BRITISH HYDROPOWER ASSOCIATION

Tidal Range Levelised Cost of Energy Study

British Hydropower Association
29 February 2024

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Jacobs U.K. Limited

1180 Eskdale Road
Winnersh, Wokingham
Reading RG41 5TU
United Kingdom

T +44 (0)118 946 7000
F +44 (0)118 946 7001
www.jacobs.com

Executive summary

The purpose of this study has been to analyse how tidal range generation could best contribute to the renewable and low-carbon generation mix to meet the UK's net zero objectives by 2035 and 2050.

The prime objective has been to determine the Levelised Cost of Energy (LCoE) for tidal range generation for a range of tidal range sites across the UK and compare these with the LCoE of other renewable or low-carbon generation sources. The LCoE is a composite indicator which expresses the cost per unit of electricity generated (£/MWh) as a function of the discounted costs and energy generation over a given lifetime. This metric enables the ability to consistently compare the costs of tidal range against other renewable and low carbon generation technologies.

A further objective has been to carry out a whole system analysis of the GB power system, to evaluate different mixes of renewable and low carbon generation, together with associated energy storage requirements, and hence determine an indicative overall LCoE for the GB system as a whole, including large scale tidal range generation within the overall generation mix, needed to achieve net zero.

The scope of this study has included the following tasks:

- Zero-D tidal range power modelling to estimate the potential energy outputs at a variety of tidal range sites, including, tidal barrage and tidal lagoon schemes within the UK, for different modes of tidal operation, including no energy storage, co-located storage and grid balancing storage, with and without pumping and for conventional and enhanced tidal turbine technologies.
- Power system modelling to estimate the potential contribution of tidal range generation to the GB power system, for comparison with other renewable and low carbon generation types, including identification of the required level of energy storage needed for grid load balancing, for each type.
- Development of generic cost functions used for the estimation of high-level capital and operating costs for a variety of tidal range sites, on a consistent basis. The costs considered scheme size, power and plain caissons details, locks and building requirements, energy storage, M&E Plant, preliminary, engineering and environmental contingency resulting in a total installed cost.
- Estimation of indicative levelised costs of energy (LCoE) for a variety of tidal range sites and modes of operation, including comparison with the LCoE of other renewable and low carbon generation, as well as an assessment of the impact of tidal range on the overall system LCoE based on the forecast generation mix for 2050, as set out in National Grid ESO's latest future energy scenarios (FES 2023).

The conclusions of the study can be summarised as follows:

- Based on our findings, there are a number of potential tidal range schemes that are estimated to have a lower levelised cost than the current CfD Round 5 and Administrative Strike Price Round 6 for tidal stream at the commercial pilot hurdle rate.
- Relative to other low carbon generation sources, there are significant advantages to tidal range such as its high level of predictability, operational capability and the ability to act as a flood barrier which are not able to be fully captured within the LCOE metric. When evaluating tidal range generation contribution to the UK's low carbon generation, it is therefore important to consider both the financial and non-financial aspects of tidal range.
- Tidal Range generation using conventional bulb turbine technology can achieve a LCoE of £123/MWh similar to that of nuclear £128/MWh (for NOAK case) in the long term, see figure 1, based on existing levelised costs published by DESNZ in their Electricity Generation Cost Reports[1], uplifted as necessary to 2021 prices;

[1] DESNZ/BEIS Electricity Generation Cost Reports 2016, 2021, 2023.

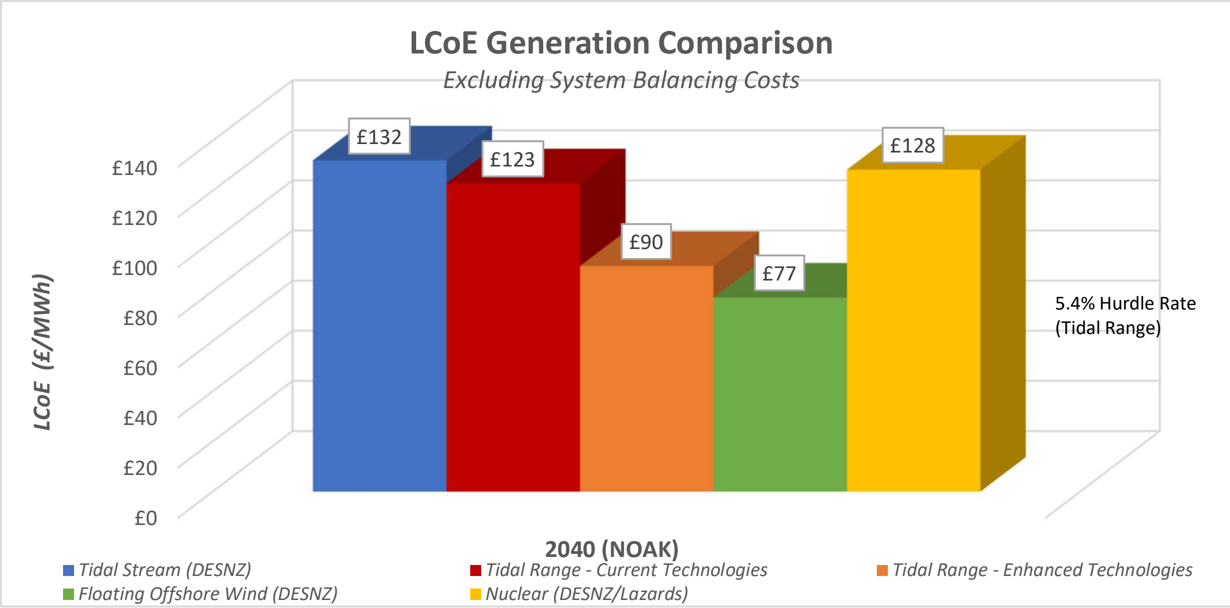

Figure 1 LCoE Generation Comparison – Excluding System Balancing Costs

- Using enhanced turbines technologies the LCoE can be reduced further to £90/MWh, below that of nuclear and approaching that of floating offshore wind (£77/MWh for NOAK case) in the long term;
- By adopting a whole system approach, utilising grid connected storage together with demand management measures, it would be possible to provide effectively firm tidal energy generation at an LCoE similar to that of nuclear;

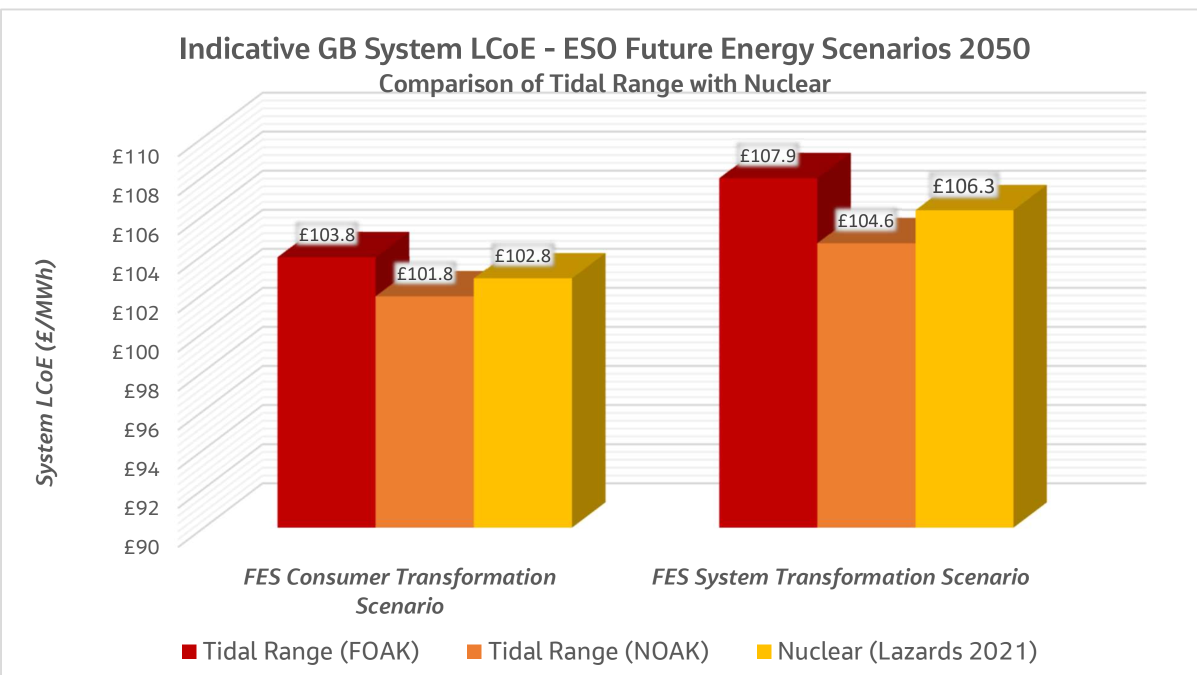

Figure 2 Indicative GB System LCoE – FES 2050 Generation Comparison

- This demonstrates that Tidal Range has a clear case for inclusion in the overall renewable generation mix needed to achieve the UK's net zero targets.

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1. Introduction

The purpose of this study has been to analyse how tidal range generation could best contribute to the renewable and low-carbon generation mix to meet the UK's net zero objectives by 2035 and 2050.

With the planned phasing out of all unabated non-renewable thermal generation by 2035, this will require a major phased development of renewable generation such as wind, solar and tidal, but also low-carbon generation such as nuclear, biomass and natural gas with carbon capture and storage (CCS). In addition, there will be a requirement for a large tranche of energy storage, that will be required to be kept in reserve for use during times of reduced renewables generation when the 'sun doesn't shine' or the 'wind doesn't blow'. Hydrogen generation is expected to play a major role in this energy transition, either in the production of green hydrogen by electrolysis from surplus renewable generation, or blue hydrogen by reforming of natural gas with CCS, that can be stored using long duration energy storage (LDES) for later hydrogen generation during periods of low renewables output.

There is thus likely to be a complex mix of both renewables and low carbon generation technologies that, together with long duration energy storage, will have the capacity to meet these net zero objectives. Currently, the main focus has been on the development of wind and solar, together with nuclear, but tidal range can play a role in this by providing further renewable generation capacity that is more predictable and reliable than other intermittent renewable technologies and hence reduce the quantum of long duration energy storage needed to meet these objectives.

Previous studies have shown that small scale tidal range schemes using conventional bulb turbines would likely have a unit cost of generation much higher than that of nuclear generation. However, recent research we have carried out has indicated that large scale tidal range schemes, could potentially have a unit cost of generation approaching that of nuclear generation. For the largest schemes, and where more efficient turbines are considered, the unit cost of generation could potentially be lower than that of nuclear generation. Also, as tidal generation is more predictable than other types of intermittent renewable generation (particularly wind), the energy storage requirements needed to balance the cyclical tidal output is less than that needed for those other technologies, and will be easier to manage at the system level. Thus, developing tidal range could offer potential economic and operational system level benefits. It should also be emphasised that even nuclear generation is not flexible and thus also needs energy storage for daily load balancing; that used to be provided primarily by pumped hydro in the 70's and 80's, before the introduction of more flexible natural gas generation in the 90's. Thus, once all unabated gas generation has been phased out by 2035, the need for further energy storage for balancing nuclear generation will return.

The prime objective of this study has been to determine the Levelised Cost of Energy (LCoE) for tidal range generation for a range of tidal range sites across the UK and compare these with the LCoE of other renewable or low-carbon generation sources.

A further objective has been to carry out a whole system analysis of the GB power system, to evaluate different mixes of renewable and low carbon generation, together with associated energy storage requirements, and hence determine an indicative overall LCoE for the GB system as a whole, including large scale tidal range generation within the overall generation mix, needed to achieve net zero.

2. Study Approach

For this study we have developed a Zero-D tidal range analytical model (see Section 4 for details) for determining the potential long term energy outputs of alternative tidal power schemes, comprising both tidal range barrages across estuaries, as well as tidal range lagoons at selected sites around the UK coast. The outputs of this model have been utilised with a generic tidal cost model we have also developed (in consultation with some of the developers represented by the Tidal Range Alliance), to determine the Levelised Cost of Generation (LCoE) for a selected set of tidal range sites on the west coast of England and Wales.

The scope of this study has included the following tasks:

- Zero-D tidal range power modelling to estimate the potential energy outputs at alternative tidal range sites, for different modes of tidal operation and for alternative tidal turbine technologies;
- Power system modelling to estimate the potential contribution of tidal range generation to the GB power system, for comparison with other renewable and low carbon generation types, including identification of the required level of energy storage needed for grid load balancing, for each type;
- Development of generic cost functions used for the estimation of high-level capital and operating costs for alternative tidal range sites, on a consistent basis;
- Estimation of indicative levelised costs of energy (LCoE) for alternative tidal range sites, including comparison with the LCoE of other renewable and low carbon generation, as well as an assessment of the impact of tidal range on the overall system LCoE based on the forecast generation mix for 2050, as set out in National Grid ESO's latest future energy scenarios (FES 2023).

The majority of the earlier tidal range schemes developed to date including La Rance (France), Annapolis in the Bay of Fundy (Canada) and Sihwa (South Korea), generate primarily on the ebb tide, as they are unable to operate efficiently in the reverse direction, needed for flood tide generation. Also, earlier turbine designs were unable to operate efficiently at the lower head range needed for tidal operation, which restricted their operating range, and due to their high rotational speed had issues with fish mortality.

However, recent advances in turbine technology, including the development of bi-directional, variable speed bulb turbines with more fish friendly blade design and lower blade tip speeds, can potentially overcome many of the issues encountered with the earlier turbine technologies. Also, further research and development is currently under way on other innovative types of tidal range turbines, advancing concepts similar to those that were identified in the government supported 'Severn Embryonic Technology Scheme' (DECC (Rolls Royce & Atkins) 2010)[2]. These innovative turbines include the following:

- Triple regulated bulb turbines that not only have variable pitch blades and guide vanes, but also variable speed generators, which can provide improved efficiency at lower heads, as well as partial improvement in efficiency under reverse flow;
- Rotating turret turbines that can be rotated to generate equally efficiently, in either direction, on both the ebb and flood tide;
- Very low head (VLH) turbines that utilise dual rotors with contra-rotating blades, that could operate at higher efficiency at lower heads, in either direction, at reduced flow velocities and at lower blade tip speeds.

These 'Next generation' turbines could thus improve still further the operational efficiency and environmentally acceptability of tidal range schemes, both in terms of maintaining the natural tidal cycle for inter-tidal habitats, while also reducing the adverse impact on marine life. Thus, a range of alternative tidal turbine technologies has been investigated and compared in the preparation of this report.

It should be appreciated that this study has been focussed on determining an LCoE for tidal range across the UK, assuming the entire capital cost of tidal range schemes are met by power benefits alone, and has not

[2] Severn Embryonic Technology Scheme - Final Report and Development Route Map (Rolls Royce), 18th October 2010, Department of Energy & Climate Change.

taken account of any flood protection benefits that could be accrued if such tidal range schemes were developed as multi-purpose power generation and flood protection projects. Thus, if tidal range schemes were to be developed as multipurpose projects, with capital costs allocated according to usage, then the resulting net LCoE for such schemes could well be lower than those presented in this report.

3. Tidal Turbine Technologies

For this LCoE study the following tidal range technologies have been assessed:

- Conventional one-directional bulb turbines;
- Triple regulated bulb turbines adapted for bi-directional operation;
- Bi-Directional rotating turret turbines;
- Bi-Directional, dual rotor, very low head (VLH) turbines.

To reduce the number of turbine combinations to be evaluated, LCoE analyses have been carried out for the case with bulb turbines adapted for bi-directional operation and for the case with bi-directional, dual rotor, very low head (VLH) turbines.

3.1 Conventional One-Directional Bulb Turbine

Conventional bulb turbines are designed principally for one-directional operation, generating usually on the ebb tide and using sluices to fill the upstream basin on the flood tide. This is the current mode of operation of existing tidal range schemes such as the 240 MW La Rance tidal range scheme in France and the 254 MW Sihwa Lake tidal scheme in South Korea. A typical arrangement for one-directional tidal range plant is shown in Figure 3-1 below, courtesy of K-Water (South Korea).

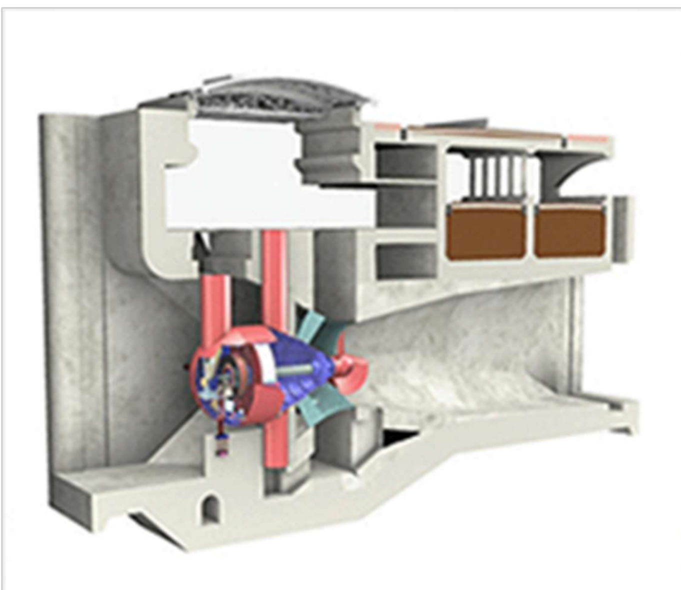

Figure 3-1 Conventional Bulb Turbine and Caisson
(Source: Andritz/K-Water[3])

One of the principal disadvantages of the one-directional bulb turbine is its reduced efficiency when operated under reverse flow, hence its usual mode of operation for ebb tide generation only. There is little documented evidence for the precise turbine efficiency, when operated in reverse flow, but Tidetec have estimated this to be of the order of 60% compared to that of 90% when operated in the normal direction, as shown in Figure 3-2 below. One-directional bulb turbines are typically double regulated, possessing both variable pitch guide vanes, as well as variable pitch blades on the turbine runner.

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[3] https://www.kwater.or.kr/eng/tech/sub01/sub02/patentPage.do?s_mid=1207

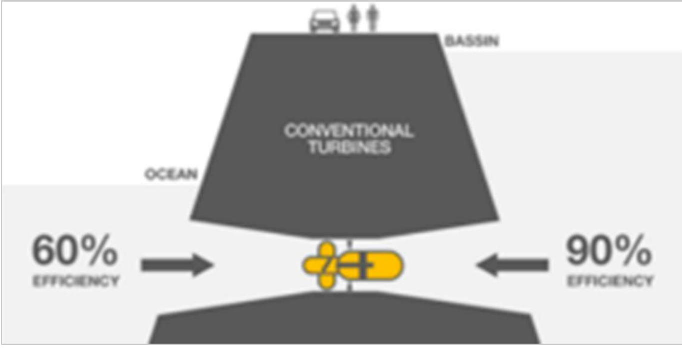

Figure 3-2 Conventional Bulb Turbine Efficiency
(Source: Tidetec[4])

3.2 Next Generation Bi-Directional Bulb Turbine

A variant of the one-directional bulb turbine is a bi-directional bulb turbine that has been adapted for improved efficiency under reverse flow. Turbine manufacturers claim that improved efficiency in the reverse direction can be achieved by utilising triple regulated turbines, which have variable speed generators, as well as variable pitch guide vanes and variable pitch blades. In addition, bulb turbines require diffusers (draft tubes) at each end, which increases the width of the power caisson (and hence cost) used to house the turbines. A typical arrangement for bi-directional tidal range plant is shown in Figure 3-3, courtesy of TEES.

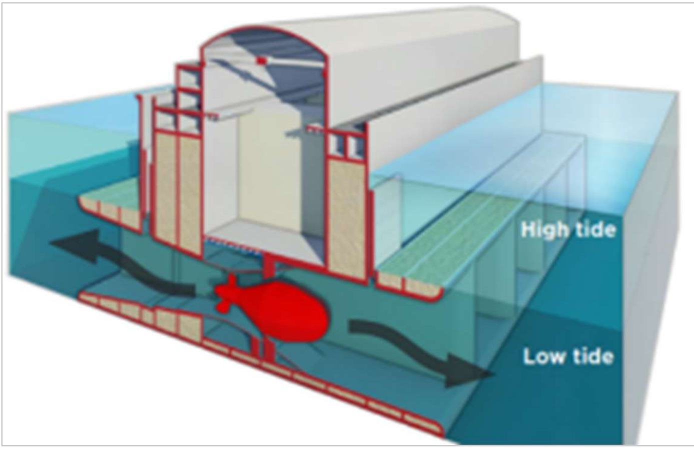

Figure 3-3 Bi-Directional Bulb Turbine and Caisson
(Source: TEES[5])

Tidetec estimate that the maximum achievable efficiency for the 'next generation' bulb turbine could be up to 75% in reverse flow, an improvement of some 15%, as shown in Figure 3-4 below. However, this is likely to be an upper limit, due not only to the positioning of the guide vanes on the exit of the turbine runner under reverse flow conditions (which is not ideal hydraulically), but also due to the more abrupt flow transition in the second diffuser, which would likely result in increased exit head losses.

[4] https://tidetec.com

[5] https://tidalengineering.co.uk

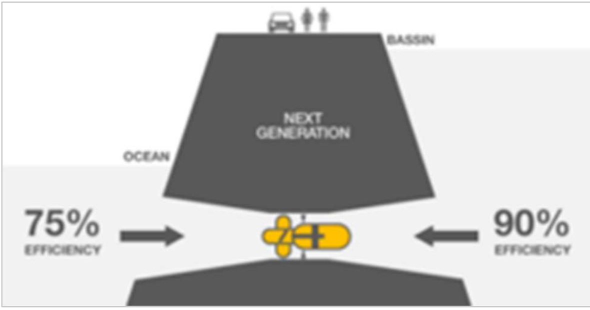

Figure 3-4 Next Generation Bulb Turbine Efficiency
(Source: Tidetec[5])

3.3 Bi-Directional Rotating Turret Bulb Turbine

An alternative to an adapted bi-directional conventional bulb turbine is a bulb turbine integrated within a rotating turret that provides optimal efficiency in either flow direction. Tidetec AS (Oslo) have developed a patented rotating turret turbine, as shown in Figure 3-5 below.

Figure 3-5 Bi-Directional Rotating Turret Turbine
(Source: Tidetec[6])

Tidetec claim that this turbine achieves an efficiency of 90% in either direction as shown in Figure 3-6 below.

