK, amounting to a combined capacity of 115 GW, illustrate the global ambition to scale up tidal energy infrastructure. The next phase of tidal energy development is expected to see increased investment in tidal Stream Energy projects, supported by significant capital funding. While tidal range systems are considered more mature and capable of large-scale deployment. These developments underscore the need for continued research, policy support, and innovation to overcome existing barriers and fully integrate tidal energy into the global renewable energy mix.

Title	Reference	Key Findings
Magallanes Array Project Information Summary	[22]	Magallanes Removables projects demonstrate tidal energy's predictability and reliability, demonstrating its critical role in supporting the UK’s energy transition by providing consistent and renewable power generation. Their innovative floating tidal platform, the ATIR, aligns with national renewable energy targets by contributing to decarbonization efforts and fostering local economic growth using domestic supply chains and expertise in marine operations. The ATIR platform’s cutting-edge design, featuring counter-rotating turbines and a modular structure, highlights significant advancements in tidal energy technology. These innovations aim to reduce both capital expenditure (CAPEX) and operational expenditure (OPEX), paving the way for tidal energy to become a cost-effective and scalable renewable resource.
Energy and Climate Change Committee Written evidence	[23]	The Severn Barrage, proposed by Hafren Power, is a tidal energy project designed to harness the predictable and consistent tidal power of the Severn Estuary. Capable of generating 16.5 TWh/year (5% of the UK’s electricity demand), the barrage would provide clean, base-load electricity for an average of 15.25 hours daily. However, the Hafren Power Inquiry found significant downsides with timescales that were not credible, inaccurate cost analyses and optimistic outputs from untested technologies?
Income optimisation of a fleet of tidal lagoons	[24]	A vector for economic optimization of a tidal lagoon consists of modulating production according to the needs of the electrical system in real time, in the manner of a STEP (pumped storage energy transfer station).Thus, electricity production could be shifted by advancing or delaying the start-up time of the turbine phases according to the evolution of the spot price on the intraday or Day Ahead (D-1) markets. A study by Imperial College London estimated annual revenue gains of over 30% for a lagoon farm whose operation is modulated according to price signals from the Day Ahead electricity market. This flexible mode of operation allows tidal lagoons to provide different types of services to the electricity system — either baseload production by playing on the tide shift between sites located on different sea fronts, or storage and discharge of electricity according to fluctuations in demand in near real time.

A.1.4 Summary of literature review: Tidal energy – other aspects

Technological advances

Although there have been technological advancements in proposed types of turbines and material science, the proposed technology for the scale of tidal range assets considered in the Severn has not significantly changed in the last fifteen years. The use of existing, proven turbine technology and civil engineering solutions is a key advantage of tidal range assets, giving cost and performance certainty. Proposed new turbine types are discussed in section A.2.1, including those with proposed prototypes. It is unlikely that any of the proposed new technologies will make a significant difference the cost-benefit analysis of a proposed tidal range asset, especially those to be delivered in the early-mid 2030s as proposed in this study.

Energy storage mechanisms have advanced in the same timeframe – these are discussed in A.2.1.3 and the implications on the power grid in the relevant target cases.

Policy and economic aspects

The regulatory, economic, and market-driven aspects of tidal energy have been extensively studied. Regulatory frameworks play a crucial role in the development of tidal energy projects, with policies often focusing on environmental protection and grid integration. Economic studies highlight the high initial costs of tidal energy projects, are due to underwater construction and advanced materials, which can be mitigated through subsidies and financial incentives. Market competitiveness is another critical factor, with tidal energy needing to compete with other renewable sources like wind and solar. Studies suggest that with technological advancements and economies of scale, tidal energy can become more cost competitive.

Environmental Impact Studies

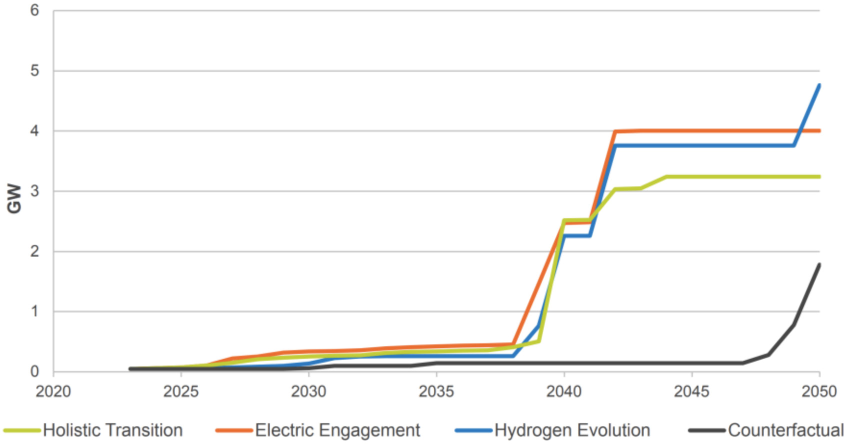
The ecological impact of tidal energy projects, particularly in sensitive regions like the Severn Estuary, has been a major area of research. Studies have shown that tidal barrages can significantly alter water flow and sediment transport, impacting local ecosystems. For example, the proposed Severn Barrage has raised concerns about its potential effects on fish migration and intertidal habitats. However, adaptive management strategies and careful site selection can help mitigate these impacts. Research also indicates that tidal lagoons may have less severe environmental impacts compared to barrages, making them a more sustainable option.

1.1.1 Key industry publications

Table 0-4 outlines recent key industry publications regarding tidal energy in Great Britain.

Table 0-4: Key GB industry publications and auctions

Title	Reference	Key Findings
Future Energy Scenarios (FES) 2024	[25]	Tidal energy, which harnesses the natural movement of water to generate electricity, is a highly predictable and reliable renewable resource available year-round. The UK holds approximately 50% of Europe's tidal energy resource, underscoring its strategic importance. The British Energy Security Strategy highlights intentions to explore tidal opportunities further, though development is constrained by high upfront costs and limited subsidy support. While Tidal Range is a well-established technology with the potential for large-scale deployment, it requires significant government backing to advance. Increased support, such as allocating additional funding through the Contracts for Difference (CfD) scheme, will be critical to unlocking the potential for a thriving and competitive UK tidal energy sector. In future pathways: Holistic Transition projects 3 GW of combined tidal stream and range capacity by 2050, the lowest across scenarios due to competition with lower-cost alternatives. Electric Engagement and Hydrogen Evolution foresee large-scale tidal range projects by the early 2040s, achieving 4 GW capacity by 2042, with Hydrogen Evolution reaching 5 GW by 2050. The Counterfactual Pathway, which does not meet net-zero targets, estimates only 2 GW of tidal capacity by 2050, relying more heavily on thermal generation.