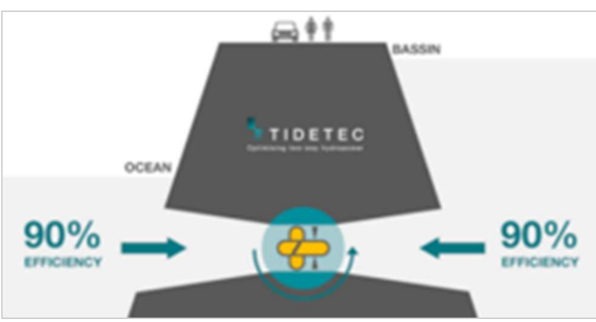

Figure 3-6 Rotating Turret Bulb Turbine Efficiency
(Source: Tidetec)

[6] https://tidetec.com

3.4 VLH Bi-Directional Dual Rotor Contra-Rotating Turbine

An alternative to the bi-directional rotating turret turbine (above), is a very low head (VLH) turbine that comprises two contra-rotating runners, that together can provide an equal efficiency in either flow direction, but without the need of a rotating turret. This turbine does not require guide vanes, as the first runner receives the longitudinal flow that, while generating power, rotates the flow onto the blades on to the second runner, which counteracts the rotational flow, such that the flow exits the runner with no swirl.

In this respect, the first runner performs a similar function to the guide vanes on a conventional bulb turbine, while at the same time generating power. This turbine currently utilises asymmetric variable pitch blades that can be rotated by 180° for reverse operation. Another option would be to utilise symmetrical fixed pitch blades at a reduced cost but also lower efficiency, that is currently being researched under another study.

A bi-directional dual rotor VLH turbine was featured in the Severn Embryonic Technologies Scheme (SETS), funded by DECC, Welsh Assembly, SW Regional Development Agency & DEFRA, and carried out by Atkins and Rolls-Royce in 2010. An isometric view of the dual rotor VLH concept design, as developed and modelled in the SETS study is presented in Figure 3-7 below.

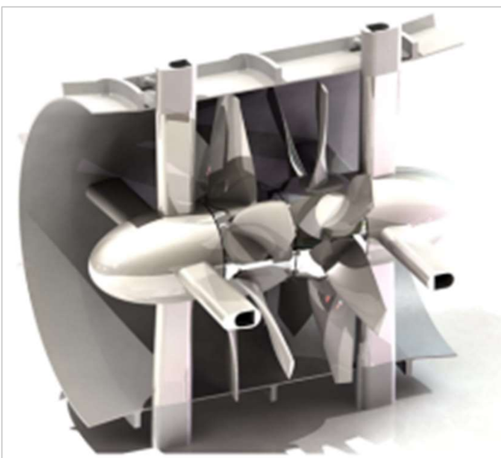

Figure 3-7 VLH Bi-Directional Contra-Rotating Turbine
(Source: Atkins/Rolls-Royce[7])

The proposed caisson arrangement for the VLH turbine is shown in Figure 3-8 below.

Figure 3-8 VLH Turbine and Caisson
(Source: Atkins/Rolls-Royce)

[7] Severn Embryonic Technology Scheme - Final Report and Development Route Map (Rolls Royce), 18th October 2010, Department of Energy & Climate Change

3.5 Turbine Characteristics

For the Zero-D modelling carried out under this study, energy outputs have been assessed for both conventional bulb turbines, as published by Andritz/Lancaster University, and very low head (VLH) turbines, as used in the earlier SETS study.

A turbine hill chart, from Andritz Hydro published in a modelling study for the Morecambe Bay Tidal Range Scheme by Lancaster University in 2020, has been utilised to derive an efficiency curve for bulb turbines. This hill chart, for a typical bulb turbine, is presented in Figure 3-9 below.

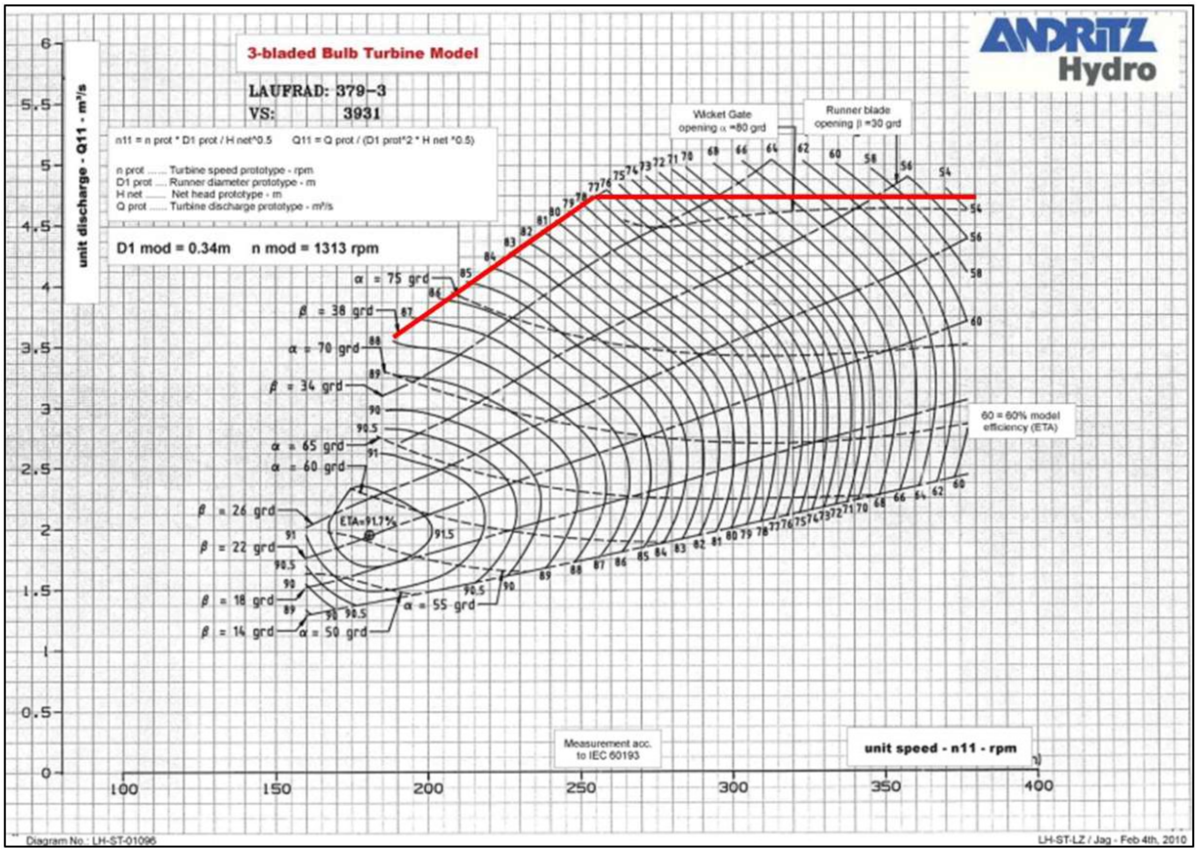

Figure 3-9 Conventional Bulb Turbine Hill Chart
(Source: Andritz/Lancaster University[8])

From this hill chart, a typical head/efficiency curve has been derived for bulb turbines, which has been compared with an equivalent head/efficiency curve for the prototype VLH turbine utilised in the SETS study.

This turbine efficiency comparison is presented in Figure 3-10 below.

[8] https://eprints.lancs.ac.uk/id/eprint/151442/1/2020bakermres.pdf

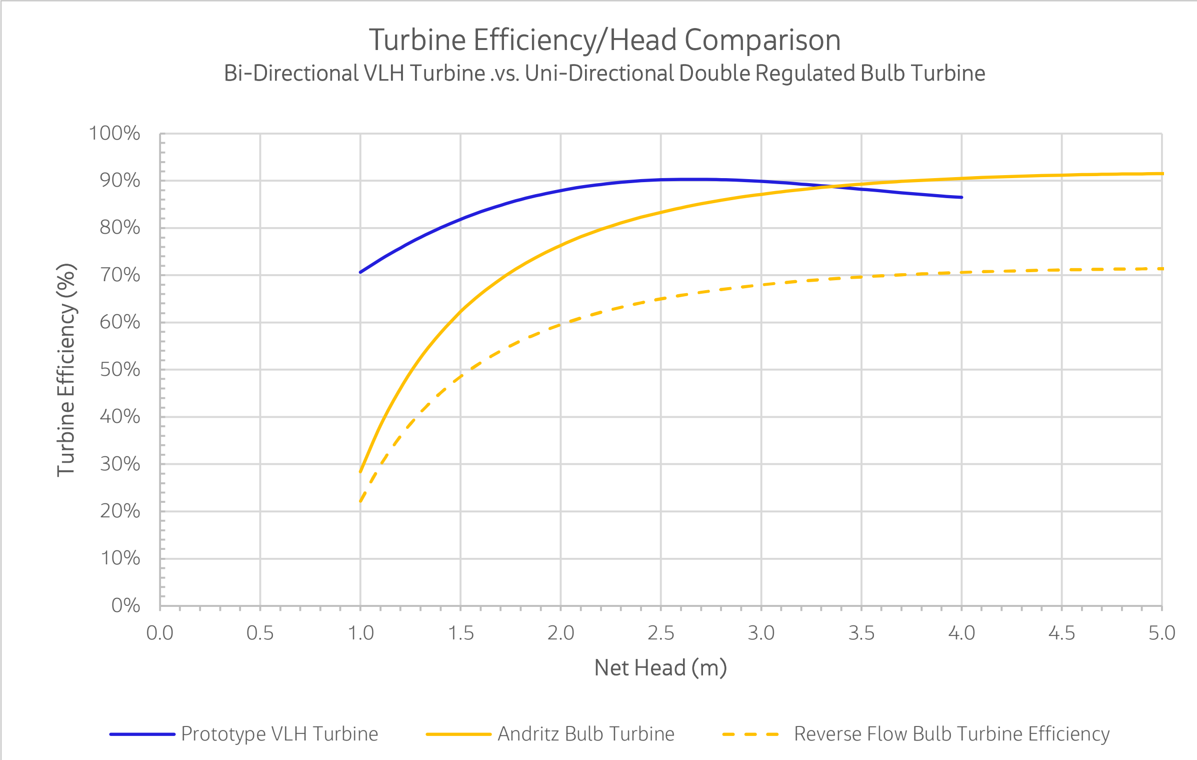

Figure 3-10 VLH and Bulb Turbine Efficiency Comparison (Jacobs)

This shows that while both types of turbine can achieve similar peak efficiencies, the bulb turbine (orange line) achieves this at a higher net head than the VLH turbine (blue line). However, as can be seen from the figure, at lower operating heads the efficiency of the bulb turbine drops off significantly.

Also, due the reduced efficiency of a conventional bulb turbine when operating under reverse flow, the turbine efficiency is reduced still further (orange dashed line).

4. Zero-D Tidal Range Modelling

A Zero-D tidal range model, developed by Jacobs, has been utilised for evaluating the tidal range options investigated under this study.

Features of the Zero-D tidal model include:

- Tidal range operation simulations based on historic tidal record data (2015-2020);
- Upstream basin levels derived by flow simulation through the barrage;
- 5-minute modelling time step over 60 days or 6 years for extended simulations;
- Flows through barrage based on net head and the given turbine flow characteristics;
- Simulation of both very low head (VLH) turbines and bulb turbines;
- Generation carried out during both ebb and flood tides;
- Energy outputs can be maximized by optimizing ‘hold’ levels before generation commences;
- Simulations can be carried out either with or without pumping and for different pumping rates;
- Sluicing during the period of slack water, after generation ceases and before pumping starts;
- Zero-D model has been calibrated with previous 2-D model outputs over same tidal period;
- Simulates required energy storage needed to balance outputs to match system demands;
- Can handle co-located long and short duration storage as well as embedded system storage;
- Allows a whole-system approach by integrating the operation of tidal range generation with other forms of intermittent renewable generation such as wind and solar, including low carbon generation such as nuclear, together with long and short duration energy storage.

For this study a range of potential tidal range projects, covering a wide range of installed capacities have been investigated using our Zero-D tidal range model, covering the following candidate sites:

- 8,000 MW Severn Estuary Tidal Bar;
- 320 MW Swansea Bay Tidal Lagoon;
- 2,000 MW Severn Estuary Tidal Lagoon;
- 500 MW Severn Estuary Tidal Lagoon;
- 2,500 MW North Wales Tidal Lagoon;
- 700 MW Mersey Tidal Barrage;
- 160 MW Wyre Tidal Barrage.

Other sites could have been included such as Morecambe Bay, Mostyn, Wash and Thames Estuary, but this study was constrained by time, and the above sites had readily available information in the public domain. Other sites could be assessed as part of any further studies, and the range of installed capacities modelled by this study should still provide a useful reference point for other sites in the UK.

4.1 8,000 MW Severn Estuary Tidal Bar

The Severn Estuary Tidal Bar (SETB) was the primary tidal range site analysed under this study, as this site has the most information in the public domain, including reports from several earlier studies funded by DECC, Welsh Assembly, SW Regional Development Agency, DEFRA and others. Also, Jacobs was previously involved with the Corlan Hafren study that included our 2-D modelling of the SETB, the results from which have been utilised to calibrate the Zero-D model used for this study.

The principal criteria used in the Zero-D model, for this tidal range option are as follows:

- Installed capacity: 8,000 MW
- Length of barrage: 18.5 km
- Area of basin: 504 km²
- Tidal gauge: Hinkley
- Gauge record utilised: 2015-2020
- Tidal gauge datum: -5.9m AOD

4.1.1 Time Series Simulations

Example outputs from the Zero-D tidal model showing tidal simulations for this site are presented below. Estuary tidal levels and simulated basin levels over a typical eight-week cycle of neap and spring tides, for the condition without pumping, is presented in Figure 4-1 with the resulting net head in Figure 4-2 below.

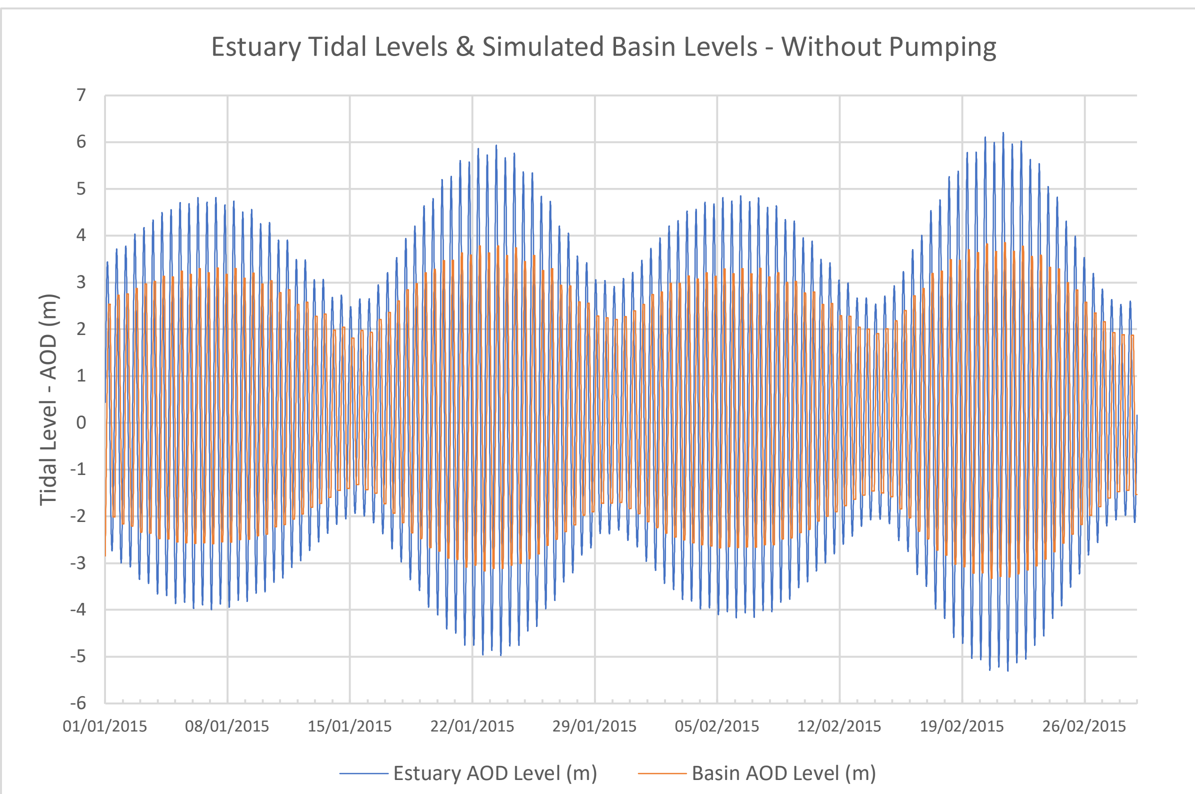

Figure 4-1 Estuary Tidal Levels and Simulated Basin Levels – without Pumping

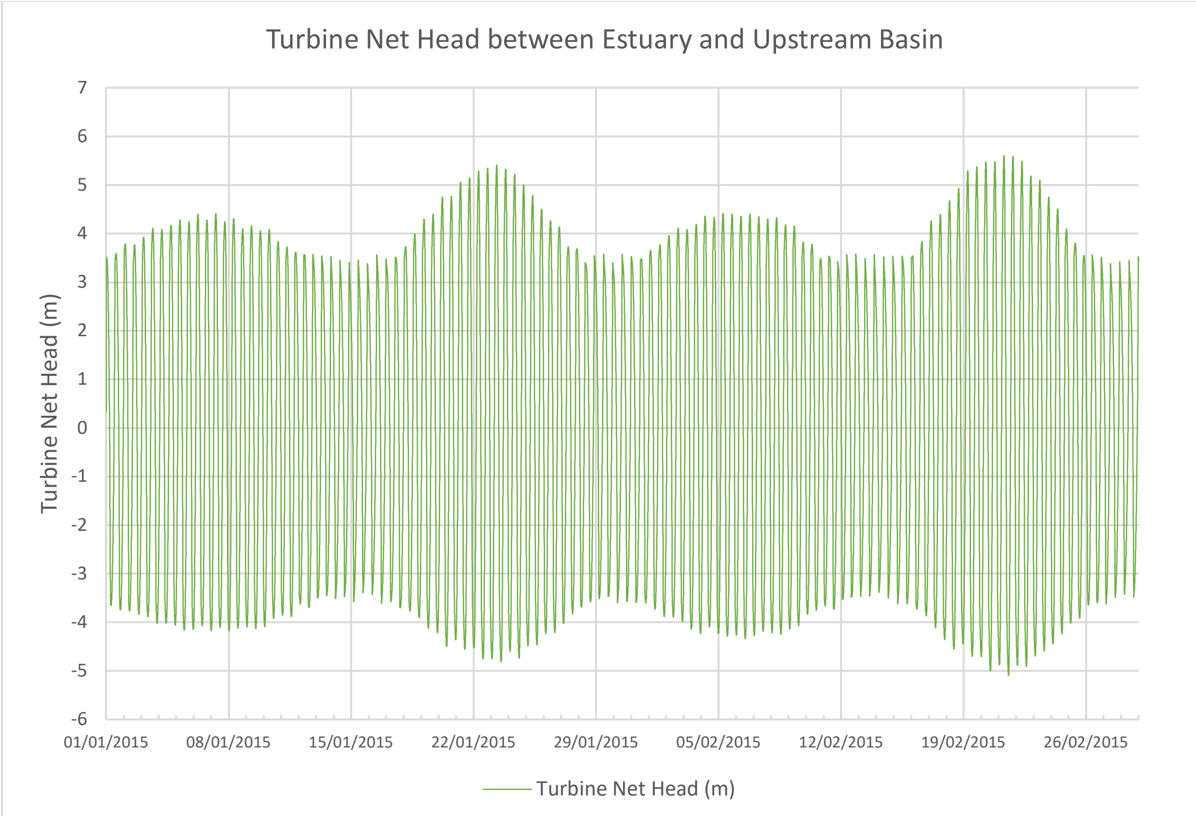

Figure 4-2 Turbine Net Head between Estuary and Upstream Basin

4.1.2 Model Calibration

As the Zero-D model does not take account of the hydrodynamic effect of large estuaries, it has been necessary to calibrate the model using the results of previous 2-D modelling of the SETB scheme for the earlier Corlan Hafren study. For that study DHI's Mike 21 was used for modelling the estuary, with Mike 11 used for modelling flows through the barrage and turbines. The two models were integrated using the Mike Flood shell.

Implementation of the barrage will have an impact on tidal levels in the Severn estuary, by attenuating both the levels in the main estuary as well as levels in the upstream basin. In an attempt to reflect this and the associated reduction in tidal energy, a calibration factor has been applied to the historical tidal gauge record at Hinkley to equate the energy output from the Zero-D model with that of the 2-D model, over the same period of simulation. It was found that by applying a level reduction factor of 12.5% to the Hinkley gauge data in the Zero-D model, this produced similar energy outputs to that obtained in the 2-D modelling and thus this factor has been used to calibrate the Zero-D model for the SETB scheme. The effect of this tidal level reduction is shown in Figure 4-3 below.

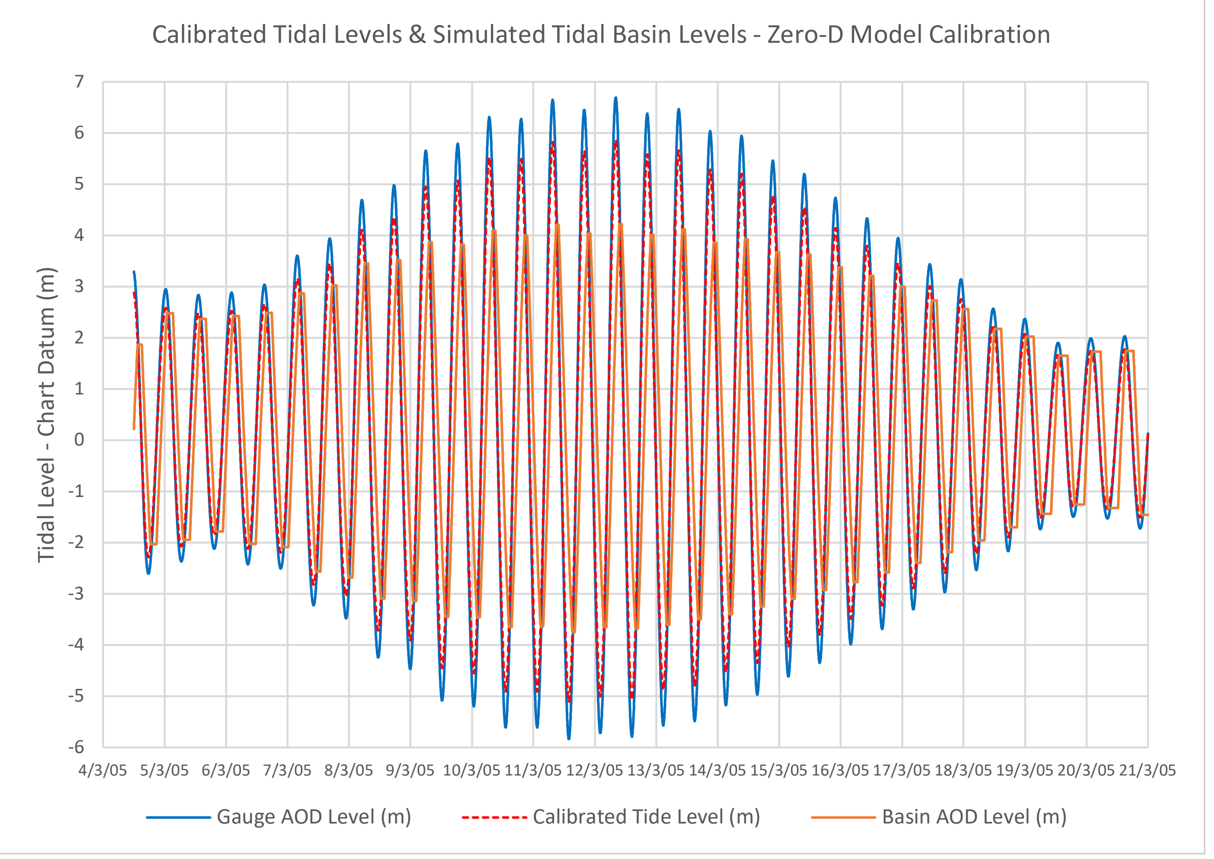

Figure 4-3 Zero-D Model Calibration with Mike 21 Model Outputs

Note that, as other smaller lagoon schemes are likely to have a negligible hydrodynamic effect on tidal levels particularly in the basin, no calibration factor has been applied to these schemes, although a nominal calibration reduction factor of 5% has been applied to the Mersey estuary and Wyre estuary tidal schemes.

4.1.3 Tidal Hold Levels

One of the key factors that determines the potential tidal range energy output is the 'hold' level or head. The hold level in our Zero-D model can be set to any starting head and is determined by an iterative optimization procedure that maximises the energy output over the full tidal sequence. In this study the 'hold level' is defined as the minimum head required before generation commences, after which generation is curtailed at the minimum generation head of the turbine (e.g. 1m for the VLH turbine). Following that, sluicing is carried out until the tide turns after which either pumping is started (if pumping mode is selected) or levels are again held until the minimum 'hold level' head is achieved, after which generation commences again.

The optimum hold level is sensitive to the installed capacity being simulated, but our analyses have shown that although the absolute 'hold' level varies each tide, the optimum holding 'head' is effectively the same for each tide and does not vary significantly between tides. Applying hold levels has the greatest impact on the energy output during neap tides, by increasing the generating head during such periods.

The impact of the hold level during the lowest neap tide is illustrated in Figure 4-4 below.

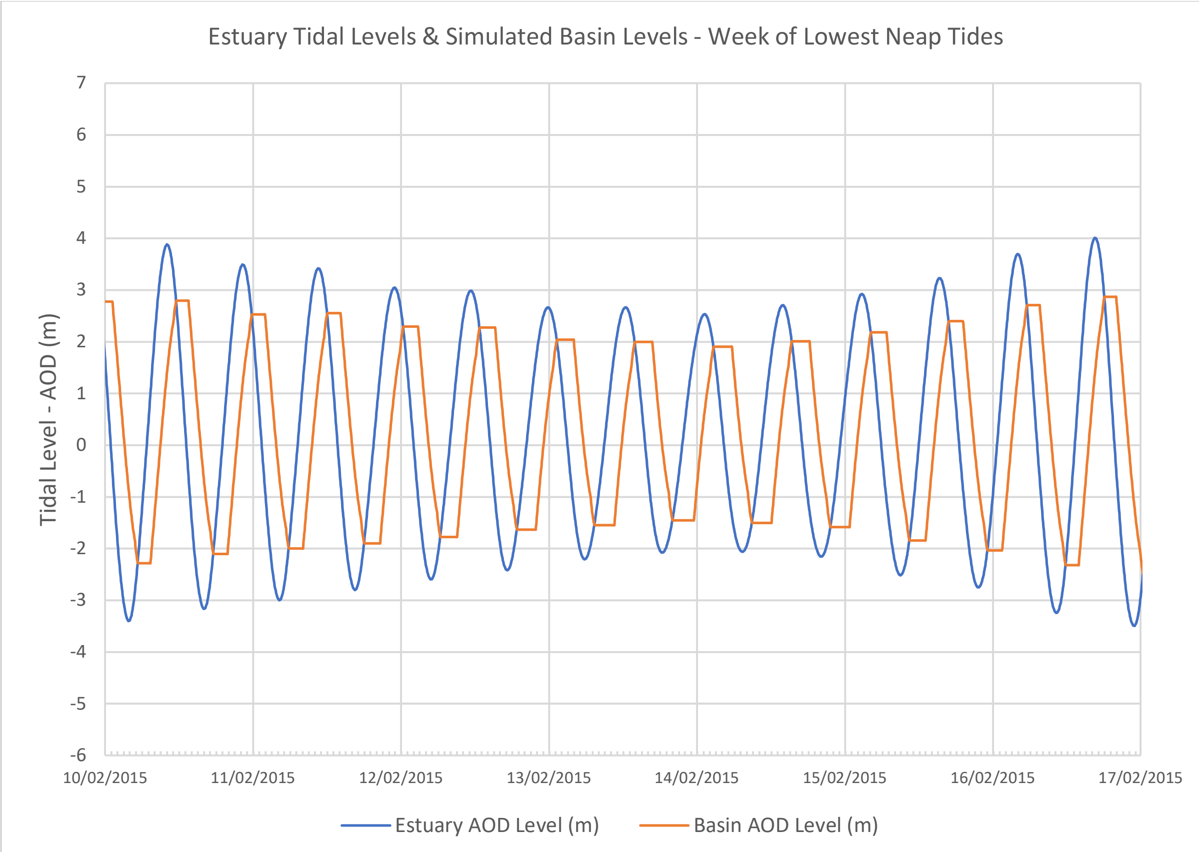

Figure 4-4 Impact of Hold Levels during Neap Tides

This graph shows how the commencement of generation is delayed on the ebb tide by 'holding' the level in the upstream basin until the head difference between the basin and the falling tide in the estuary has reached the optimum 'holding' head, which in this case was determined as 3.25m for VLH turbines and 4.0m for bulb turbines. Likewise on the flood tide, the level in the upstream basin is 'held' until the head difference between the basin and the rising tide in the estuary has reached the same holding head. This has the effect of extending 'slack water' by about 4 hours during neap tides, both on the rising and falling tides, and by about 2 hours during spring tides, as illustrated in Figure 4-5 overleaf.

Notice that this also has the effect of reducing the tidal range in the upstream basin by about 1m during neap tides and 4m during spring tides, which could provide flood protection during extreme spring tides, although this would reduce the natural tidal variation in the upstream basin during other tides. However, this effect can be mitigated by pumping as described later in Section 4.1.5.

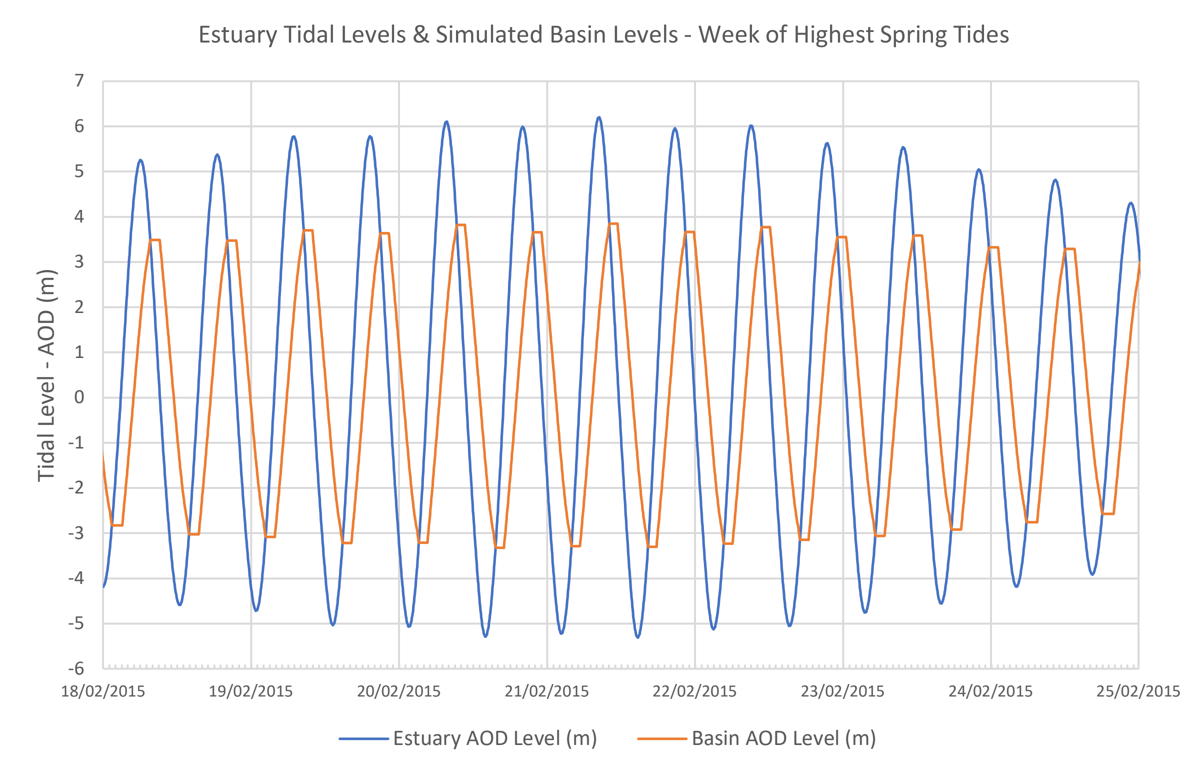

Figure 4-5 Impact of Hold Levels during Spring Tides

Figure 4-6 shows the tidal generation profile, including the variation between spring and neap tides, with the optimum hold level applied.

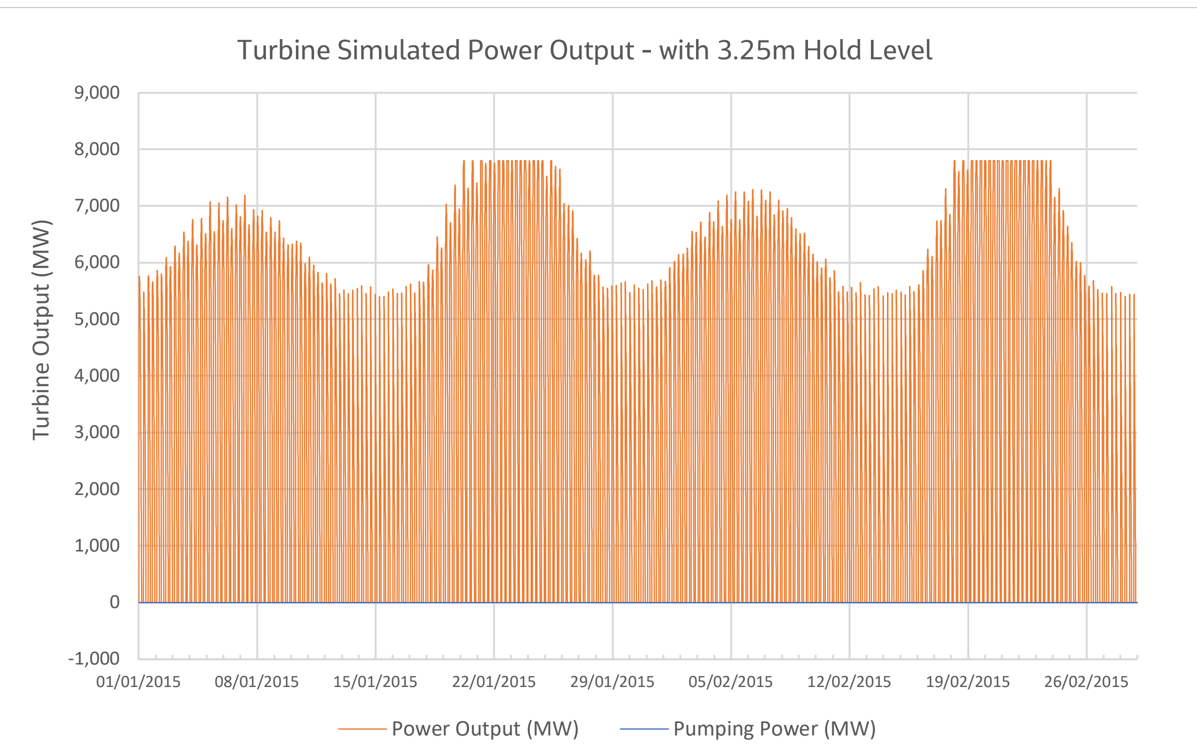

Figure 4-6 Simulated Generation with 3.25m Hold Level

Our modelling analyses have shown that applying hold levels can increase generation by up to 20%, which results in a generation period of about 3 hours per tide, with longer generation during spring tides and shorter generation during neap tides. If no hold levels were applied (above minimum turbine generating head), then our modelling has shown that the generation period would be extended to about 4 hours, with a more sinusoidal generation profile, but with less energy generated.

4.1.4 Sluicing Regime

Sluicing can be carried out both at the end of the ebb and flood tides during slack water, after generation ceases, either to lower the level of the upstream basin further (towards the end of the ebb tide) or increase the level of the basin (towards the end of the flood tide). The purpose of this is to increase the net head across the turbines at the start of the next tidal cycle and the effect is to increase tidal generation by approximately 10%.

One of the key advantages of the VLH turbine is the ability to pass sluicing flow directly through the turbine, together with a reduced time needed for sluicing, which our modelling has shown to be about 20 minutes at spring tides and 40 minutes at neap tides. Thus, for this study we have assumed that sluicing is performed through the turbines, thus avoiding the need for separate sluices.

Simulated sluicing flows from the Zero-D model, covering a typical four-week cycle are shown in Figure 4-7.

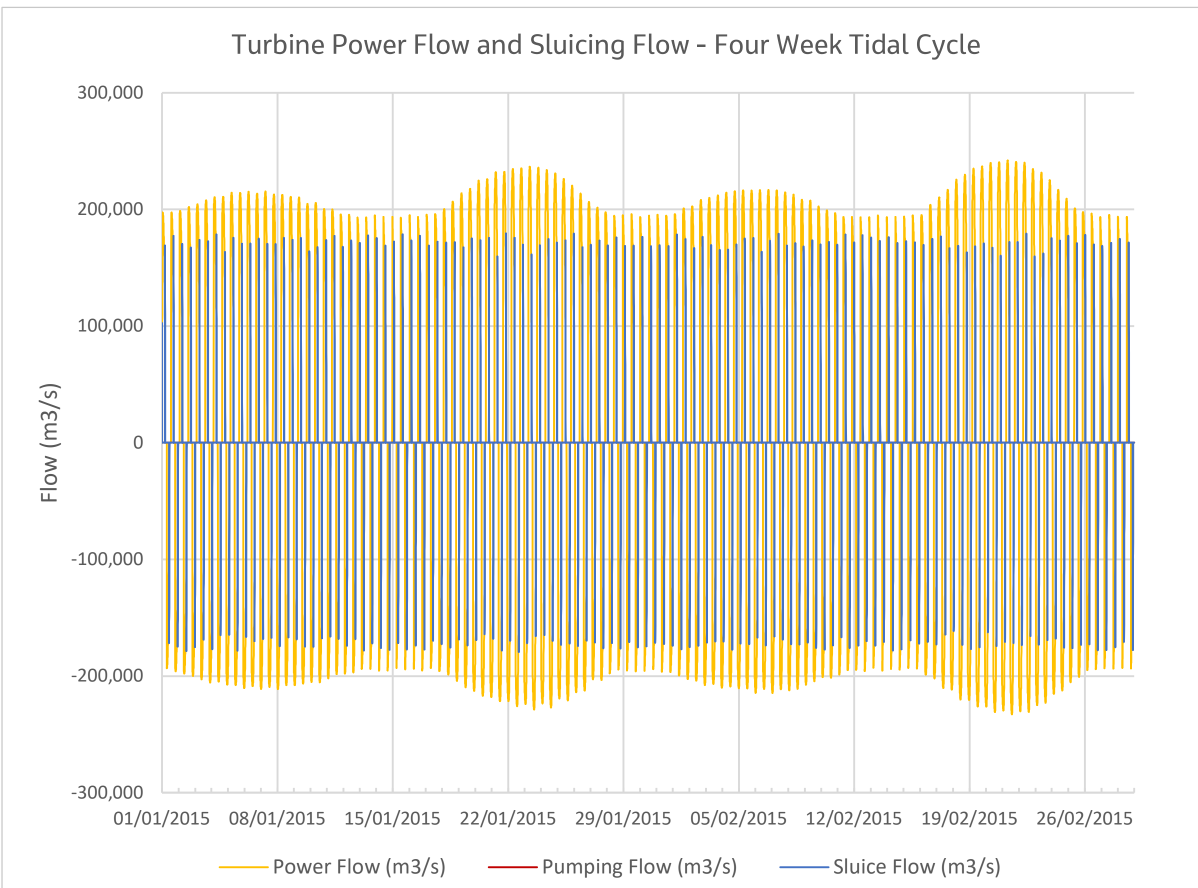

Figure 4-7 Simulated Sluicing Flows over a typical four-week tidal cycle

It has been conventional practice to provide separate sluices when utilising bulb turbines, especially for ebb-only generation. However, if the bulb turbines are designed for bi-directional operation, it may therefore be possible to pass sluicing flows directly through these turbines, given that they would likely be equipped with variable pitch guide vanes and/or turbine blades. Also, if variable speed pump/turbines are used (as in triple regulated turbines), it may also be possible to keep generating at lower heads, even if the power output is very small, thus reducing further the time needed for sluicing.

In addition, it may be feasible to keep the machines turning at low speed until levels each side of the barrage reach equilibrium, before pumping commences, thus eliminating completely the need for sluicing. However, for this study we have assumed that generation would cease once the tidal difference had fallen below the minimum generation head of the turbine, following which sluicing would commence.

Simulated sluicing flows are shown in more detail for the week of lowest neap tides in Figure 4-8 below.

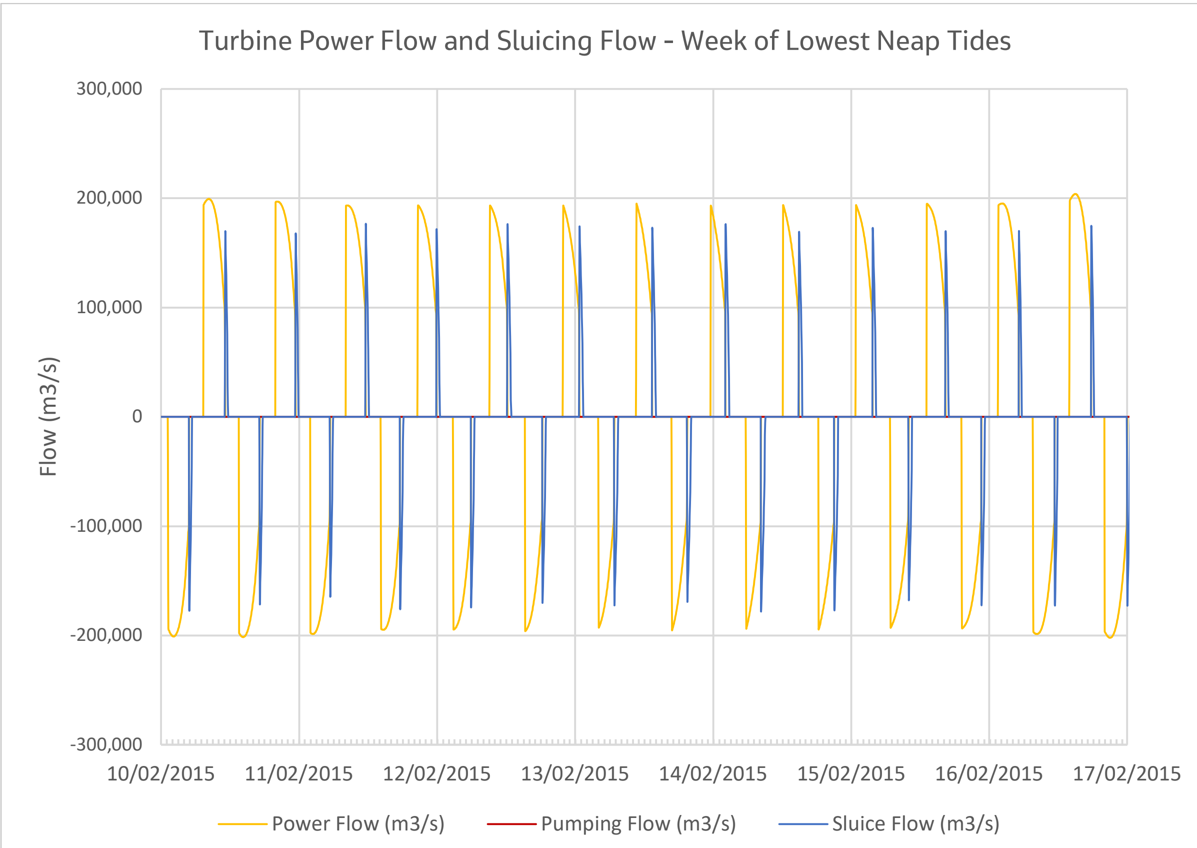

Figure 4-8 Detailed Sluicing Flows during lowest neap tides

4.1.5 Pumping Regime

Once the sluicing cycle has been completed and levels each side of the barrage have reached equilibrium, it is then possible to commence pumping, in the same direction as sluicing, to increase further the level difference between the estuary and the basin. This is in effect a form of 'power sluicing' and enables the head to be increased still further before the generation cycle for the next tide commences. Our Zero-D modelling has shown that the net increase in energy output (i.e. the additional energy output less the pumping energy input) can be up to a further 10%, over and above that achieved by applying the holding levels, but varies according to the scheme's configuration. Thus, the combined effect of applying an optimum holding level, as well as utilising pumping, has a significant effect on the potential energy output from tidal range schemes.

The pumping regime simulated in the Zero-D model is illustrated in Figure 4-9 and demonstrates how the pumping regime increases the operating range of the upstream basin and produces similar high water and low water levels each tide.