Title	Reference	Key Findings
		 Figure 0-1: Tidal capacity (NESO)
Current GB tidal project pipeline		
CfD Auctions AR6	[26]	In Allocation Round 6 (AR6) of the Contracts for Difference (CfD) scheme, no awards were granted to tidal range projects.
TEC Register	[27]	NESO's Transmission Entry Capacity (TEC) register shows only one tidal range project, Port of Mostyn. This is planned for connection at Connah's Quay 400kV Substation with a capacity of 210 MW by 2027. All other projects, including MeyGen Tidal and Menter Môn Morlais Anglesey Marine Energy, are tidal stream projects. The Mostyn Tidal Lagoon, developed by Mostyn SeaPower Limited, a subsidiary of the Port of Mostyn.
The Port of Mostyn Limited	[28]	The Port of Mostyn is advancing plans for a £590 million tidal lagoon project, aiming to generate low-carbon electricity for approximately 82,000 homes in North Wales. The project seeks to harness tidal energy in the Dee Estuary through the construction of a 6.7-kilometer lagoon wall extending from the Port of Mostyn to Point of Ayr. The lagoon is designed to generate 298 GWh annually, contributing to the UK's renewable energy targets. The generated power will connect to the national grid via the Connah's Quay 400kV Substation. The lagoon wall will be two metres above sea level and another major benefit is it will provide flood protection to surrounding low-lying areas. The project is in the scoping stage, with Mostyn SeaPower Limited conducting ecological and seabed assessments to address environmental concerns. The company aims to submit a formal development application, with construction targeted to begin, and power generation expected, by mid-2027.
Mersey Barrage	[29]	The formal planning process for the new Mersey Tidal Power scheme began in 2024 for the new 700MW development led by the Liverpool City Region Combined Authority. A scoping report submitted to Planning Inspectorate starting the Development Consent Order (DCO) process which is expected to take two to three years. The full planning application is expected to be submitted in July 2026 with the tender for the Front-End Engineering Design (FEED) phase currently in progress.
West Somerset Lagoon	[30]	West Somerset Lagoon is still in the pre-planning stage with the project carrying out preliminary studies. The project consists of a 22km semi-circular embankment with 125 turbines with a total capacity of 2,500MW. The current timeline proposes that environmental studies, development consent order process and detailed design and construction tenders are complete by 2032 with energy first being generated in 2037.
Swansea Tidal Lagoon (Blue Eden)	[31]	As part of a wider port redevelopment project called Blue Eden, DST Innovations are proposing to construct the Swansea Tidal Lagoon consisting of a 9.5km structure with a capacity of 320MW. The development is still in its initial phases which are due to be completed by the end of 2027 and the DCO process and construction progressing in parallel with an aimed completion of 2031.

A.2 Review of New Technologies

Despite the small number of operational schemes, tidal range energy has had multiple proposed advancements in technology designed to make its implementation more feasible and sustainable. Emerging technologies in tidal energy focus primarily on advancements in turbine design, energy extraction methods, optimised operational models and improvements in foundation design. These have been proposed to address some of the traditional challenges of tidal range energy, such as high costs, environmental impacts, and scalability.

This section explores the current state and potential of these new and emerging technologies in relation to tidal range energy, analysing their readiness, infrastructure innovations, and performance improvements.

Assessing the maturity of emerging technologies is essential for understanding their readiness for commercial deployment. The Technology Readiness Level (TRL) system, developed by NASA and adopted across industries, provides a metric to evaluate how close a technology is to market readiness.

The TRL levels and definitions are as follows [32]:

- TRL 1: basic principles observed and reported
- TRL 2: technology concept or application formulated
- TRL 3: analytical and experimental critical function or characteristic proof-of-concept
- TRL 4: technology basic validation in a laboratory environment
- TRL 5: technology basic validation in a relevant environment
- TRL 6: technology model or prototype demonstration in a relevant environment
- TRL 7: technology prototype demonstration in an operational environment
- TRL 8: actual technology completed and qualified through test and demonstration
- TRL 9: actual technology qualified through successful mission operations.

A.2.1 Mechanical & Electrical

As discussed in Section 2.2, the modified representative projects in this study utilise 8m diameter bulb turbines, operating in a range of modes. It is not expected that new proposed tidal range projects in the Severn Estuary (either those in the MRP or similar) would require new turbine designs given the established use of bulb turbines in existing tidal and other hydroelectricity projects. The sections below discuss current and new mechanical and electrical technologies which could impact tidal range projects.

A.2.1.1 Bi-directional turbines

Technology

Bi-directional turbines operate in both ebb and flood tides, allowing for energy generation four times a day where there are semidiurnal tides (such as in the Severn Estuary), as well as increasing total energy output. Bi-directional turbines are used in the La Rance tidal barrage in France and were proposed for use in the Swansea Bay Tidal Lagoon (see Table 0-1). Advances in the control of the turbines such as variable speed operation and improved guide vane and turbine blade angle control increase efficiency of these turbines.

Technology availability and readiness

Bi-directional turbines have reached TRL 9 and are in full-scale operational use, with demonstrated performance in several tidal energy projects globally. Their deployment in projects like La Rance and significant testing by manufacturers underscores their readiness for widespread commercial adoption. Bi-directional turbines are therefore not considered a new technology and are now the standard for most tidal range studies and proposals in the UK, apart from where other factors may influence the required operating mode.

A.2.1.2 Low head turbines

Technology

Low-head turbines operate effectively at lower water heads than the more established bi-directional bulbs, enabling tidal energy to be captured in environments where traditional turbines would be inefficient or where creating large head differences across the turbines would be difficult. This design innovation is suggested for the construction of tidal range projects with minimal alteration to existing water levels, which could reduce environmental impacts.

A current consortium project, led by Jacobs, is progressing the development of a very low head turbine which reduces the required head differential over the asset by utilising a large number of smaller turbines, which would increase the energy generation range of a tidal barrage or lagoon beyond that of more traditional bulb turbines [30]. One of the key challenges in deploying tidal range projects is the potential negative environmental impacts, particularly key in the Severn Estuary which has sensitive marine environments. One of the further claimed benefits of the proposed new turbine design is its' ability to operate at reduced velocities which could help in minimising impacts on intertidal zones and migratory fish species.