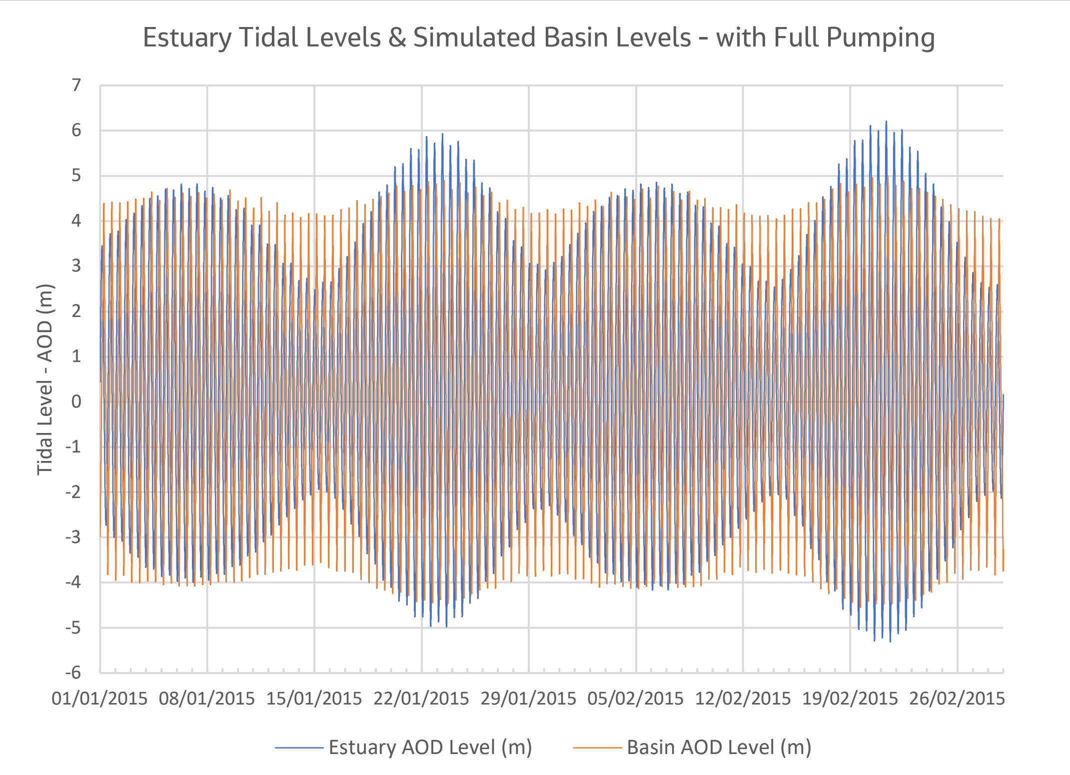

Figure 4-9 Pumping Regime Simulated Basin Levels

The full pumping regime is shown in more detail in Figure 4-10 for the week of lowest neap tides and shows the pumping duration each tide compared to the sluicing duration, assuming maximum pumping.

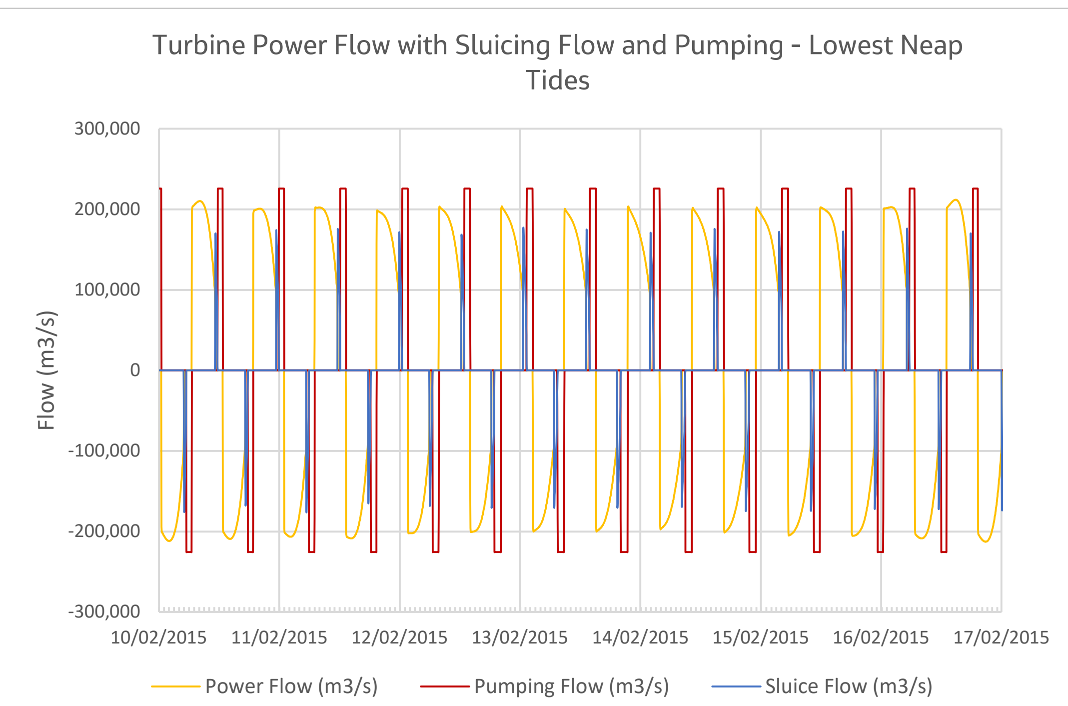

Figure 4-10 Detailed Pumping and Sluicing Flows during lowest neap tides

This has the effect of reducing the tidal variation between spring and neap tides and results in neap tide levels being increased to that of a mean spring tide. While this can increase generation appreciably during neap tides, this may not be acceptable environmentally and thus a compromise pumping regime for neap tides may be necessary, to maintain the natural tidal cycle. In this way, partial pumping could thus be utilised to preserve the natural tidal variation in the upstream basin.

The Zero-D modelling indicates that average pumping duration is approximately 60 minutes for VLH turbines and 90 minutes for bulb turbines, due to the higher operating head required by the latter turbine.

The combined generation outputs and associated pumping inputs are presented in Figure 4-11 below.

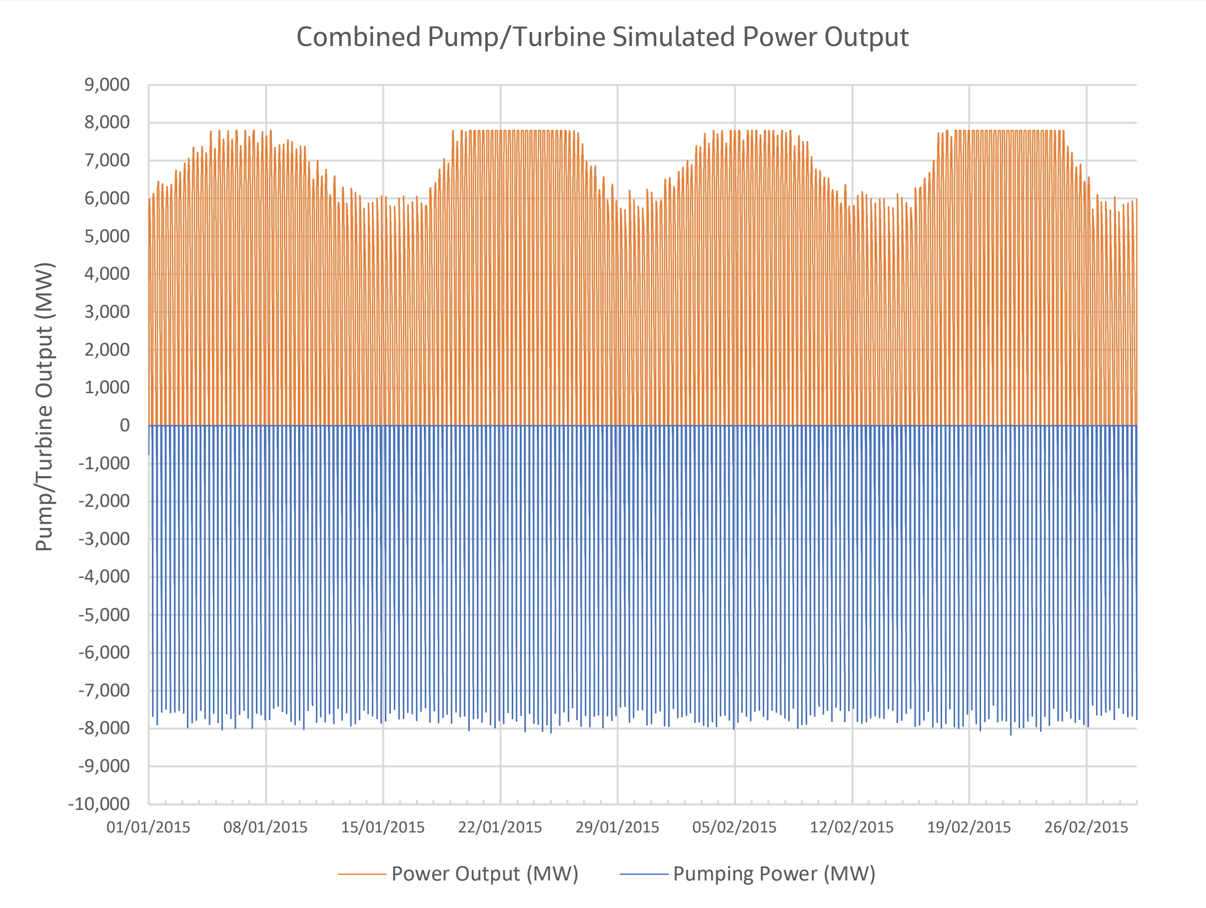

Figure 4-11 Simulated Generation with Pumping

Note that this mode of operation would also result in major power swings on the grid, as the tidal turbines switch from generation to pumping and vice versa, between each tide. This will thus likely require energy storage to avoid placing excess stress on the transmission network, which is addressed further in Section 4.4.

4.1.6 Tidal Energy Balancing using Long and Short Duration Energy Storage

It is clear from the foregoing that the variation in tidal generation, due not only to the daily tidal cycle (including pumping), but also the weekly variability between spring and neap tides, will require some form of load balancing to ensure tidal generation can be fully utilised by the grid. Currently, combined-cycle gas-turbine (CCGT) plants, fuelled by natural gas, together with batteries and pumped hydro are used to provide the necessary system balancing for the grid. However, such unabated CCGT plants are due to be phased out by 2035 (to meet net-zero) and thus the intention is that this will need to be replaced by a major intervention of both long and short duration energy storage to support intermittent renewables generation, such as wind and solar. Such long and short duration storage could also equally well be utilised for balancing the variability of tidal generation and our analysis has shown that due to the greater predictability of tidal, less energy storage is needed, compared to that required for other intermittent renewables, particularly wind.

Recent research that Jacobs has carried out on the energy storage requirements for the GB grid, needed to achieve net zero storage (ref. Strategy for Long Term Energy Storage – Jacobs 2020[9]), has shown that the least-cost energy storage solution would principally be a combination of pumped hydro (in Scotland) with hydrogen storage (in England) providing long duration storage (LDES) at transmission level, with short duration storage being provided principally by batteries, at distribution level. Our latest analyses show that up to 10TWh of long duration energy storage (LDES) will be required for balancing the grid by 2050 (5 TWh by 2035). The majority of this would likely be hydrogen storage, comprising underground salt caverns supplied with green hydrogen produced by electrolysis from surplus wind generation, with an associated 40 GW of hydrogen fuelled CCGT capacity. Together, these could provide the necessary supporting generation during periods of low renewables output, including critical 'dunkelflaute' wind drought events in winter.

As the main tidal range sites are in England, it has been assumed that load balancing for tidal generation would thus comprise a combination of long duration energy storage (hydrogen storage) to balance the weekly cycle between spring and neap tides, with short duration energy storage (batteries) to balance the daily tidal cycle. This could be provided by either co-located energy storage, near the site of each tidal range scheme, or by utilising grid connected energy storage, as currently being developed for wind and solar. It is also anticipated that centres of demand will have increased embedded flexibility as they continue to decarbonise (e.g. through further uptake of domestic and EV batteries), which would thus reduce the need for co-located short duration storage.

Figure 4-12 shows how co-located energy storage could be utilised for balancing tidal generation, covering both inter-tidal daily variation, including pumping, as well as the variability between spring and neap tides.

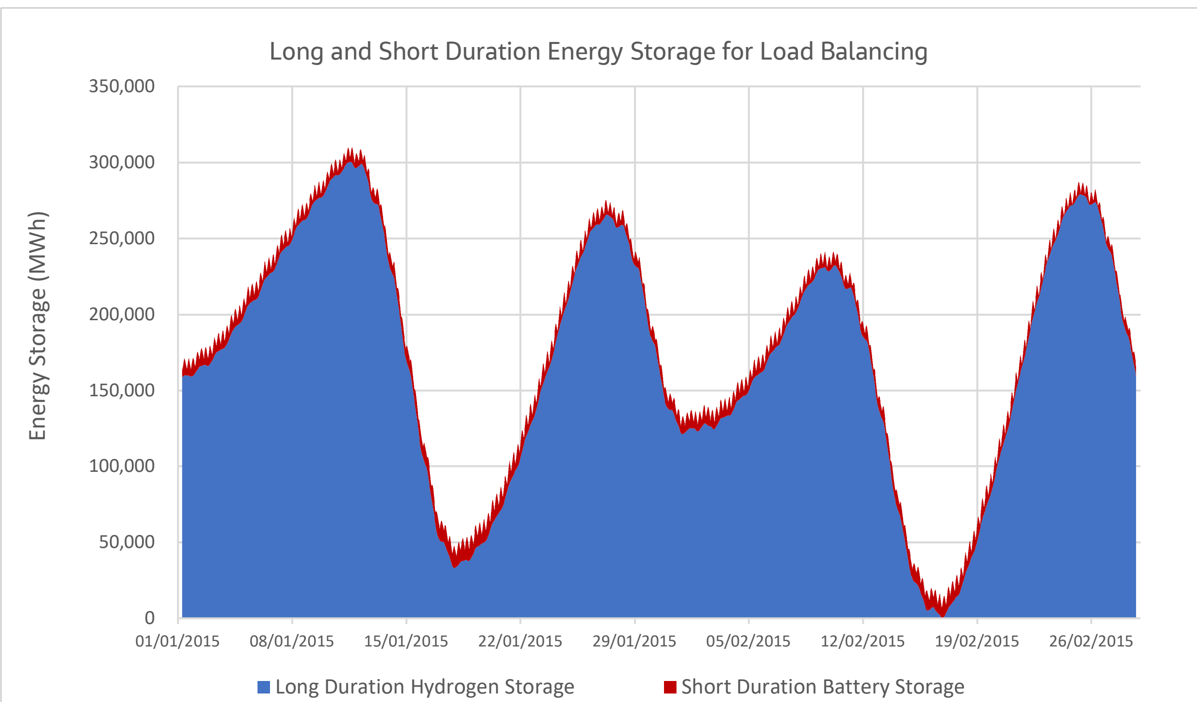

Figure 4-12 Use of Co-Located Energy Storage for Balancing Tidal Generation – SETB

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[9] Strategy for Long-Term Energy Storage

It can be seen from Figure 4-12 how short duration battery storage (shown in red) can be utilised for balancing the daily tidal cycle (comprising two ebb and two flood generation periods), but that the majority of energy storage (in terms of MWh) would likely need to be long duration hydrogen storage (shown in blue) for balancing tidal generation between spring tides and neap tides.

Figure 4-13 shows how such co-located energy storage could be used to balance tidal generation, to match the daily load curve, thus enabling all tidal range generation to be fully utilised.

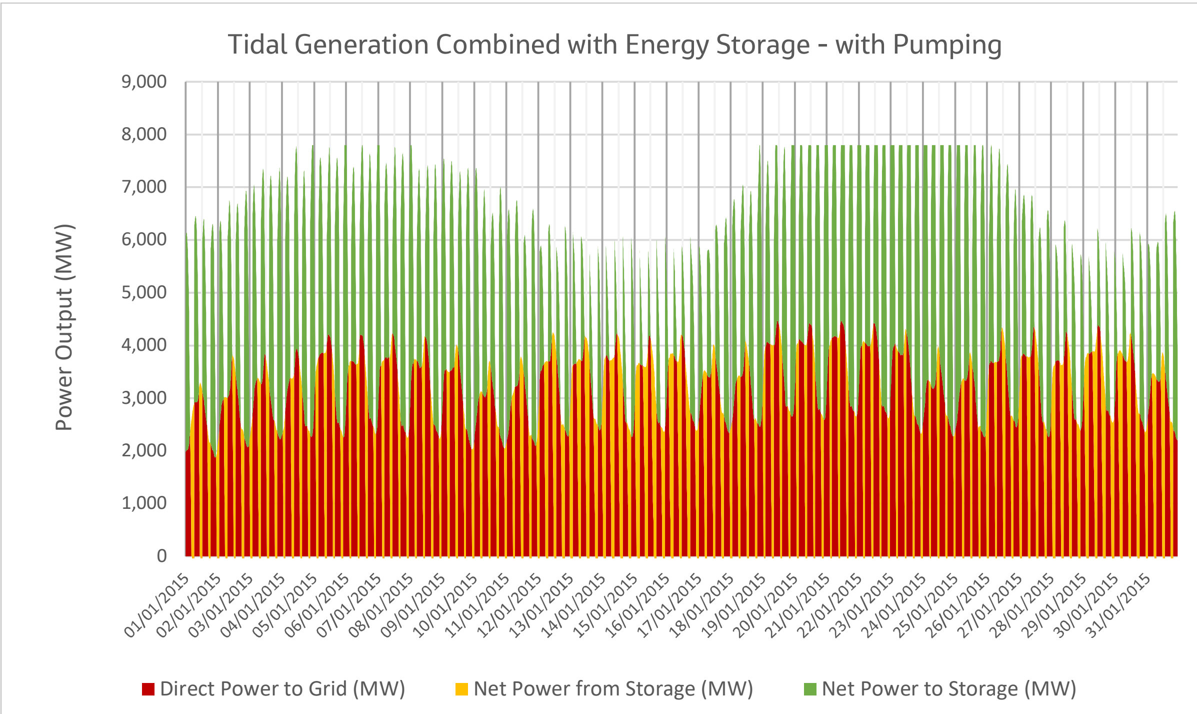

Figure 4-13 Tidal Energy Balancing using Energy Storage – with Pumping

The whole question of grid load balancing for not only tidal generation, but also the proposed generation mix of wind, solar and nuclear, using both grid-based energy storage as well as CCGT with CCS, to meet net-zero by 2035/2050, requires a whole-system approach which is addressed further in Section 4.4.

Estimated tidal energy outputs from this tidal range scheme, both with and without pumping, for a range of energy storage scenarios and for the cases with VLH turbines and bulb turbines, are presented in Section 0.

4.2 Alternative Tidal Range Options Analysed

While the previous section dealt in more detail with the Zero-D modelling carried out for earlier proposed Severn Estuary Tidal Bar (SETB) scheme, this section summarise the Zero-D modelling carried out for other potential tidal range schemes around the UK coast, including the following candidate options:

- 2,000 MW Severn Estuary Tidal Lagoon;
- 500 MW Severn Estuary Tidal Lagoon;
- 320 MW Swansea Bay Tidal Lagoon;
- 2,500 MW North Wales Tidal Lagoon;
- 700 MW Mersey Tidal Barrage;
- 160 MW Wyre Tidal Barrage.

4.2.1 2,000 MW Severn Estuary Tidal Lagoon

The principal criteria used in the Zero-D model, for this tidal range option, are as follows:

- Installed capacity: 2,000 MW
- Length of barrage: 19.5 km
- Area of basin: 80 km²
- Tidal gauge: Hinkley
- Gauge record utilised: 2015-2020
- Tidal gauge datum: -5.9m AOD

Example results from the Zero-D model for this option, with pumping, are presented in Figure 4-14 and Figure 4-15.