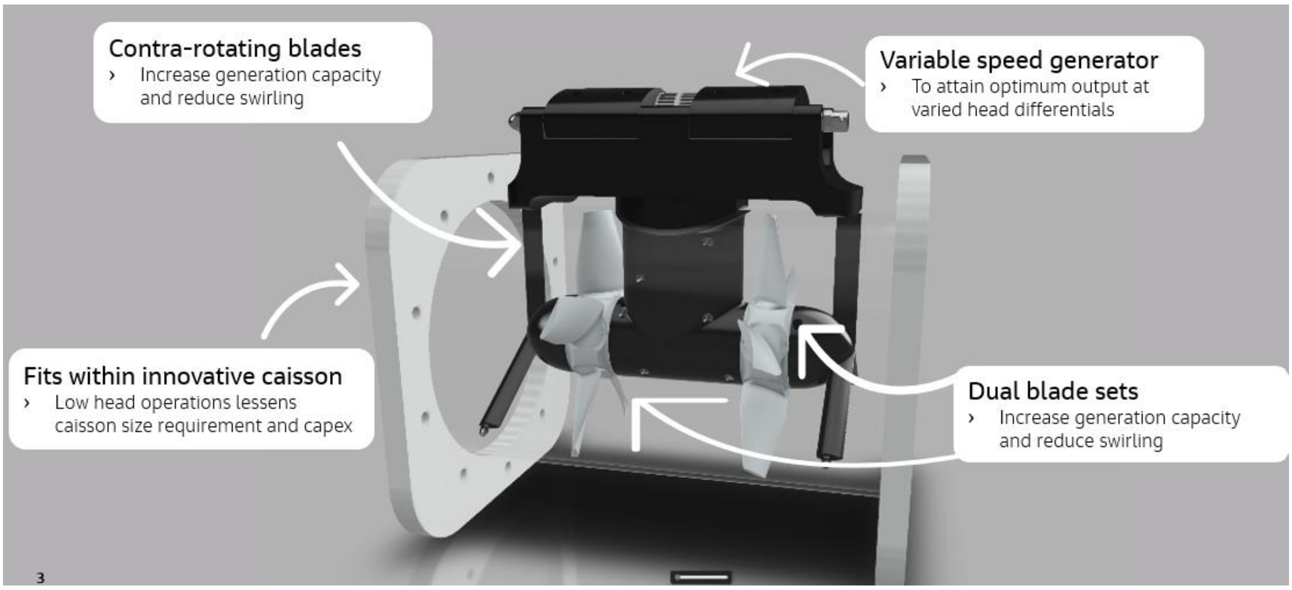


Figure 0-2: Very low head turbine key features (© Jacobs, Amentum, SETB Ltd, accessed from [30]

The energy output from a single low head turbine will be much lower than from a single large bi-directional bulb, therefore smaller systems will still require large numbers of turbines to match the same capacity.

Potential cost / carbon impact

Jacobs' very low head turbine is designed to fit within an innovative caisson with a reduced size, thus potentially lowering CAPEX and installation costs in comparison with bulb turbines. Low-head turbines could have simpler installation requirements than traditional high-head turbines, contributing to lower installation costs. However, this may be well be offset by the need for more turbines being required for the same energy output from a given tidal range asset. The large number of turbines may also put pressure on manufacturing supply chains.

The current research is also focusing on identifying cheaper construction materials for the hub and blades. This help to may offset the increased number of turbines required per GW installed capacity.

Technology availability and readiness

Very low head turbines being developed by Jacobs are currently at TRL 3-4. These are being progressed towards the laboratory demonstrator stage. The next step following this would be to develop and test a demonstrator in a relevant environment, with Jacobs' preferred location for this to be the flue gas desulphurisation lagoon channel within the decommissioned Aberthaw power station [30].

The applicability of these turbines to schemes similar to those in the MRP remains to be seen, given that the proposed projects seek to have high power outputs resulting from large bulb turbines, however they could be used in schemes in the Severn in future. Detailed cost-benefit analysis for a specific tidal range asset would be needed to determine if VLH turbines should be used, however it is expected that they are more likely to be suitable on smaller scale projects.

A.2.1.3 Energy storage

Given the cyclical nature of tidal energy, energy storage solutions are an option for balancing supply with demand. Battery storage, particularly lithium-ion and flow batteries, offer potential for short to medium term energy storage. By capturing excess energy generation during off-peak tides, these systems help balance the grid and ensure energy availability during peak periods when demand does not align with the natural tidal cycle. The use of redox flow batteries in tidal applications is under study, as they offer scalability and long-cycle performance suited to tidal schedules.

Converting surplus tidal energy into (green) hydrogen through electrolysis provides an alternative storage method with long-term potential. This approach is especially viable in locations with established hydrogen infrastructure, offering a way to store and transport energy beyond local grid limits.

Whilst tidal range energy is predictable due to the predictability of the tides, its energy generation could be made to better match demand profiles by co-locating with short term storage. As part of this study, we are therefore considering co-location with battery storage as a sensitivity in our modelling.

Changing the time at which energy is generated from a tidal range asset could also be considered as a de facto form of storage. However, the benefits would need to be considered against:

- Reduced overall energy output (and hence revenue)
- The ability to empty (or fill) the impounded area in order to generate energy on subsequent tides
- Changes in environmental impacts (for instance leaving intertidal areas flooded for longer)

Multiple battery and other storage options are already available and deployed on the grid and so this has TRL of 9 – noting that storage has not been specifically combined with tidal generators.

A.2.2 Civil

Whilst not having a direct impact on energy generation, innovative solutions regarding the civil engineering elements of tidal range projects could result in reduced construction programmes and costs. This is particularly pertinent given the long-life cycle and planning application times of such major projects, alongside ambitious net zero targets and the high costs associated with previous tidal range schemes. The scale of the proposed tidal range projects in the Severn Estuary could pose a strain on the relevant supply chain (particularly if being delivered concurrently with offshore wind projects). This includes materials, but also manufacturing facilities, offshore transport, workforce and logistics which will overlap with offshore wind projects. Whilst this also provides an opportunity for UK manufacturing capabilities, a range of construction techniques may be required to reduce supply chain pressures and accelerate delivery.

The key unique civil engineering elements of a tidal range scheme are the bund walls (used to enclose a body of water) and the powerhouse structure (used to house the turbines and associated M&E elements). Although these are well established techniques, some innovation in relation to how previous constructed and proposed tidal projects have been designed is considered.

A.2.2.1 Bund design

La Rance power station, and the proposed Swansea Bay Tidal lagoon (see Table 0-1) utilised bunds consisting largely of rock armour, with a core of ungraded fill material or dredged sand. The scale of proposed projects would require very large construction volumes to construct these, with long construction timescales. An alternative construction method could utilise concrete caissons for bund which would largely be constructed offsite and floated into position, similar to recent UK projects including the Aberdeen port upgrade [33].