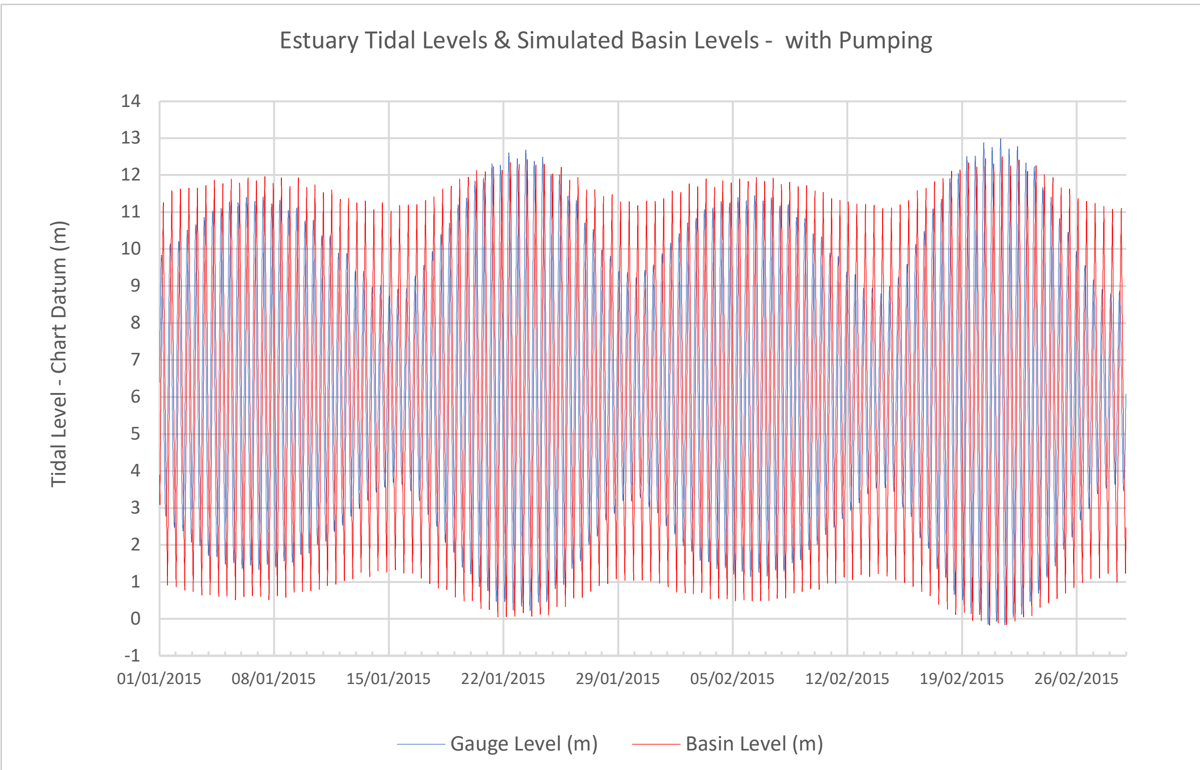

Figure 4-14 2000 MW Tidal Lagoon Simulated Tidal Levels – with Pumping

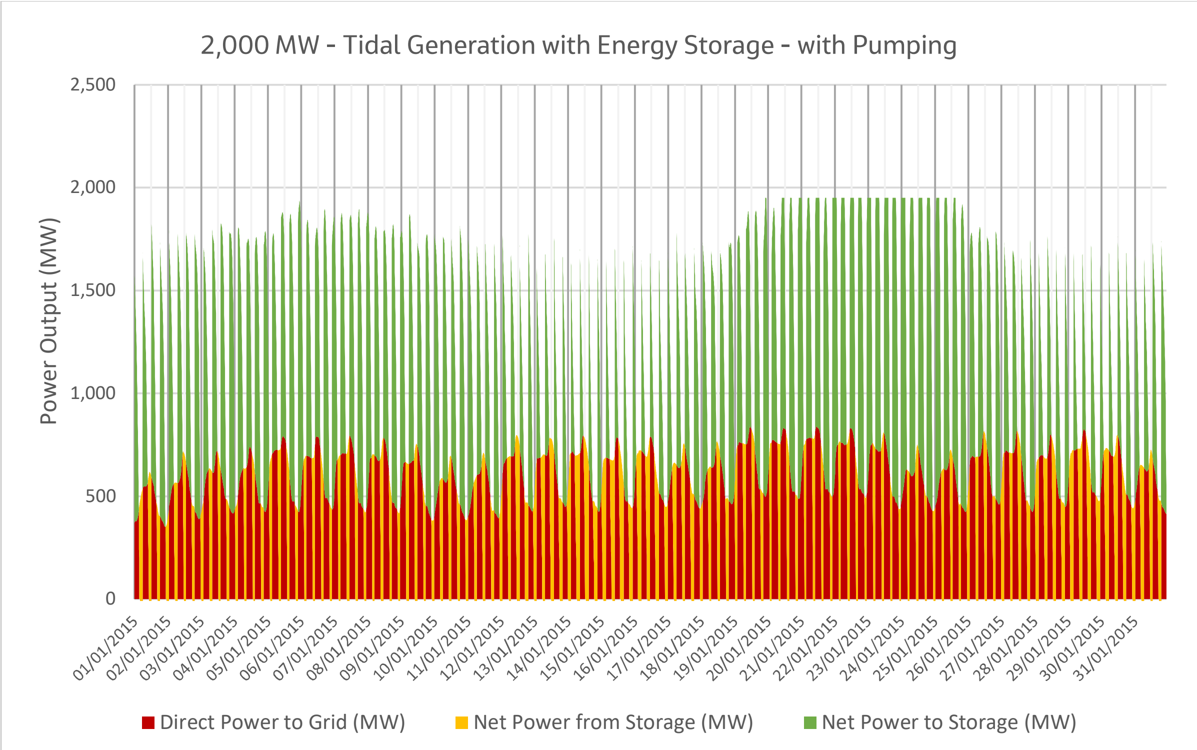

Figure 4-15 Tidal Energy Balancing using Storage – with Pumping

Note that under full pumping mode, this results in the tidal range in the lagoon being equivalent to the highest spring tide (for both high water and low water) for every tide, which may have adverse environmental implications. Estimated tidal energy outputs from this tidal range scheme, both with and without pumping, for a range of energy storage scenarios and for the cases with VLH turbines and bulb turbines, are presented in Section 0.

4.2.2 500 MW Severn Estuary Tidal Lagoon

The principal criteria used in the Zero-D model, for this tidal range option, are as follows:

- Installed capacity: 500 MW
- Length of barrage: 10.9 km
- Area of basin: 20 km^2
- Tidal gauge: Hinkley
- Gauge record utilised: 2015-2020
- Tidal gauge datum: -5.9m AOD

Example results from the Zero-D model for this option, with pumping, are presented in Figure 4-16 and Figure 4-17 overleaf.

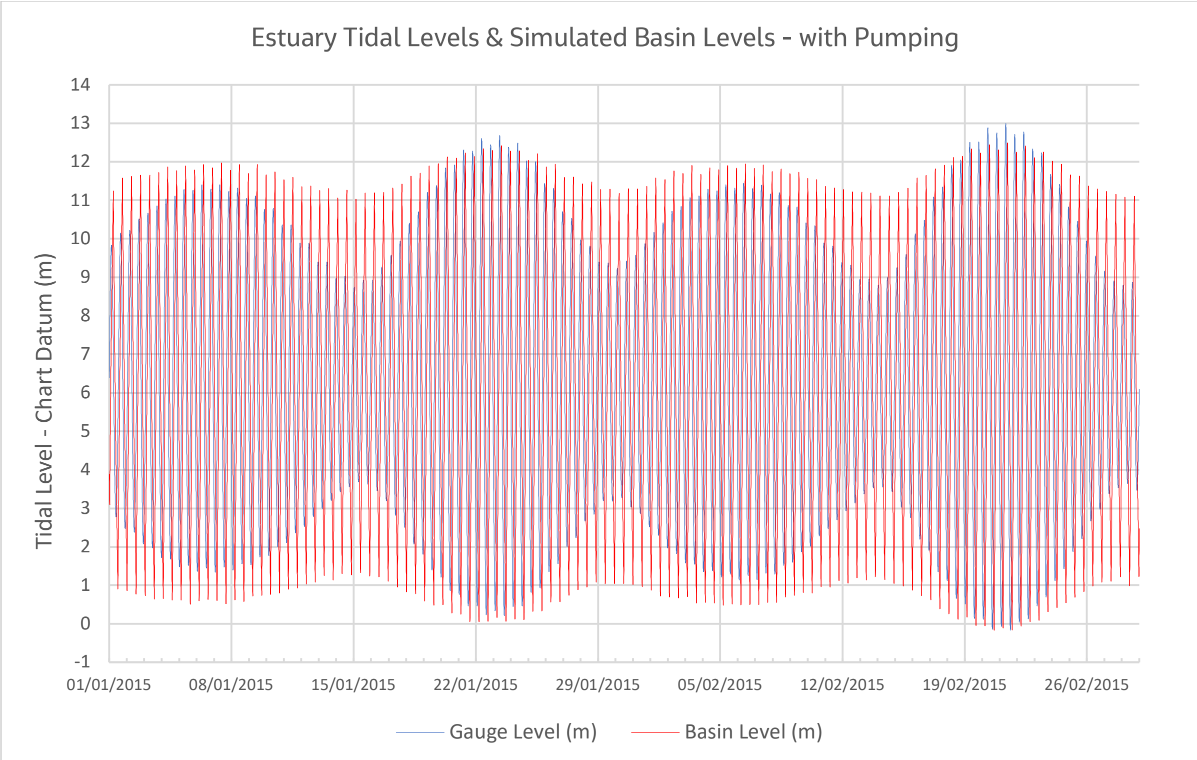

Figure 4-16 500 MW Tidal Lagoon Simulated Tidal Levels – with Pumping

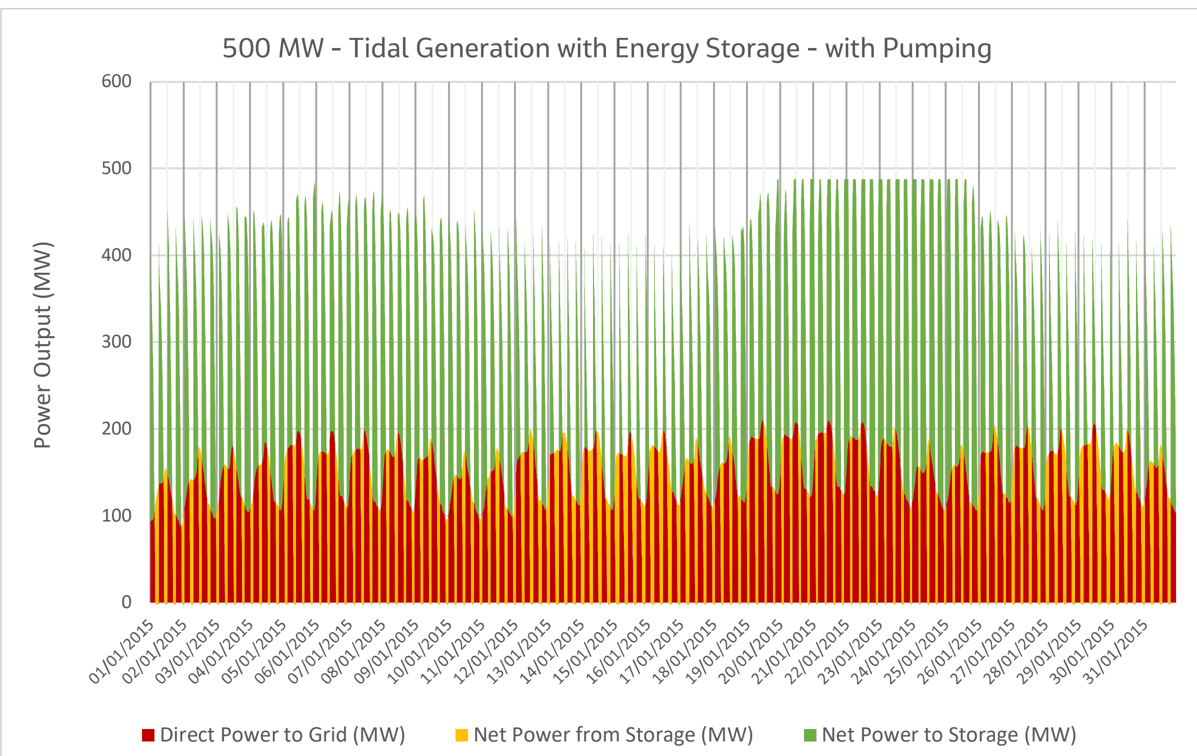

Figure 4-17 Tidal Energy Balancing using Storage – with Pumping

Estimated tidal energy outputs from this tidal range scheme, both with and without pumping, for a range of energy storage scenarios and for the cases with VLH turbines and bulb turbines, are presented in Section 0.

4.2.3 320 MW Swansea Bay Tidal Lagoon

The principal criteria used in the Zero-D model, for this tidal range option, are as follows:

- Installed capacity: 320 MW
- Length of barrage: 9.5 km
- Area of basin: 11.5 km^2 (effective area ~8.5 km^2)
- Tidal gauge: Hinkley
- Gauge record utilised: 2015-2020
- Tidal gauge datum: -5.9m AOD

Example results for this option, without pumping, are presented in Figure 4-18 and Figure 4-19 below.

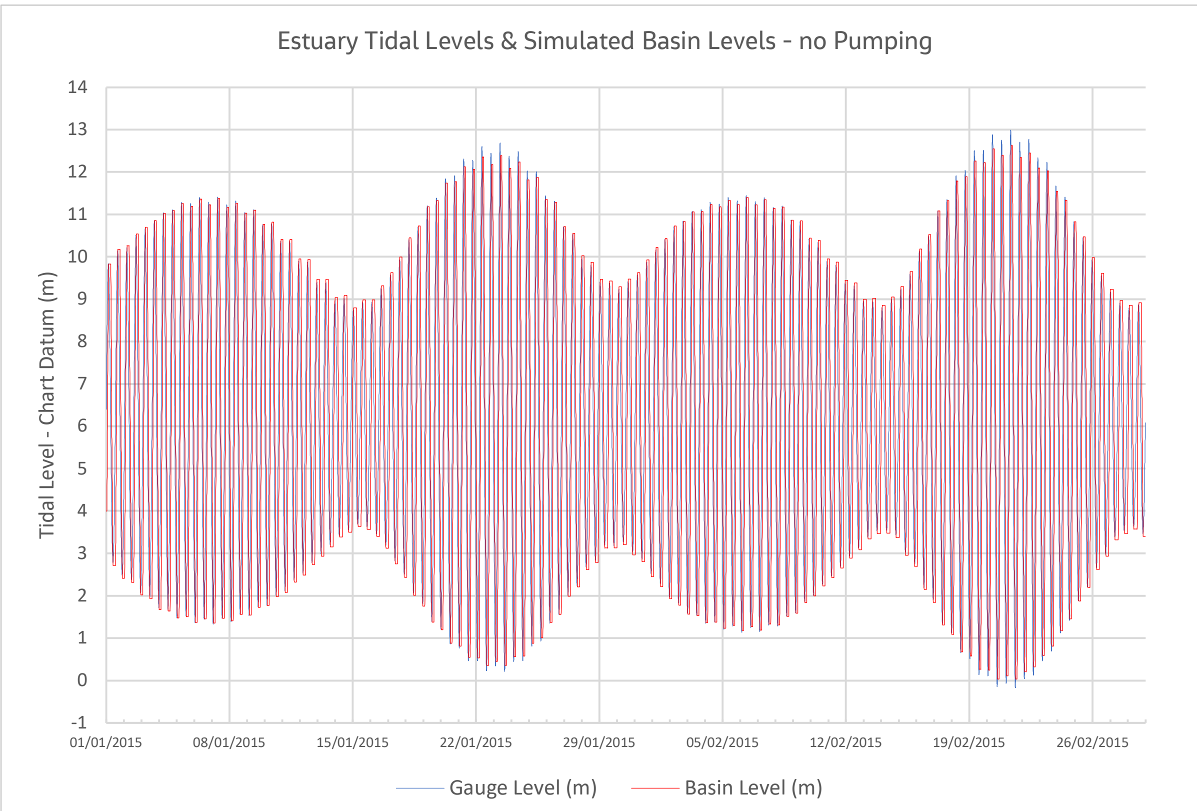

Figure 4-18 320 MW Tidal Lagoon Simulated Tidal Levels – without Pumping

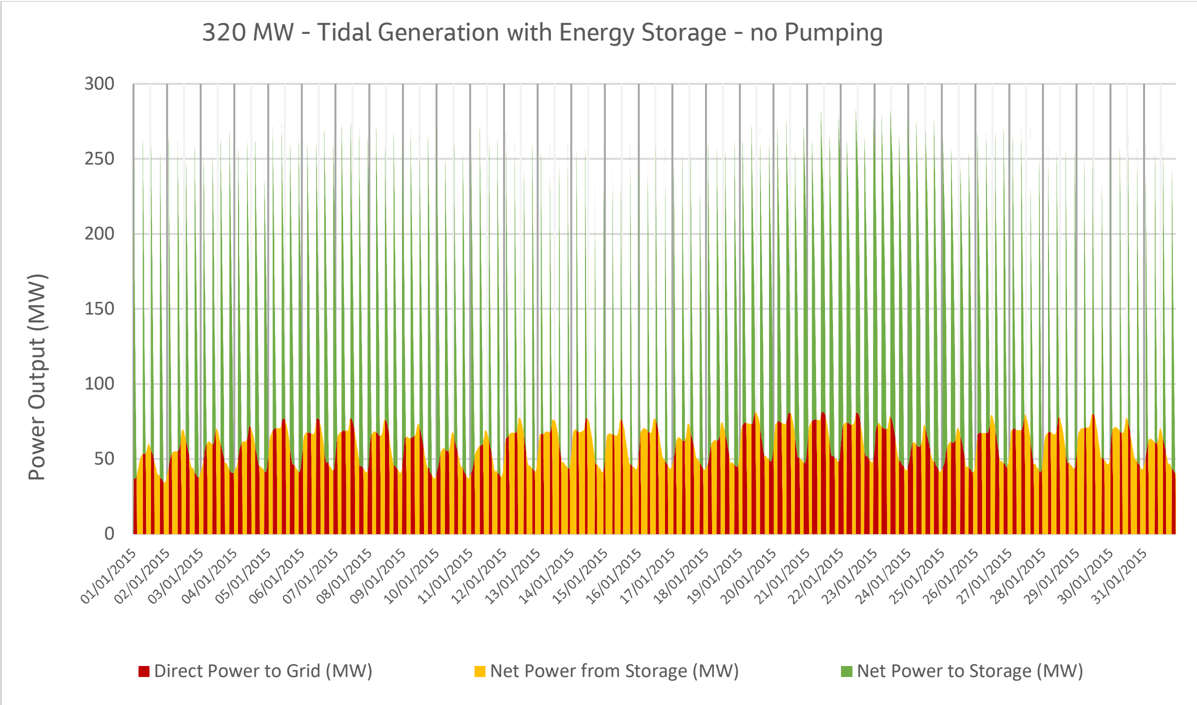

Figure 4-19 Tidal Energy Balancing using Storage – without Pumping

Estimated tidal energy outputs from this tidal range scheme, both with and without pumping, for a range of energy storage scenarios and for the cases with VLH turbines and bulb turbines, are presented in Section 0.

4.2.4 2,500 MW North Wales Tidal Lagoon

The principal criteria used in the Zero-D model, for this tidal range option, are as follows:

- Installed capacity: 2,500 MW
- Length of barrage: 35 km
- Area of basin: 265 km^2
- Tidal gauge: Llandudno
- Gauge record utilised: 2015-2020
- Tidal gauge datum: -3.85m AOD

Example results for this option, without pumping, are presented in Figure 4-20 and Figure 4-21 below.

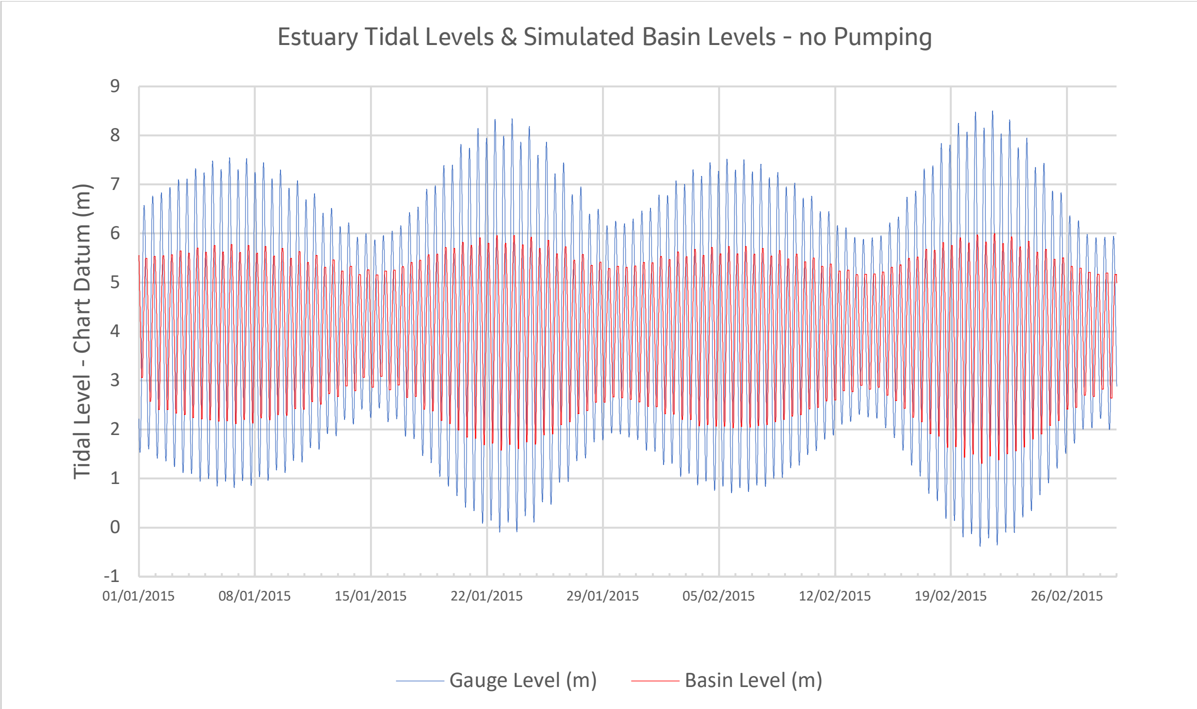

Figure 4-20 2,500 MW Tidal Lagoon Simulated Tidal Levels – without Pumping

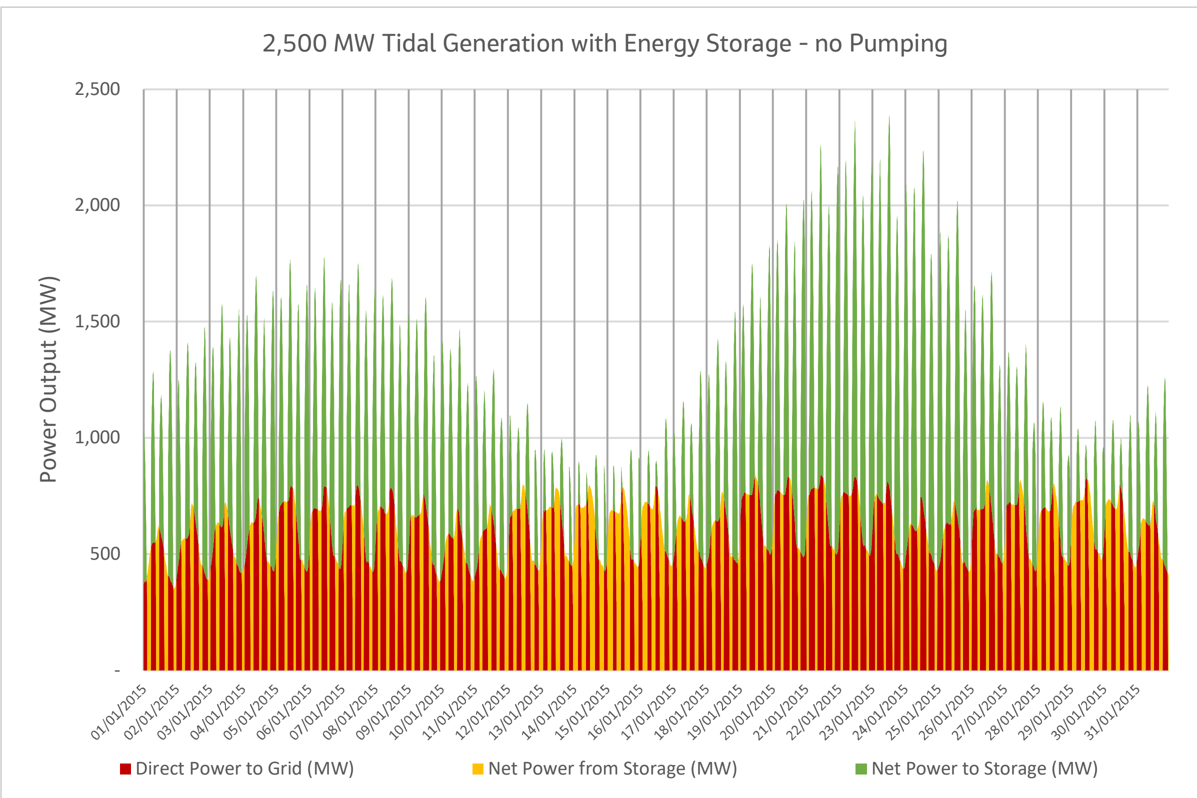

Figure 4-21 Tidal Energy Balancing using Storage – without Pumping

Estimated tidal energy outputs from this tidal range scheme, both with and without pumping, for a range of energy storage scenarios and for the cases with VLH turbines and bulb turbines, are presented in Section 0.