Potential cost / carbon impact

There are several potential benefits of this method. Firstly, utilising offshore construction at a dry dock could reduce costs compared to in-situ construction, and there would be opportunity for the 'local' mass manufacture of the concrete caissons. Furthermore, the use of caissons would reduce the need for rock and armour material and there would be a reduced requirement for dewatering using temporary cofferdams on site. The cost and time savings with using pre-cast concrete caissons are also increased if additional lagoons or barrages are constructed, allowing for re-use of the design and production facilities. It should be noted that careful consideration would be required regarding the tight weather windows required for the float out and installation of the caissons due to the wave and tidal conditions of the potential project locations, and whether this would pose too significant a constraint on installation timeframes.

The embodied carbon of a solution utilising concrete is likely to be higher than a rock armour bund, although this could be influenced by transportation emissions if rock armour material would need to be brough from abroad, which is relatively likely given the scale and number of proposed projects.

Technology availability and readiness

As highlighted above, concrete caissons have been widely used in engineering projects and so would be considered TRL 9 and could be utilised in the construction of a tidal range project. Caissons could also be used in the powerhouse construction, with similar advantages and disadvantages.

A.2.2.2 Powerhouse design

The key innovation around the design of the powerhouse as a general principle is utilising modular and / or offsite construction techniques, noting that at specific sites more innovative methods could be possible. A standardised powerhouse design would allow the use of Design for Manufacture and Assembly (DfMA) techniques, where elements are constructed onshore and then assembled on site. This could be applied to civil concrete elements, as well as mechanical balance of plant.

Potential cost / carbon impact

The key advantage of offsite manufacturing and DfMA is programme-related, which will have a subsequent effect on cost and potentially allow earlier 'power on' dates. It allows the powerhouse to in effect begin construction before the permanent bund is complete, as well as any temporary works to dry out the working area. Precast elements can often lead to reduced carbon emissions compared with in-situ concrete due to the controlled environment and repetitive techniques in which they are constructed.

Technology availability and readiness

As highlighted above, offsite construction and DfMA have been widely used in engineering projects and so would be considered TRL 9 and could be utilised in the construction of a tidal range project.

A.2.3 Summary

There have been relatively few technology advancements in tidal range energy over the last few decades, owing to the fact that since La Rance, only one other high-capacity project has been constructed (Sihwa Lake). Whilst there has been research into innovative turbine design, as discussed above, these designs offer limited benefits compared to standard bulb design, in particular for the scale of projects proposed in the Severn Estuary and the large tidal ranges involved. They are likely to be more relevant in small scale projects or where tidal ranges are smaller. Due to their low TRL these designs would require significant time and costs to be commercially available at scale, and we anticipate they are therefore not viable options for use in tidal range projects in the Severn Estuary in the near future.

The integration and/or use of existing technologies with tidal range projects should be considered, such as concrete caissons for construction and co-locating with short term energy storage or electrolysis for more dispatchable generation. A key benefit of tidal range energy schemes in general is that the individual technologies themselves are generally well established, increasing confidence in both cost and performance once constructed. Many of the proposed technologies are therefore for incremental improvements and will generally require consideration on a case-by-case basis.

A.3 Other Tidal Range Projects: Stakeholders Engagement

In order to maximise synergies across related initiatives, meetings were held with representatives for the following projects.

A.3.1 MOSAIC (Marine energy OptimiSAtion for system securIty enhanCement)

The MOSAIC project investigates the roles of tidal stream, tidal range and wave energy in overcoming energy security challenges in the UK. Energy security is defined as 'the uninterrupted process of securing the amount of energy that is needed to sustain people's lives and daily activities while ensuring its affordability'. MOSAIC builds on recent research that has started to show how tidal stream, tidal range and wave power generation can lead to energy security benefits.

The project will deliver a roadmap that sets out the amount, locations and cost of new tidal/wave energy projects to deliver energy security enhancements between 2035-50. The roadmap will be informed by novel energy system modelling outputs at three different scales based on the energy systems of Great Britain, Wales and the Isle of Wight. The incorporation of three different scales allows the energy system models to simulate and optimise the transmission and distribution grids as well as power generation and energy storage. This novel approach is critical to fully understand the compatibility of different technologies.

At the time of the meeting, the MOSAIC project had only recently begun. The meeting therefore focused on informing the project lead on this study, in order to align assumptions. Some key differences between the Severn Estuary Commission study and the MOSAIC study are:

- Study areas – unlike the SEC study, MOSAIC will study local, regional and national scale impacts. The goal is to align the regional study to the Western Gateway area for validation purposes
- Weather years – the SEC work has focused on a single, typical weather year, where MOSAIC intends to look into the impacts of marine energy on the system at time of extreme weather conditions
- Energy generation types – while this study is focused on tidal range, MOSAIC will also incorporate tidal stream and wave as generating assets
- System model – MOSAIC is building a custom energy system model, unlike SEC which uses PLEXOS.

A.3.2 TARGET (Tidal range schemes as configurable grid-scale energy storage facilities)

The TARGET project explores the potential of tidal range schemes as both renewable energy generators and grid-scale energy storage solutions.

The TARGET project explores the how the operation of a tidal range scheme could be optimised, either for maximum generation or for maximum revenue through delaying generation to meet demand, thus capitalising on higher value electricity, i.e. contributing to different electricity markets. The project also explores maximising revenue as a proxy for energy storage.

This report does not consider flexible lagoon operation but instead has investigated how fixed operation with and without performance pumping, as well as a case looking at incorporating battery storage, could impact constraint cost and short run marginal costs. It is recommended that these studies be read in conjunction with one another to look into similarities and draw a deeper conclusion.

A.3.3 FLOMax (Flexible Lagoon Operation for Maximal Value)

The FLOMax project seeks to determine how the predictable and potentially flexible electricity generated via tidal lagoons can support the UK's grid infrastructure. The research project focuses on three main objectives:

modelling the flexible operation of tidal lagoons, quantifying their true long-term economic value, and offering recommendations for policy support.

The project will model various tidal lagoon configurations to gauge their power potential over their expected lifespan of approximately 100 to 200 years. The results will yield annual yield estimates for each scheme.

This data will be utilised to assess the economic value of tidal lagoons, aiding in the justification of tidal lagoon projects through economic and financial analysis, alongside other evaluation approaches. We recommend the assumptions used in the SEC study are shared to better align the studies where possible.

The key difference between this project and the Severn Estuary Commission study was the focus on flexible lagoon operation, which has not been a variable in the SEC work. The two studies will complement each other and should they show similar results help to validate any outcomes and provide nuance as to what operability mechanisms can create the most value.

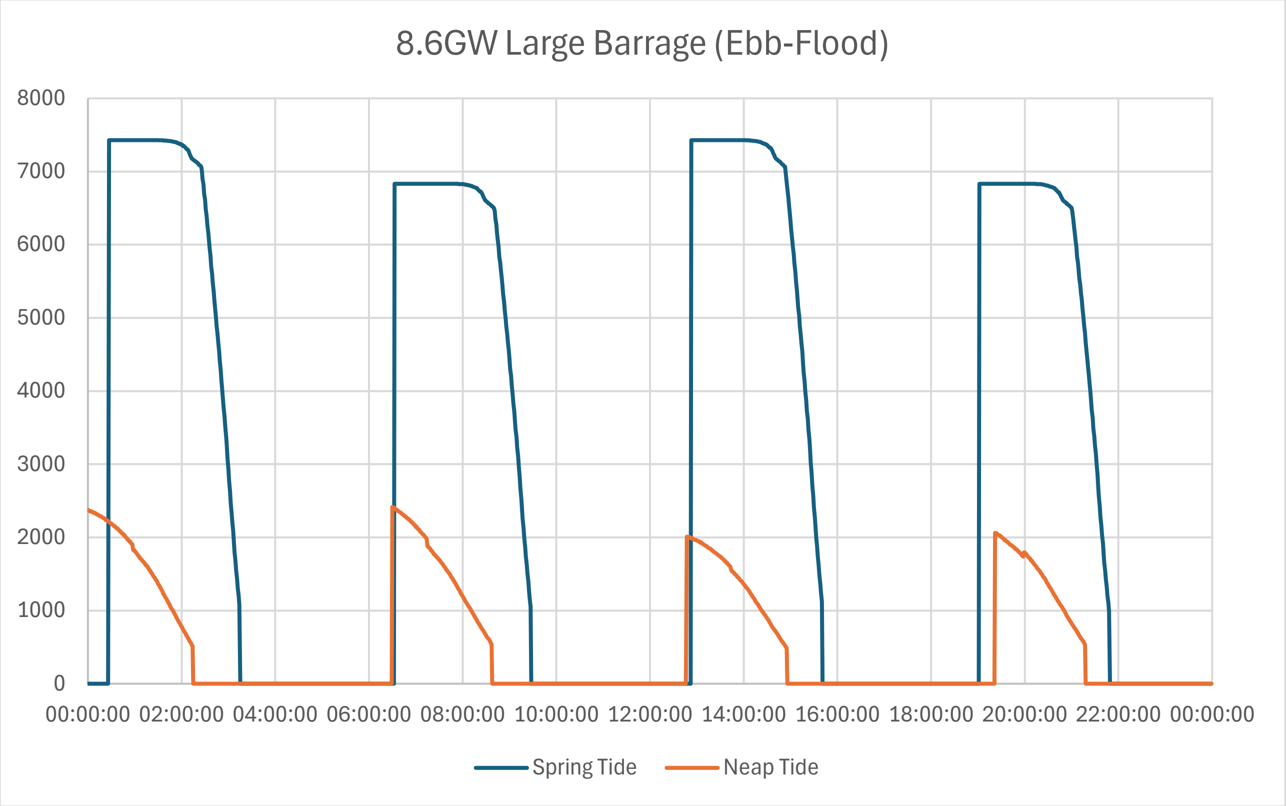
The outcomes of this report should therefore be taken in conjunction with these projects, to enable conclusions to be drawn across a bigger picture.