4.2.5 700 MW Mersey Estuary Tidal Barrage

The principal criteria used in the Zero-D model, for this tidal range option, are as follows:

- Installed capacity: 700 MW
- Length of barrage: 1.7 km
- Area of basin: 59.7 km^2
- Tidal gauge: Liverpool
- Gauge record utilised: 2015-2020
- Tidal gauge datum: -4.93m AOD

Example results for this option, without pumping, are presented in Figure 4-22 and Figure 4-23 below.

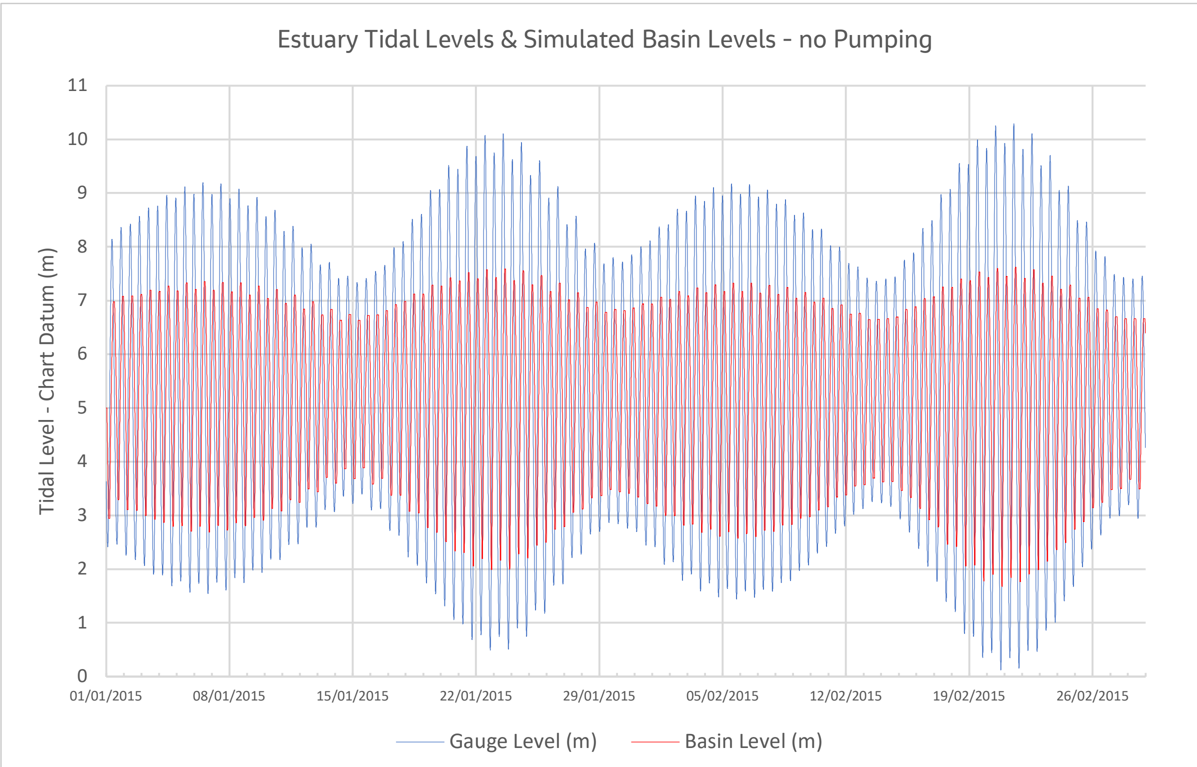

Figure 4-22 700 MW Tidal Estuary Simulated Tidal Levels – without Pumping

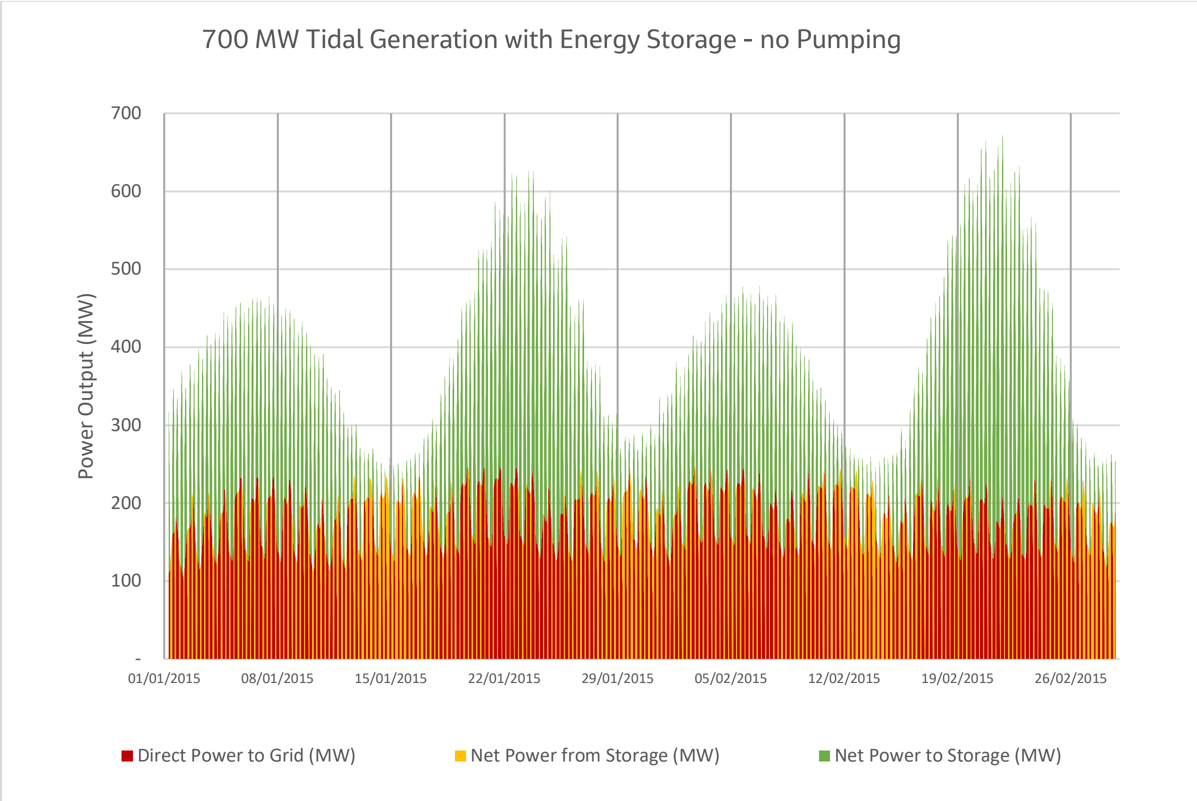

Figure 4-23 Tidal Energy Balancing using Storage – without Pumping

Estimated tidal energy outputs from this tidal range scheme, both with and without pumping, for a range of energy storage scenarios and for the cases with VLH turbines and bulb turbines, are presented in Section 0.

4.2.6 160 MW Wyre Estuary Tidal Barrage

The principal criteria used in the Zero-D model, for this tidal range option, are as follows:

- Installed capacity: 160 MW
- Length of barrage: 0.4 km
- Area of basin: 7.4 km^2
- Tidal gauge: Heysham
- Gauge record utilised: 2015-2020
- Tidal gauge datum: -4.9m AOD

Example results from the Zero-D model for this option are presented in Figure 4-24 and Figure 4-25 below.

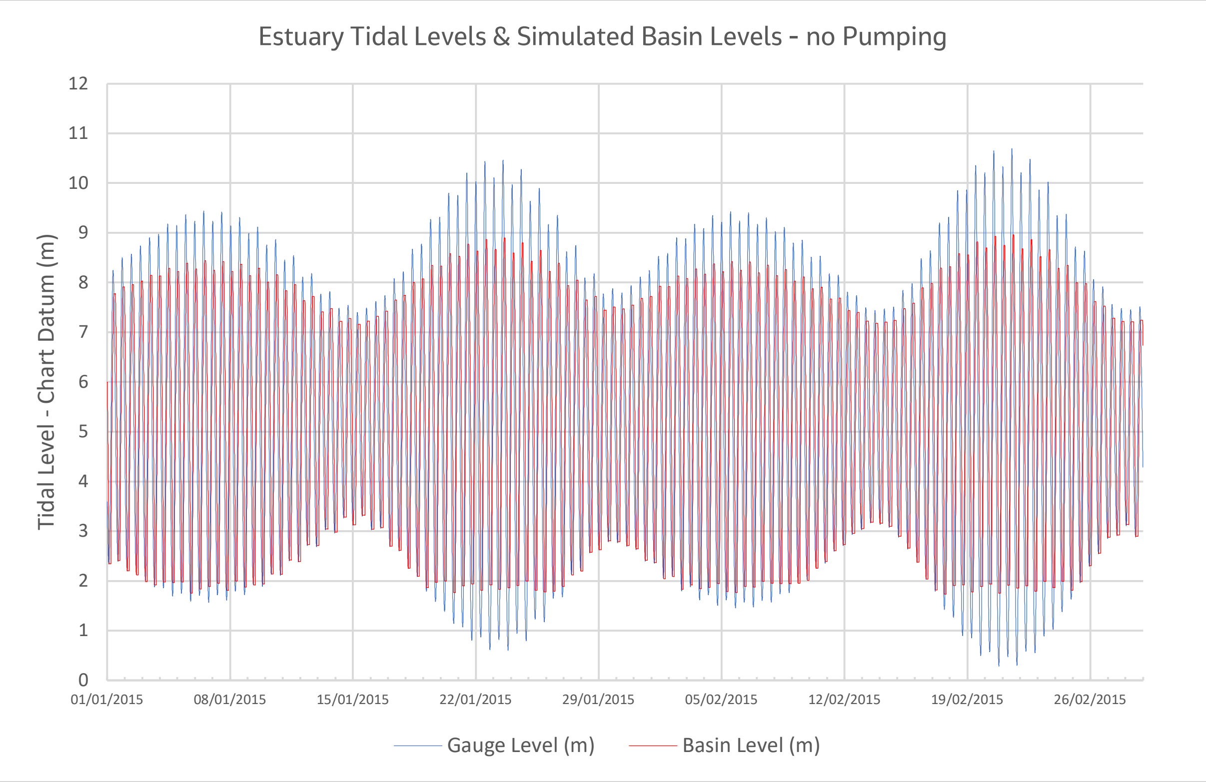

Figure 4-24 160 MW Tidal Estuary Simulated Tidal Levels – without Pumping

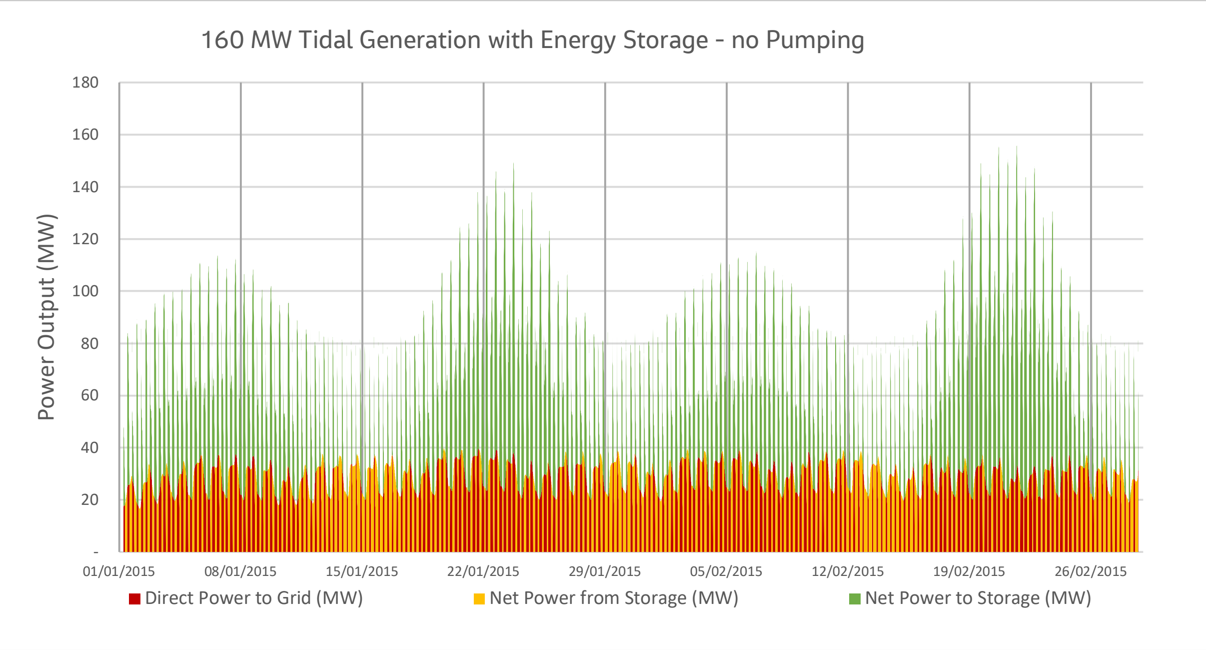

Figure 4-25 Tidal Energy Balancing using Storage – without Pumping

Estimated tidal energy outputs from this tidal range scheme, both with and without pumping, for a range of energy storage scenarios and for the cases with VLH turbines and bulb turbines, are presented in Section 0.

4.3 Combined Tidal Range Generation

The combined generation of the principal tidal lagoon schemes on the Severn Estuary with the tidal range schemes simulated on the NW coast of England & Wales is presented in Figure 4-26 for spring tides and Figure 4-27 for neap tides.

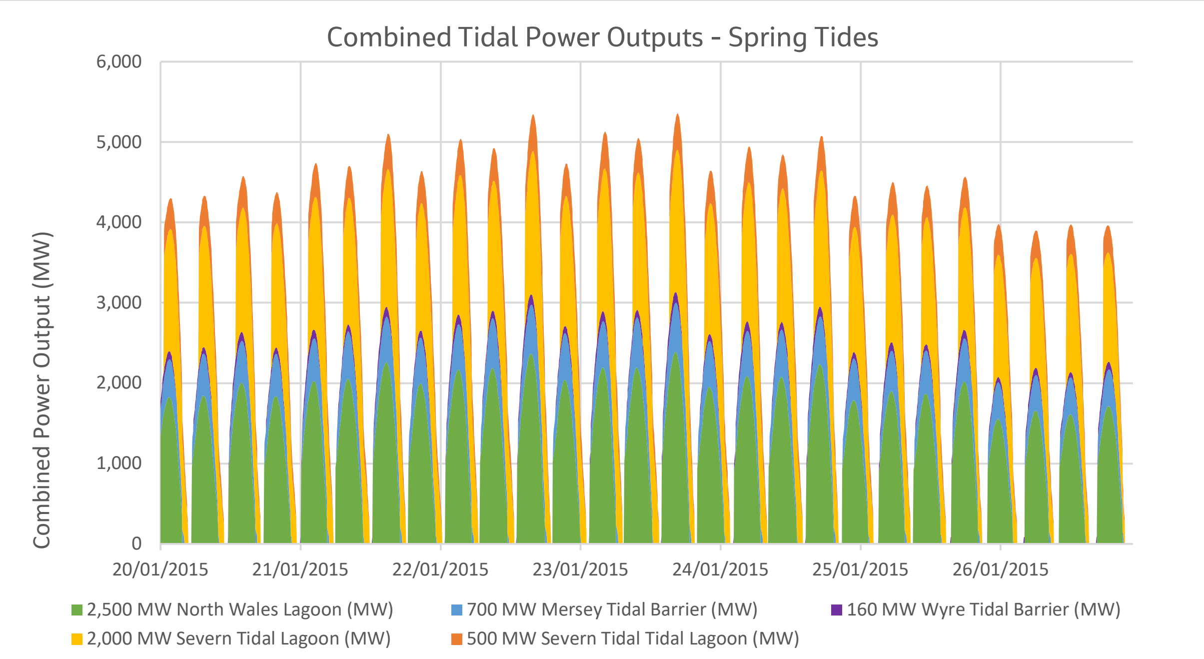

Figure 4-26 Combined Tidal Generation at Spring Tides – without Pumping

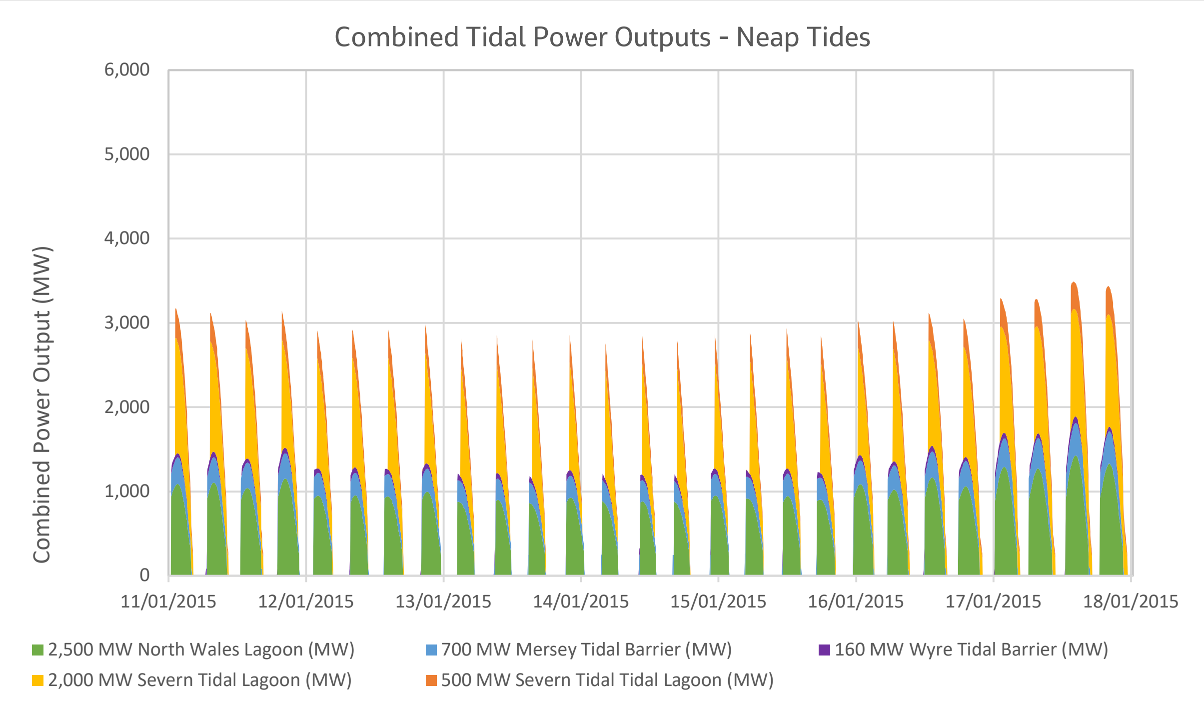

Figure 4-27 Combined Tidal Generation at Neap Tides – without Pumping

These figures show two things. Firstly, that even though the tidal difference between the Severn Estuary and North Wales/Mersey is about five hours, there is still a major variation in the combined generation between tides, four times a day. Secondly, as spring tides and neap tides occur at the same time across the UK, there is also a major generation variation between spring tides and neap tides at an approximate weekly cycle.

The reason for the first occurrence is that high tide in the Severn occurs within about an hour of low tide in North Wales, which means that ebb generation occurs over a similar period as flood generation between the two locations, and vice versa. Also, as spring and neap tides occur during the same week at each location, the combined generation between springs and neaps varies by about a factor of two, at all locations.

This means that to balance tidal generation effectively to meet system demands, either dedicated co-located energy storage at each tidal site is required, or a whole system approach is needed comprising a combination of integrated grid storage (as already required for balancing wind and solar generation), including innovative demand management measures, to enable this variable generation to be fully utilised. This issue is addressed further in the next section.

4.4 Energy Storage for System Load Balancing

It is clear from the Zero-D modelling carried out, that some form of energy storage may be required for load balancing, not only for the short-term cycle between daily tides, but also the longer term cycle between spring tides and neap tides. In addition, due to the major power swings that could be experienced when operating in pumping mode, it may also be necessary to utilise short term energy storage, to avoid placing excessive stress on the transmission network between tides.

Energy storage could be applied in two ways, either by introducing co-located energy storage at each tidal range site or by utilising integrated grid storage that will also be required for balancing the large tranche of intermittent wind and solar generation planned to be in place by 2050 to meet the UK's net zero targets.

4.4.1 Co-Located Energy Storage

As discussed earlier in Section 4.1.6, we have divided energy storage into short duration (e.g. batteries) and long duration (e.g. pumped hydro and hydrogen storage) and carried out simulations to balance tidal generation as shown in Figure 4-28 below.