Appendix B

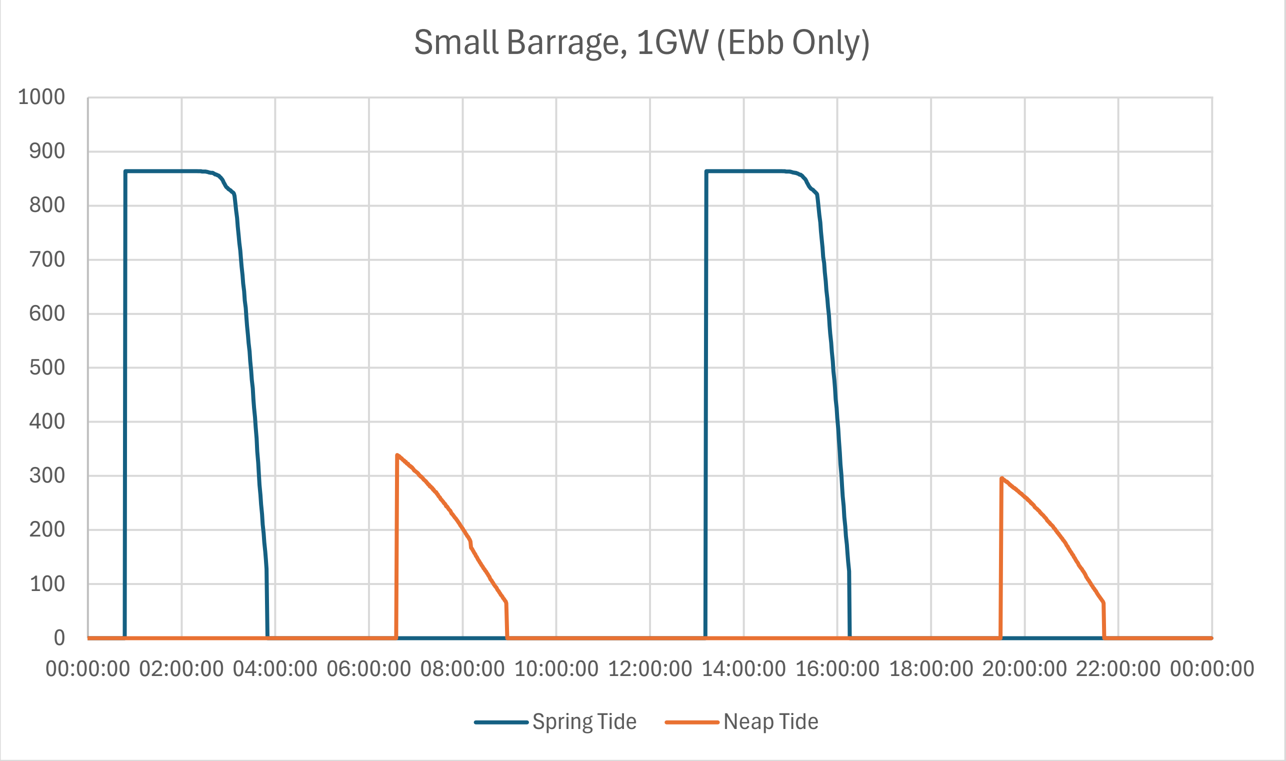
Energy Generation Graphs

B.1 Energy Generation Graphs

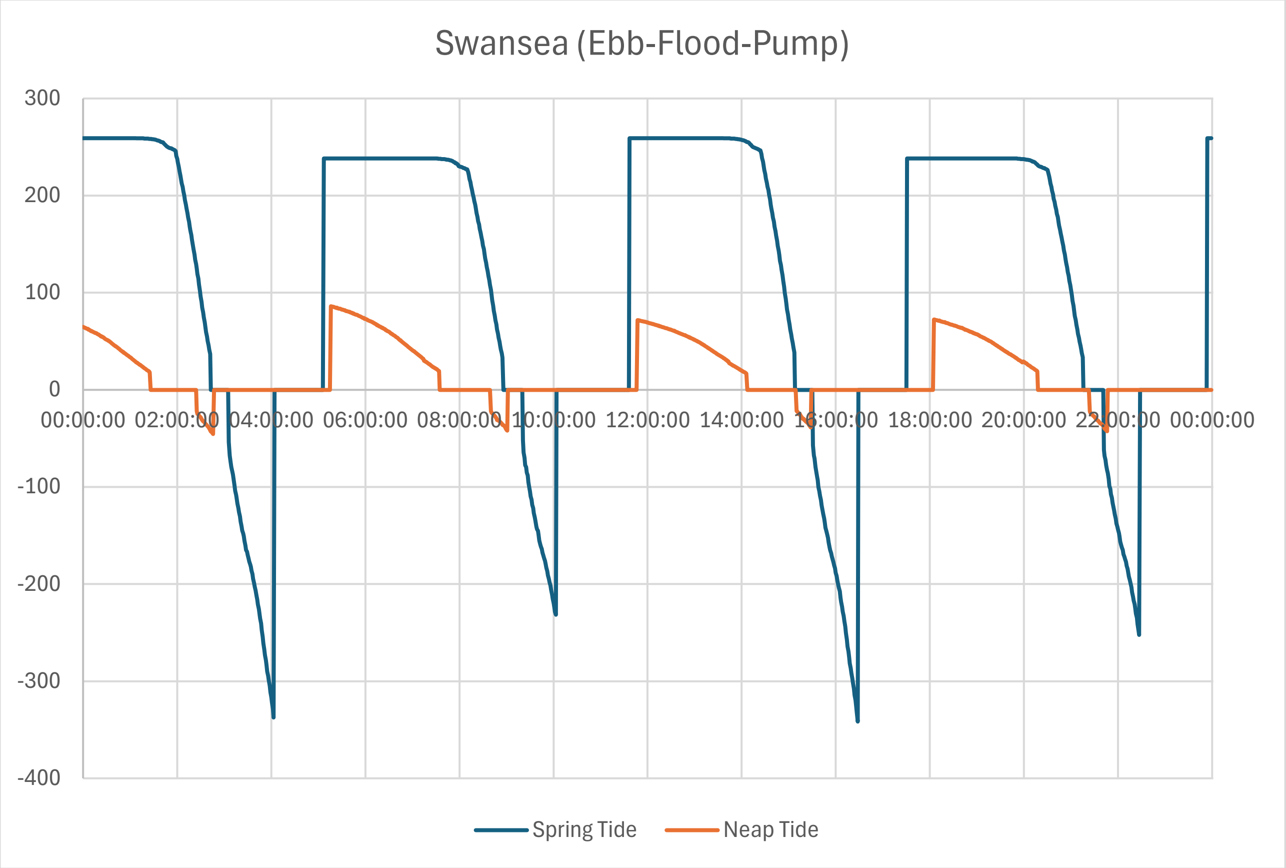
B.1.1 8.6GW Large Barrage Generation Profile (Ebb-Flood)



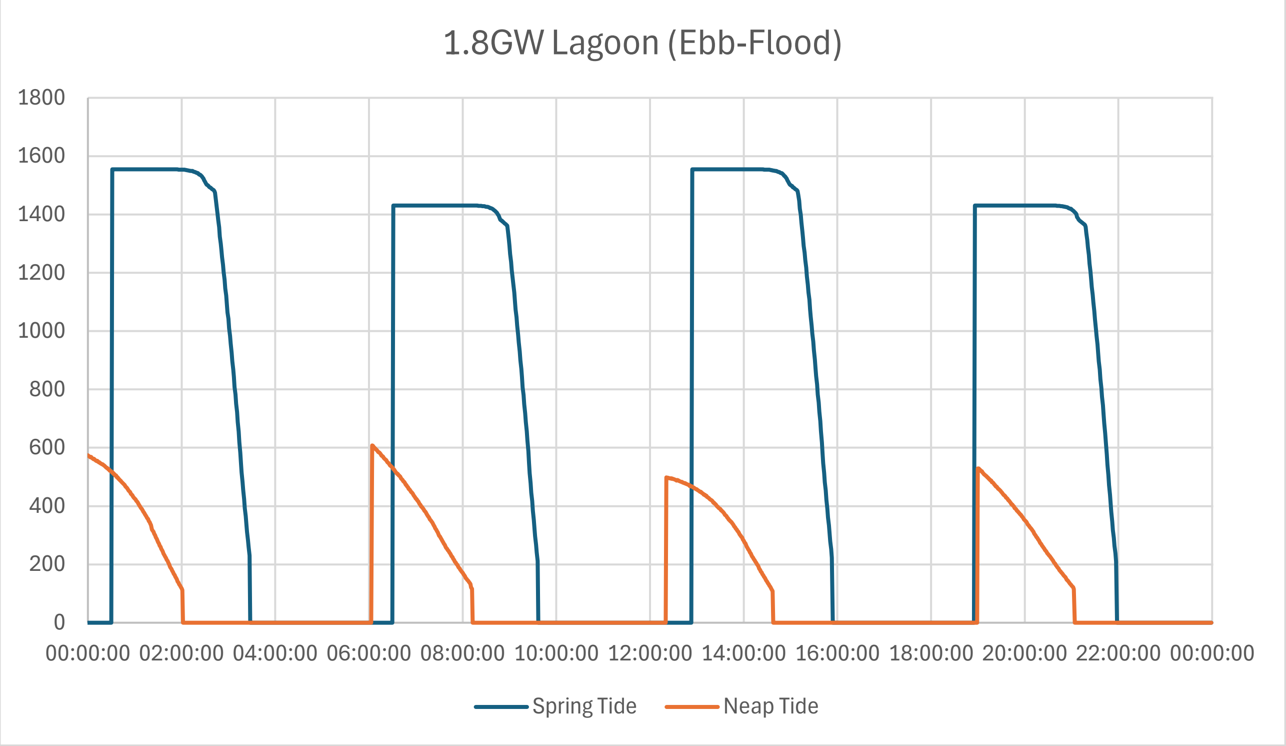
B.1.2 1GW Small Barrage Generation Profile (Ebb only)



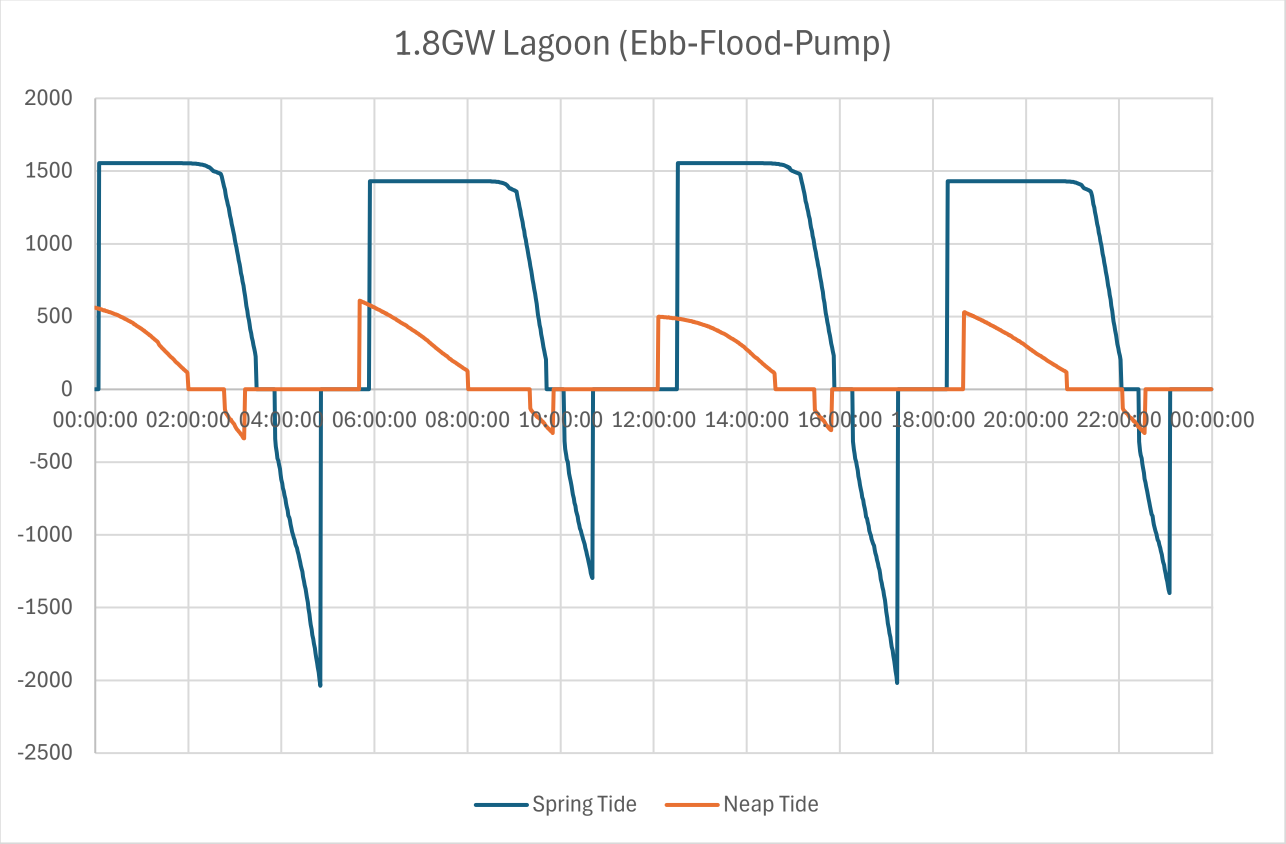
B.1.3 0.3GW Small Lagoon (Ebb-Flood with Pumping)



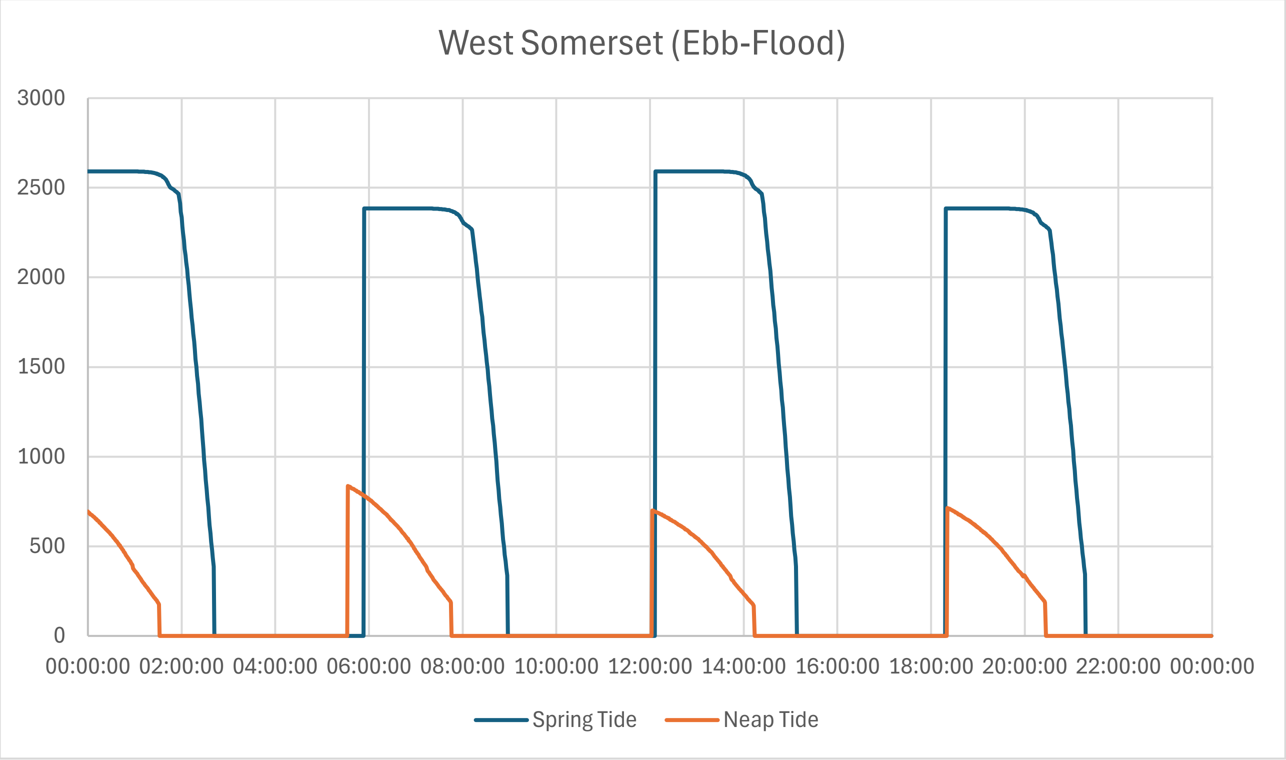
B.1.1 1.8GW Lagoon Generation Profile (Ebb-Flood)