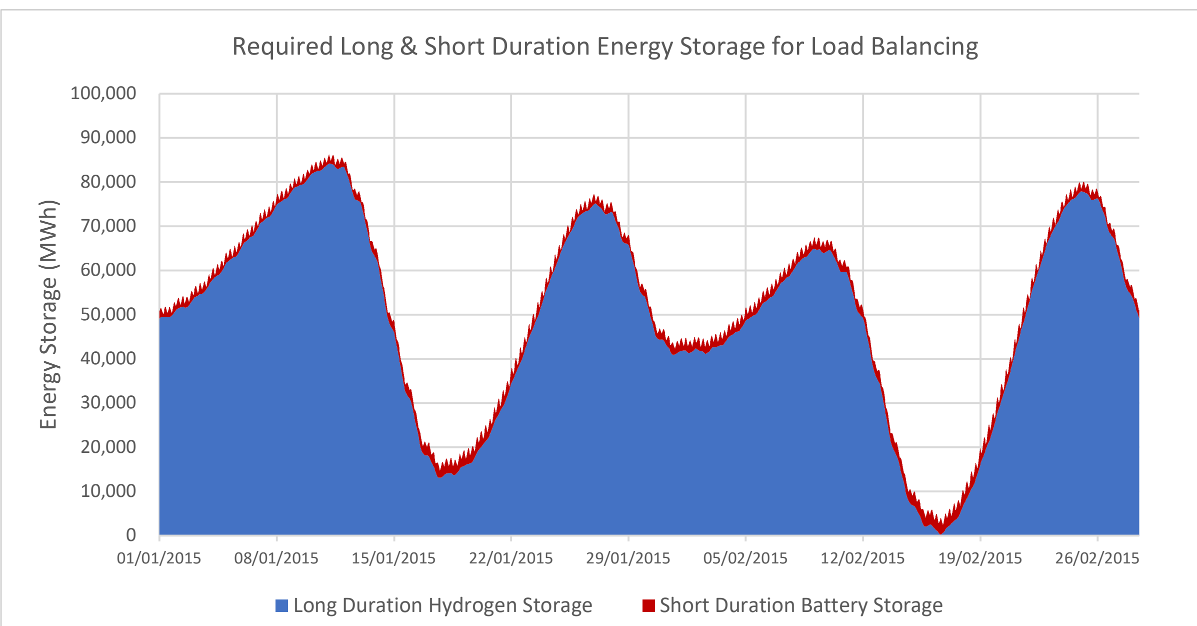

Figure 4-28 Co-Located Energy Storage – North Wales Tidal Lagoon

This shows how co-located short-duration storage (shown in red) may be used to balance the daily tidal cycle and long-duration storage (shown in blue) can be used to balance the variation in tidal generation between spring tides and neap tides. Note the relatively small storage volume needed for daily tidal balancing, compared to the much larger storage needed for balancing generation between spring and neap tides.

The resulting net firm generation that could be achieved from tidal range by utilising co-located energy storage is presented later in the report in Section 0 and the direct costs of short-term and long-duration energy storage needed to achieve this are presented in Section 5.2.

An alternative to co-located energy storage, at each tidal, site would be to utilise grid-based storage distributed across the network, as described in the next section.

4.4.2 Integrated Grid Energy Storage

An alternative approach would be to utilise the proposed grid-based energy storage needed for balancing other intermittent renewables such as wind and solar, with that of tidal.

National Grid ESO's future energy scenarios (FES 2023) show that approximately 125 GW of wind generation is forecast by 2035 and 150 GW by 2050, with about 60 GW of solar by 2035 and 90 GW by 2050. Studies we have carried out (Jacobs white paper[10]) have shown that to balance this major development of intermittent renewables will require 5 GW of short, 10 GW of medium and 50 GW of long duration storage by 2050.

An important factor to consider is that with the forecast large capacity of wind generation by 2035 and 2050, there will be times when there will be excess renewables generation on the system which would require to be either stored or curtailed. At other times there may be periods of minimal wind generation (dunkelflaute) extending over many days, where generation will need to be augmented either from energy storage or backup CCGT with carbon capture and storage (CCS). Thus, tidal range generation will also need to be equipped with energy storage or other demand management measures to cope with such eventualities.

To illustrate such a situation, Figure 4-29 shows the situation when wind generation historically has been reduced to very low levels over an extended period.

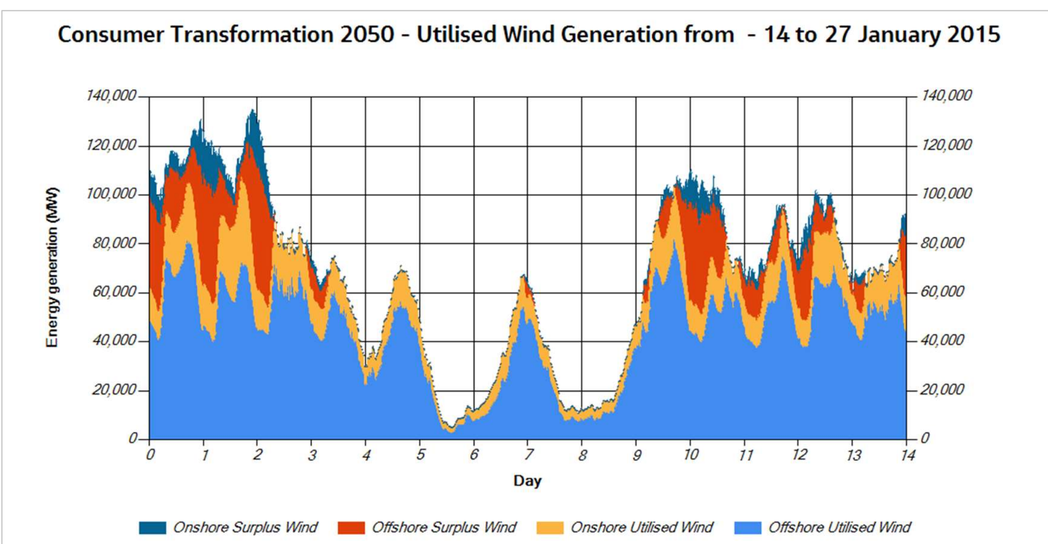

Figure 4-29 Utilised Wind Generation – FES Consumer Transformation Scenario

To cope with such events, Figure 4-30 shows how energy storage would be required to balance the system load over such periods, under the FES Consumer Transformation scenario. Note also that under this scenario,

[10] Long, Medium & Short Duration Energy Storage - role in reducing costs for the transition to net zero – Jacobs 2022

there is a forecast tidal range capacity of about 5 GW, which would contribute to meeting the load over this period, hence reducing the dependency on other backup generation such as non-renewable CCGT with carbon capture and storage (CCS).

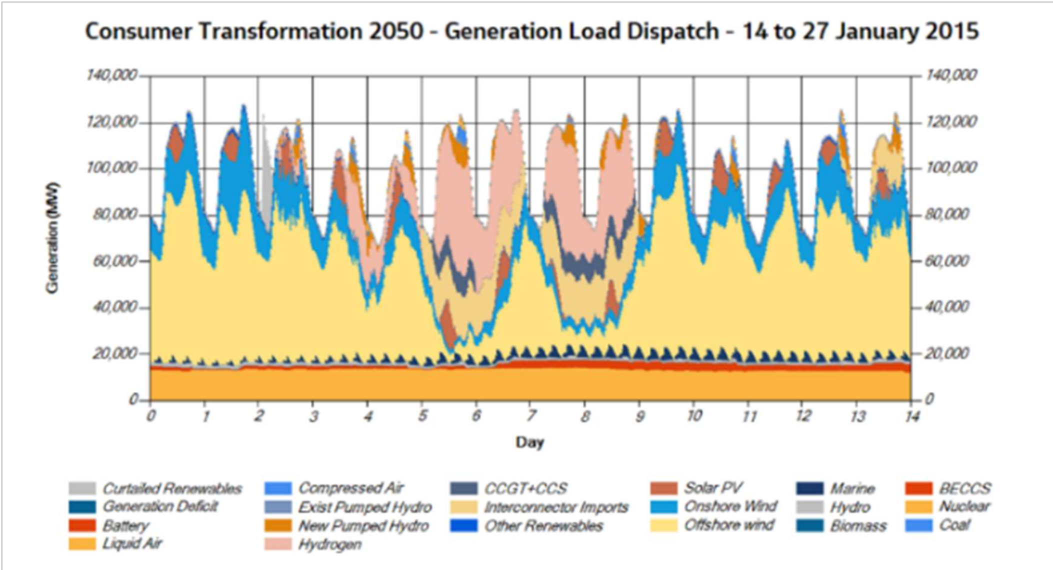

Figure 4-30 Tidal Generation Load Dispatch – FES Consumer Transformation Scenario

Figure 4-31 shows how the combination of energy storage, backup CCGT with CCS together with imports from the European interconnectors could be dispatched to meet such situations.

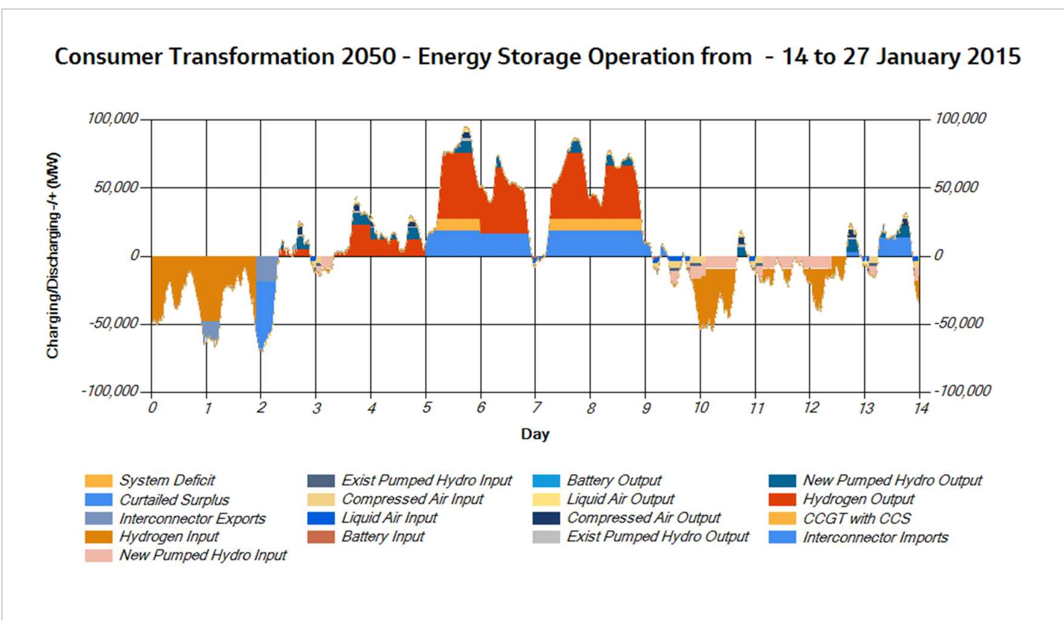

Figure 4-31 Energy Storage System Balancing – FES Consumer Transformation Scenario

This therefore demonstrates that if the tidal range capacity were also supported with grid-based energy storage, its full energy output could be fully utilised. We have therefore estimated, using our load-dispatch model of the GB power system, the *incremental* energy storage needed for fully balancing tidal range generation under all historic wind generation events over the period 2015-2020.

This has shown that by utilising grid-based energy storage, that can be used to balance the combined generation variation of wind, solar and tidal, then this would require approximately 60% of the equivalent dedicated co-located energy described above. A further advantage of grid-located storage is that the incremental energy storage needed for balancing tidal can also be used together for balancing wind and solar, that allows the losses from the round-trip efficiency of energy storage (which is higher for long duration storage) to be recovered by utilising surplus wind energy that would otherwise be curtailed.

This has two principal benefits: firstly, that the balancing system costs borne by the ESO (which are passed onto the consumer) would be less using grid-based energy storage and secondly, as a Contracts for Difference (CfD) arrangement gives no credit to energy storage, this would neither cover the capital cost nor the operating cost/losses of providing such storage. Thus energy storage would probably be best promoted under other financing arrangements such as the ESO's ancillary services contracts, or under a cap-&-floor model as is currently being proposed by DESNZ for long duration storage.

In reality, it is likely that short duration storage would be located at the nearest demand centre, which will require batteries for load balancing in any case, in close proximity to a tidal range site. This would enable the inter-tidal power variations (particularly during pumping) to be attenuated, thus assisting in reducing stress on the grid at such times. Long duration storage, on the other hand, would likely need to be located near to where the main offshore wind farms reach land-fall. Our modelling studies have shown that operating short and long duration storage in this way, could not only maximise utilisation of the various intermittent renewables technologies, but could also minimise curtailment and hence reduces the scale of grid reinforcement that might otherwise be required.

It can be seen from Figure 4-30 that at least one (or possibly two) of the four daily tidal generation periods coincide (approximately) with the time of the morning and evening peak demand and thus this could potentially reduce the total requirement for short duration storage needed for load balancing. Our analyses have taken account of this marginal benefit in determining the requirement for short duration storage, for the case with integrated grid-located storage, in our system load-dispatch modelling. There may also be an opportunity to load-shift, by advancing or delaying generation by +/- 1hr each tide, if market conditions permit. However, the potential for this would be small, as the principal tidal storage requirement will be for long duration energy storage, for balancing the weekly variation between spring and neap tides, as shown in Figure 4.28.

The resulting net firm generation that could be achieved from tidal range, by balancing generation in this way, is presented in Section 0 below and the costs of the *incremental* short-term and long-duration energy storage needed to achieve this is presented in Section 5.2.

4.5 Energy Outputs for Tidal Range Options

4.5.1 Simulated Energy Outputs – Conventional Tidal Technologies

The total modelled energy outputs (MWh/yr) for each candidate option for the case with conventional tidal range technologies, both with and without pumping and for different energy storage scenarios, is presented in Figure 4-32 below.

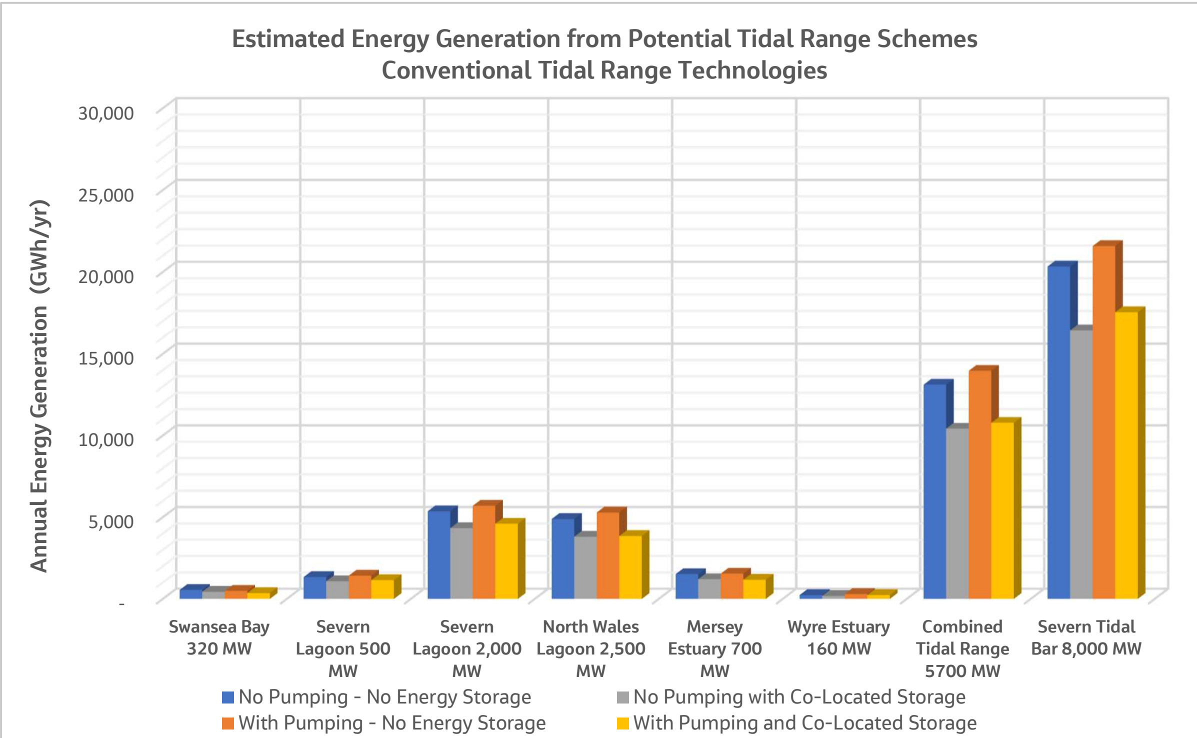

Figure 4-32 Estimated Energy Generation from Tidal Range – Existing Turbine Technologies

It should be appreciated that as energy storage technologies have a round-trip-efficiency (RTE), this results in a proportion of the energy stored being lost in the charging/discharging process. Thus, for co-located storage, a proportion of the stored energy is lost due to RTE losses, which reduces the energy output to the grid. However, for the case of grid-located storage, all tidal energy can be absorbed by the grid and provided sufficient incremental grid storage is provided, then this should be sufficient for both balancing the intermittent tidal output, as well as making up for the associated RTE losses. There is, of course, a cost associated with the provision of the necessary energy storage for these two cases, which is addressed later in this report.

The total modelled energy outputs (MWh/yr) for the case with conventional tidal range technologies, both with and without pumping and for different energy storage scenarios, is presented in more detail in

Table 4-1.

Table 4-1 Simulated Energy Outputs – Conventional Tidal Technologies

Energy Outputs (GWh/annum)	Swansea Lagoon 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Estuary Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	553	1,341	5,365	4,893	1,518	238	13,117	20,340
Co-Located Storage	440	1,082	4,329	3,805	1,205	183	10,421	16,431
Grid Storage	553	1,341	5,365	4,893	1,518	238	13,117	20,340
With Pumping								
No Energy Storage	492	1,425	5,701	5,292	1,546	302	13,964	21,587
Co-Located Storage	357	1,150	4,602	3,852	1,175	237	10,779	17,548
Grid Storage	492	1,425	5,701	5,292	1,546	302	13,964	21,587

4.5.2 Simulated Energy Outputs – Enhanced Tidal Technologies

The total modelled energy outputs (MWh/yr) for each candidate option for the case with enhanced turbine technologies, both with and without pumping and for different energy storage scenarios, is presented in Figure 4-33 below.

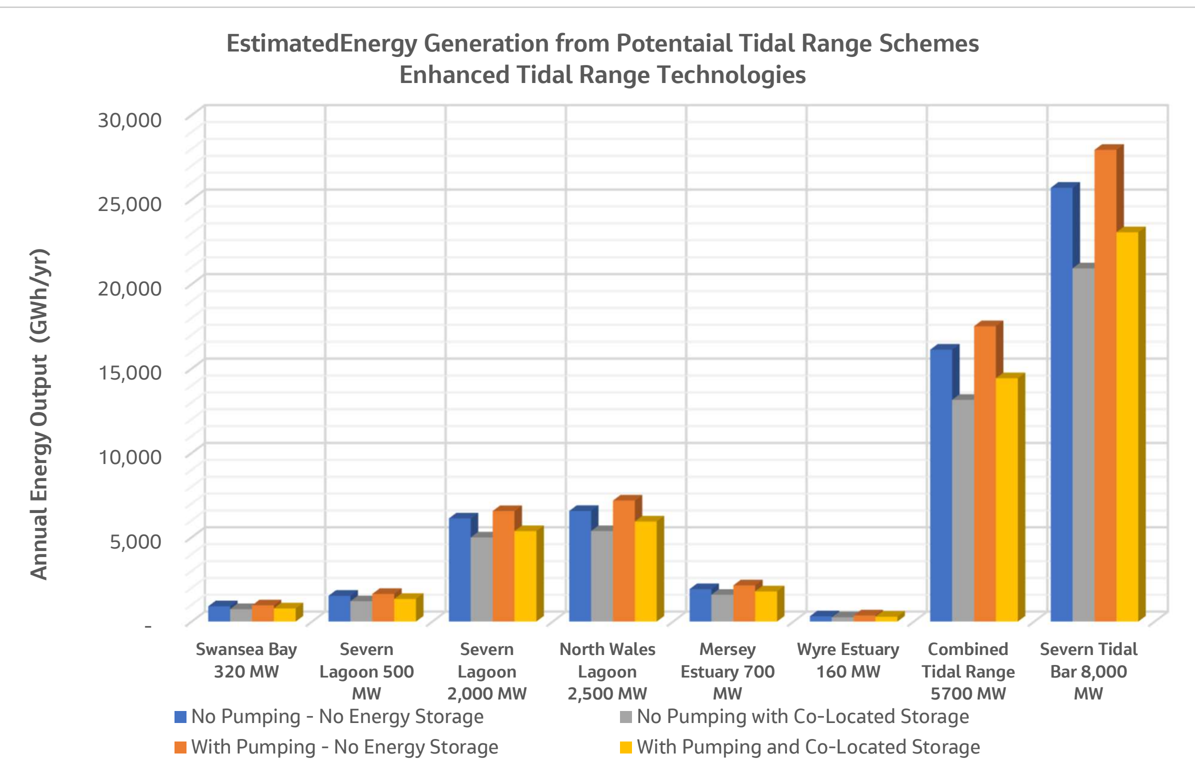

Figure 4-33 Estimated Energy Generation from Tidal Range – Enhanced Turbine Technologies

The total modelled energy outputs (MWh/yr) for each candidate option for the case with enhanced turbine technologies, both with and without pumping and for different energy storage scenarios, is presented in more detail in Table 4-2 below.

Table 4-2 Simulated Energy Outputs – Enhanced Tidal Technologies

Energy Outputs (GWh/annum)	Swansea Lagoon 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Estuary Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	903	1,528	6,112	6,555	1,921	312	16,116	25,692
Co-Located Storage	735	1,203	4,987	5,364	1,586	253	13,140	20,927
Grid Storage	903	1,528	6,112	6,555	1,921	312	16,116	25,692
With Pumping								
No Energy Storage	960	1,637	6,550	7,173	2,144	358	17,504	27,936
Co-Located Storage	777	1,342	5,362	5,933	1,788	290	14,425	23,063
Grid Storage	960	1,637	6,550	7,173	2,144	358	17,504	27,936

Note that as explained earlier, for the case of co-located energy storage, the net energy output exported to the grid is less than that for the other storage cases, due to the associated round-trip-efficiency losses being incurred at the point of generation, prior to transmission to the grid.

5. Tidal Range Option Costing

For this study, a tidal range cost model was developed based on deriving high level cost functions for all components of each tidal range option evaluated, as described below. This enabled all candidate options to be costed on a consistent basis, which is essential when comparing differences in the LCoE between options.

5.1 Generic Cost Functions for Tidal Range Cost Model

The cost model comprised the following costing components:

Scheme Size

- Total Installed Capacity (MW)
- Number of Units
- Unit Installed Capacity (MW)
- Area of basin (km2)
- Length of Barrage (km)

Power Caissons

- Length of Power Caissons (km)
- Mean Power Caisson Depth (m)
- Length of turbine diffusers (m)
- Power Caisson cost per km (£m/km)
- Power Caisson Installation (%)
- Total Power Caisson cost (£m)

Plain Caissons

- Length of Plain Caissons (km)
- Mean Plain Caisson Depth (m)
- Plain Caisson cost per km (£m/km)
- Plain Caisson Installation (%)
- Total Plain Caisson cost (£m)

Miscellaneous

- Navigation Locks (m)
- Buildings & site costs (%)

Energy Storage

- Short duration storage capacity (MW)
- Short duration storage volume (MWh)
- Long duration storage capacity (MW)
- Long duration storage volume (MWh)
- Total Energy Storage costs (£m)

M&E Plant

- M&E plant unit cost (£m/MW)
- Total M&E cost (£m)

Preliminary, Engineering, Environmental & Contingency

- Preconstruction cost (£m)
- Engineering & Contingency
- Environmental cost (£m)

Total Installed Cost (TIC)

- Total Installed Cost (£m)
- Total Escalated Cost (£m)

Key scheme parameters such as the area of the tidal basin, length of the barrage and average depth of the power and plain caissons were derived by GIS, based on Admiralty bathymetry data for each location.