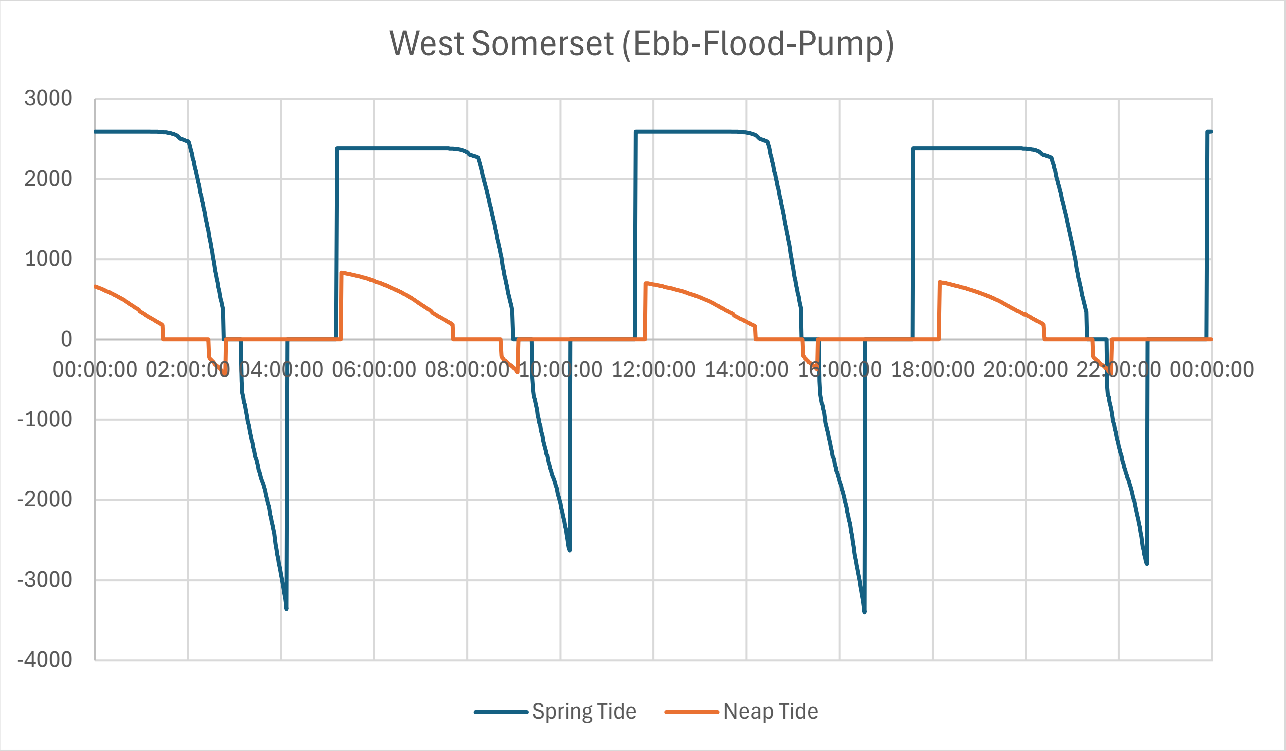
B.1.2 1.8GW Lagoon Generation Profile (Ebb-Flood with Pumping)



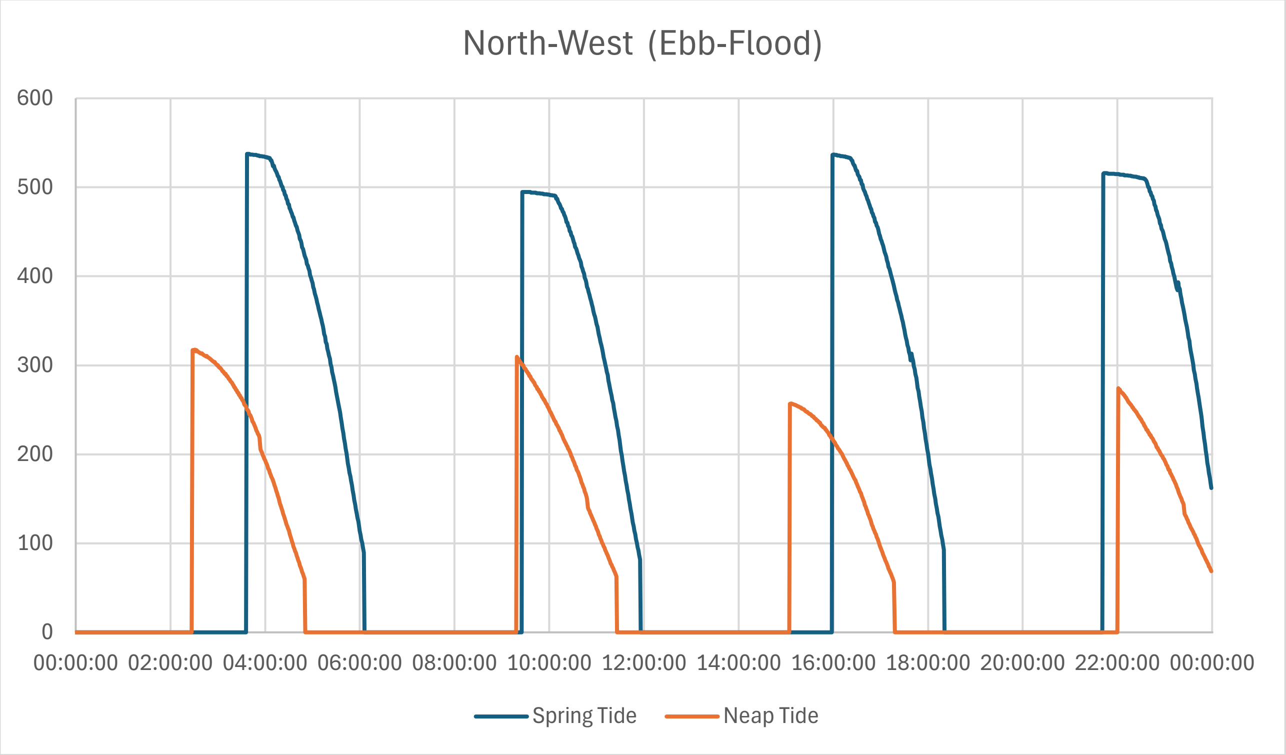
B.1.1 3GW Lagoon Generation Profile (Ebb-Flood)



B.1.2 3GW Lagoon Generation Profile (Ebb-Flood with Pumping)



B.1.3 North-West Lagoon Generation Profile (Ebb-Flood)



B.1.4 North-West Lagoon Generation Profile (Ebb-Flood with Pumping)