The resulting total installed cost (TIC), escalated to 2021 price, was used as one of the main inputs into the Financial LCoE model, described in the next Section.

5.2 Total Installed Costs for Tidal Range Options

The tidal range cost model was used to produce total installed costs for the Financial LCoE model for each tidal range option for each of the following combination of cases:

- For both current bulb turbine and enhanced tidal turbine technologies;
- For operational cases both with and without pumping;
- For alternative energy storage scenarios.

For this high-level study, we have developed a set of generic cost functions that can derive approximate overall barrage costs based on the length, width and height of power and plain caissons (for both bulb and enhanced turbines), including an allowance for caisson installation and other site costs. Separate allowances are included for ship locks (as required). M&E plant costs are based on typical turbine, generator and transformer costs (£m/MW) for similar installations, including the costs for long and short duration energy storage needed for load balancing. Note these cost functions have been based on existing relevant reports/studies available in the public domain, but we must stress a key caveat is that no new engineering design or detailed bottom-up unit costing has been carried out under this this high-level planning study.

5.2.1 Total Installed Cost – Conventional Tidal Technologies (2021 prices)

The total estimated CAPEX cost for each candidate option, for the case with conventional bulb turbine technologies, is presented in the Table 5-1 below.

Table 5-1 Total Installed Cost – Conventional Tidal Technologies

CAPEX Cost (£ million)	Swansea Lagoon 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Estuary Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£2,752	£4,178	£10,922	£15,205	£2,726	£643	£33,031	£32,754
Co-Located Storage	£3,184	£4,938	£13,704	£18,214	£3,542	£850	£40,398	£42,022
Grid Storage	£2,978	£4,596	£12,332	£16,967	£3,220	£755	£37,115	£38,394
With Pumping								
No Energy Storage	£2,752	£4,178	£10,922	£15,205	£2,726	£643	£33,031	£32,754
Co-Located Storage	£3,248	£4,938	£13,701	£18,831	£3,652	£864	£41,122	£42,371
Grid Storage	£3,009	£4,593	£12,320	£17,308	£3,287	£760	£37,507	£38,605

5.2.2 Total Installed Cost – Enhanced Tidal Technologies

The total estimated CAPEX cost for each candidate option, for the case with enhanced tidal turbine technologies, is presented in the Table 5-2 below:

Table 5-2 Total Installed CAPEX Cost – Enhanced Tidal Technologies

CAPEX Cost (£ million)	Swansea Lagoon 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Estuary Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£2,702	£4,045	£10,393	£14,593	£2,622	£617	£31,652	£31,053
Co-Located Storage	£3,178	£4,989	£13,409	£17,488	£3,394	£809	£39,281	£41,746
Grid Storage	£2,927	£4,463	£11,803	£16,355	£3,115	£730	£35,736	£36,694
With Pumping								
No Energy Storage	£2,702	£4,045	£10,393	£14,593	£2,622	£617	£31,652	£31,053
Co-Located Storage	£3,195	£4,908	£13,382	£17,622	£3,451	£819	£39,363	£41,398
Grid Storage	£2,935	£4,426	£11,783	£16,444	£3,156	£735	£35,811	£36,515

Note that the principal difference in the total installed CAPEX costs between the two tidal technologies is due to the difference in caisson height and width, due to their different foundation levels and diffuser lengths, which has an impact on the costs of the power caissons.

While it is recognised that plant cost savings could also be made with the enhanced tidal technologies in future, potentially using lower cost composite materials as well as reduced turbine complexity, this has yet to be proven and thus has not been taken account of in these analyses.

6. Financial LCoE Modelling

6.1 Introduction

The purpose of this section is to analyse the financial viability of tidal range power plants (lagoons and barrages) as a renewable technology within the overall generation mix to meet the UK's net zero objectives.

The financial viability of tidal range schemes is delivered through determining an overall levelised cost of energy (LCoE) and the associated energy storage requirements to balance the system. The LCoE is a composite indicator which expresses the cost per unit of electricity generated (£/MWh) as a function of the discounted costs and energy generation over a given lifetime. This metric enables the ability to consistently compare the costs of tidal range against other renewable and low carbon generation technologies.

6.2 Approach to Financial Appraisal

The following key assumptions underpin the financial appraisal to support the levelised cost analysis:

- The development of a LCoE calculation combines simulated energy outputs with capital and operating cost associated with each tidal range scheme.
- Simulated energy outputs for each tidal range scheme are estimated using our in-house Zero-D Tidal Range Model – further details are provided in Section 4.
- The capital and operating costs have been estimated based upon relevant tidal reports[11] and department guidance[12]. Further details on the different capex and opex cost components are set out within Section 6.3.
- The LCoE (£/MWh)) is defined as the net present value (NPV) of the combined CAPEX and OPEX costs (£m), divided by the NPV of the utilisable energy (MWh).
- A financial appraisal of 88 years, consisting of an 8 year construction period followed by an 80 year operating and maintenance period has been applied to all tidal range schemes. The financial appraisal is different to the operating lifespan of tidal range which is expected to be 120 years. In line with guidance, the financial lifetime should be shorter than the operating lifespan to reflect a fair appraisal of long term cost and power generation[13].
- All LCoE figures are presented in 2021 real prices in line with industry guidance[14]. Where necessary, prices have been converted from other price bases using the latest GDP deflator series at the time of analysis as published by HM Treasury[15].
- Levelised cost estimates have been generated using a bespoke financial model which aggregates energy generation and cost estimates across the appraisal period and applies technology-specific hurdle rates to present the LCoE in a single and consistent price base (i.e 2021 real prices).

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[11] Based on previous Severn Estuary Tidal Power studies including the earlier SETS, SETB and DECC project reports

[12] DESNZ (2023) Generation Cost Report

[13] Energy and Climate Change Committee: A Severn Barrage Second Report of Session 2013-14

[14] DESNZ (2023) Generation Cost Report

[15] HM Treasury (2023) GDP Deflator at market prices, November 2023

- Hurdle rates have been sourced from the latest DESNZ Generation Cost Report (2023). The LCoE is assessed across three different hurdle rates to reflect the different stages of scheme readiness of tidal range, as follows:
  - **Commercial Pilot**: 9.4% hurdle rate reflecting tidal stream initial deployments
  - **First of a kind projects (FOAKs)**: 6.3% hurdle rate as adopted for large solar deployment
  - **Nth of a kind projects (NOAKs)**: 5.4% hurdle rate as adopted for large scale hydro
- This staged process allows us to assess the LCoE of tidal range as it goes through scheme readiness where design specification would be refined to optimise generation and mitigate any potential adverse environmental impacts before it reaches full scale deployment. The level of programmatic risks would be lowered throughout the development process reflected through a reduction in the hurdle rate at each stage.
- LCoE values are calculated for different tidal specifications as follows:
  - Conceptual tidal barrage and tidal lagoon schemes within the UK
  - Different tidal scheme arrangements including no energy storage, co-located storage and grid balancing storage. These scheme arrangements were modelled with and without pumping.
  - Alternative tidal turbine technologies, including conventional bulb turbines and enhanced very low head (VLH) turbines, as described in Section 3 and costed in Section 5.

6.3 Capital and Operating Costs

CAPEX and OPEX costs are derived for each of the tidal specifications over the financial appraisal period in order to evaluate the total NPV lifetime costs. Where CAPEX is the total initial capital expenditure and OPEX is the operation and maintenance cost annually. To support the evaluation of levelised cost across different tidal schemes, a fixed construction period length of 8 years has been applied to all schemes. This is a conservative estimate as it is possible for some smaller tidal schemes to have a shorter construction period.

In line with the cost function outlined in Section 5.1, the capital cost components for each tidal range scheme were as follows:

- Pre-construction costs
- Environmental cost
- Building and site costs
- Engineering & administration
- M&E plant costs
- Power caisson civil costs
- Plain caisson civil costs
- Caisson gates, cranes and equipment costs
- Navigation locks
- Energy Storage Costs

Table 6-1 Capex Cost Breakdown

Cost Item	Description	Unit & Value
Pre-construction costs	Costs associated with the preparatory work (site feasibility, permits/licenses, design planning) required before the construction phase.	(%) - *Set at 1.5% of total civils and plant costs*
Environmental cost	Ongoing programs to track environmental impacts and implement corrective actions where needed.	(%) - *Set at 11.5% of total civils and plant costs*
Building and site costs	Costs associated with construction of the barrage, dredging, seabed preparation and other physical structures.	(%) - *Set at 17% of total civils and plant costs*
Engineering & administration	Project management, financial, legal, research and development services.	(£m) - Scheme specific
M&E plant costs	Refers to turbine, generator, auxiliaries and control equipment costs[16].	(£m/MW) - Scheme specific
Power caisson civil costs	Costs of power caisson used to house the turbines and generators situated within the barrage/lagoon.	(£m/km) - Scheme specific
Plain caisson civil costs	Costs for housing auxiliary equipment or serving as part of the barrage structure.	(£m/km) - Scheme specific
Caisson gates, cranes and equipment costs	Costs associated with activities to control water flow and facilitate maintenance activities.	(£m/km) - Scheme specific
Navigation locks (£m)	Costs associated with building locks into the barrage to allow safe passage for marine transport without disrupting tidal generation.	(£m) - Scheme specific
Energy Storage Costs (£m/MW)	Refers to battery and hydrogen storage requirements.	(£m/MW) - Scheme specific

Given the limited amount of operational tidal range projects, there is a lack of information on the level of operating and maintenance costs. In the absence of specific data, a constant 1.25% of total capital costs has been applied across all schemes to account for operating and maintenance costs. This value is in line with relevant tidal reports[17]. Additionally, location specific TNUoS charges have also been calculated utilising the latest National Grid ESO report[18] and incorporated into the Opex costs.

Recognising the inherent challenges in forecasting costs for initial technologies such as tidal range, the cost estimates in this report represent the most comprehensive analysis possible using currently available public

[16] Plant replacement costs have been factored into the analysis and occur 40 years after the operational start date.

[17] Based on previous Severn Estuary Tidal Power studies including the earlier SETS, SETB and DECC project reports

[18] National Grid ESO 2023-24 Final TNUoS Tariff Report

data. Ongoing technological advancement and project development are expected to refine cost projections in the future. The uncertainty in cost estimates is acknowledged through applying a 30% contingency factor to all civils and plant costs.

6.4 Financial Modelling Results

The following subsections present the financial modelling results for potential tidal range power plants in the UK across six distinct tidal scheme arrangements, as described in Sections 4 and 5:

- No Pumping with No Energy Storage
- No Pumping with Co-Located Storage
- No Pumping with Grid Balancing Storage
- With Pumping and No Energy Storage
- With Pumping and Co-Located Storage
- With Pumping and Grid Balancing Storage

The justification for including storage options in the financial analysis is predicated on the findings in Section 4 which demonstrates that a small additional capacity of transmission connected energy storage would be required for balancing tidal range, due to the different operational cycles of wind, solar and tidal.

Harnessing the capability of UK tides provides a promising avenue for clean energy generation, different turbine technologies may maximise efficiency and output. Within this context, our financial modelling investigates the application of two tidal turbine technologies, as described in Section 3:

- Conventional Bulb Turbine Technologies (CAPEX costs presented in Table 5-1 in Section 5)
- Enhanced Tidal Turbine Technologies (CAPEX costs presented in Table 5-2 in Section 5)

Our analyses show the impact of these tidal specifications both on single and multiple tidal range schemes, at different tidal locations around the UK. Note that the financial analyses presented in Section 6.4 are based on the current tidal technologies followed by the enhanced tidal technologies, with the results of the financial analyses for both the conventional tidal technologies and the enhanced tidal technologies presented in Section 6.5.

6.4.1 Conventional Bulb Turbine Technologies

This section evaluates the levelised cost estimates across different tidal range schemes using conventional bulb turbine technologies with and without pumping. Given that conventional bulb turbines are deployed in current tidal range schemes (e.g La Rance Tidal Power Plant), this is considered our base case.

6.4.1.1 Energy Outputs

Analysis of the total energy outputs both with and without pumping across the different tidal specifications are outlined in Table 6-2. Energy generation is estimated for each scheme using the Zero-D Tidal Range model and is a function of the installed capacity and the load factor.

The maximum energy generation is estimated to be 24,268 GWh/year at Severn Tidal Bar (8000MW), contrastingly the Wyre Estuary (160MW) has the lowest estimated energy generation at 183 GWh/year.

Table 6-2 Tidal Range Schemes - Energy Generation (GWh/year)

Energy Outputs	Firm/Non-firm Energy (GWh)	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
No Pumping									
No Energy Storage	Non-firm Energy (GWh)	553	1,341	5,365	4,893	1,518	238	13,117	23,583
Co-Located Storage	Firm Energy (GWh)	440	1,082	4,329	3,805	1,205	183	10,421	18,757
Grid Balancing Storage	Effective Firm Energy (GWh)	553	1,341	5,365	4,893	1,518	238	13,117	23,583
With Pumping									
No Energy Storage	Non-firm Energy (GWh)	492	1,425	5,701	5,292	1,546	302	13,964	24,268
Co-Located Storage	Firm Energy (GWh)	357	1,150	4,602	3,852	1,175	237	10,779	19,910
Grid Balancing Storage	Effective Firm Energy (GWh)	492	1,425	5,701	5,292	1,546	302	13,964	24,268

6.4.1.2 Capex Costs

Capital costs have been estimated using the tidal range cost model in line with the cost components outlined in Section 6.3. These costs have been aggregated over an 80 year time horizon and uplifted to 2021 prices using the GDP deflator. For a more detailed breakdown of the individual parameters that have supported the derivation of total installed cost and total energy generation please refer to Appendix A.2

The total capex costs across the different tidal range schemes and energy storage requirements, uplifted to 2021 prices are outlined in Table 6-3.

The increase in capital costs under the storage (co-located and grid network) tidal scheme arrangements is driven by battery and hydrogen storage infrastructure which is not required under the no storage scheme arrangement.

Table 6-3 Tidal Ranges Schemes Bulb Turbines - Capex (£m,2021 Prices)

Total CAPEX Costs	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW[19]	Severn Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£2,752	£4,178	£10,922	£15,205	£2,726	£643	£33,031	£32,754
Co-Located Storage	£3,184	£4,938	£13,704	£18,214	£3,542	£850	£40,398	£43,920

[19] The combined scheme (5700MW) comprises of Severn Lagoon (2000MW), Severn Lagoon (500MW), North Wales Lagoon (2500MW) and Mersey Estuary (700MW)

Total CAPEX Costs	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW[19]	Severn Tidal Bar 8,000 MW
Grid Balancing Storage	£2,978	£4,596	£12,332	£16,967	£3,220	£755	£37,115	£38,394
With Pumping								
No Energy Storage	£2,752	£4,178	£10,922	£15,205	£2,726	£643	£33,031	£32,754
Co-Located Storage	£3,248	£4,938	£13,701	£18,831	£3,652	£864	£41,122	£43,140
Grid Balancing Storage	£3,009	£4,593	£12,320	£17,308	£3,287	£760	£37,507	£37,950

To evaluate the cost effectiveness of each tidal range scheme, Table 6-4 outlines the capital cost per MW installed both with and without pumping.

Table 6-4 Tidal Ranges Schemes Bulb Turbines - Capex (£m/MW),2021 Prices

Capex (£m/MW)	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£8.6	£8.4	£5.5	£6.1	£3.9	£4.0	£5.8	£4.1
Co-Located Storage	£10.0	£9.9	£6.9	£7.3	£5.1	£5.3	£7.1	£5.5
Grid Balancing Storage	£9.3	£9.2	£6.2	£6.8	£4.6	£4.7	£6.5	£4.8
With Pumping								
No Energy Storage	£8.6	£8.4	£5.5	£6.1	£3.9	£4.0	£5.8	£4.1
Co-Located Storage	£10.1	£9.9	£6.9	£7.5	£5.2	£5.4	£7.2	£5.4
Grid Balancing Storage	£9.4	£9.2	£6.2	£6.9	£4.7	£4.7	£6.6	£4.7

6.4.1.3 LCoE Results

The following section outlines the levelised cost estimates for bulb turbine tidal range schemes.

The figures related to Co-Located Storage and Grid Balancing Storage should not be compared directly with other technology LCoE as such technologies do not account for storage.

6.4.1.3.1 Commercial Pilot

The levelised cost estimates for commercial pilot bulb turbine tidal ranges schemes is presented in Table 6.5. Under the commercial pilot schemes, a 9.4% discount rate has been applied to energy generation and costs across the financial appraisal period. Our analysis demonstrates that the commercial pilot schemes range from a lower bound of £201/MWh at Severn Tidal Bar (8000MW) to an upper bound of £1,313/MWh under the Swansea Bay (320MW) scheme.

The lowest LCoE are derived under the no energy storage tidal scheme arrangement. The energy storage solutions require additional infrastructure which in turn raises capital expenditure (Table 6-3) with a negligible impact on energy generation (Table 6-2) and thus overall contributes to a higher LCoE.

Table 6.5 Commercial Pilot – LCoE £/MWh (2021 Prices)

LCOE Costs	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£719	£450	£294	£449	£260	£391	£364	£201
Co-Located Storage	£1,045	£659	£458	£692	£425	£672	£560	£339
Grid Balancing Storage	£778	£495	£332	£501	£307	£459	£409	£236
With Pumping								
No Energy Storage	£808	£424	£277	£415	£255	£308	£342	£195
Co-Located Storage	£1,313	£620	£430	£706	£450	£527	£551	£313
Grid Balancing Storage	£883	£466	£312	£473	£308	£364	£388	£226

Source: Jacobs Analysis, hurdle rate at 9.4% for commercial pilot

6.4.1.3.2 FOAK & NOAK Projects

The levelised cost estimates for FOAK and NOAK projects are outlined in Table 6.6 and Table 6.7 respectively. In line with the scheme readiness, a prevailing hurdle rate of 6.3% and 5.4% have been applied to energy outputs and costs for FOAK and NOAK tidal range schemes.

Table 6.6 FOAK – LCOE £/MWh (2021 Prices)

LCOE Costs	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£461	£289	£190	£289	£168	£253	£234	£130
Co-Located Storage	£670	£422	£294	£444	£274	£433	£360	£218
Grid Balancing Storage	£499	£317	£214	£322	£198	£296	£263	£152
With Pumping								
No Energy Storage	£518	£272	£178	£267	£165	£199	£220	£126
Co-Located Storage	£842	£397	£276	£453	£290	£339	£354	£202

LCOE Costs	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Grid Balancing Storage	£566	£299	£201	£304	£198	£235	£250	£146

Source: Jacobs Analysis, hurdle rate at 6.3% for FOAK

Our analysis demonstrates that the LCoE ranges from £126-£842£/MWh at FOAK and £109-£725 at NOAK stage. Consistent with the VLH turbine analysis, the higher LCoE at early stage development for tidal range is reflective of the immaturity of turbine technology. As tidal range moves through to full stage deployment, greater technology testing seeks to optimise performance, lower associated risks and validate tidal energy outputs which may lower the cost of capital.

Table 6.7 NOAK – LCoE £/MWh (2021 Prices)

LCOE Costs	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£397	£249	£164	£249	£145	£218	£202	£112
Co-Located Storage	£577	£364	£253	£383	£236	£373	£310	£188
Grid Balancing Storage	£429	£273	£184	£278	£171	£256	£227	£131
With Pumping								
No Energy Storage	£446	£234	£154	£230	£143	£172	£190	£109
Co-Located Storage	£725	£342	£238	£391	£250	£293	£305	£174
Grid Balancing Storage	£488	£257	£173	£262	£171	£203	£215	£126

Source: Jacobs Analysis, hurdle rate at 5.4% for NOAK

6.4.1.3.3 Conventional Bulb Turbine Technologies Summary

The main conclusions of the conventional tidal turbine technologies LCoE analysis can be summarised as follows:

- There is significant variation in the overall capital costs of our tidal schemes. There are economies of scale where the level of construction which is a function of barrage length is minimised in proportion to basin area and amount of retained water which maximise the potential energy captured.
- This translates into a lower LCoE compared to tidal range schemes with a longer barrage length that scales up construction costs to reach seabed depths where generation assets can be installed. The area of basin is fundamental to the optimal hold level which maximises the level of retained water and increases the energy generation capability.
- Under the appropriate transmission connections there may not be a requirement to consider energy storage solutions. However, the introduction of energy storage can provide a more even load profile which is important for system balancing.
- The capex is higher under scenarios with energy storage solutions due to the cost of the additional infrastructure. These storage related costs increase construction expenditure with no impact on generation capabilities thereby increasing the LCOE relative to non-storage solutions.

6.4.2 Enhanced Tidal Turbine Technologies - without Pumping

This section evaluates the levelised cost estimates across different tidal range schemes using enhanced turbine technologies with and without pumping.

6.4.2.1 No Energy Storage

A summary of energy generation and capital and operational costs across the different tidal range schemes is outlined in Table 6-8. Energy generation is estimated for each scheme using the Zero-D Tidal Range model and is a function of the installed capacity and the load factor. The total capex and opex costs are derived from the sum of the different cost categories outlined in Section 6.3 uplifted to 2021 prices using the GDP deflator. For a more detailed breakdown of the capex and opex components and energy outputs across each tidal range scheme, please refer to Appendix A.2.1.

Table 6-8 Tidal Range Schemes No Pumping No Energy Storage - Energy Generation and Scheme Costs (2021 Prices)

Scheme	Energy Generation (GWh)/year	Total Capex (£m)	Capex (£m/MW)	Opex (£/MW/year)	Plant Replacement Costs (£m)*
Severn Tidal Barrage (8000MW)	25,692	£31,053	£3.9	£48,517	£11,771
Severn Lagoon (500MW)	1,528	£4,045	£8.1	£101,122	£736
Severn Lagoon (2000MW)	6,112	£10,393	£5.2	£64,957	£2,943
North Wales Lagoon (2500MW)	6,555	£14,593	£5.8	£72,963	£3,678
Mersey Estuary (700MW)	1,921	£2,622	£3.7	£46,812	£1,030
Combined (5700MW)[20]	16,116	£31,652	£5.6	£69,412	£8,387
Wyre Estuary (160 MW)	312	£617	£3.9	£48,225	£235
Swansea Bay (320MW)	903	£2,702	£8.4	£105,536	£471

Figure 6-1 compares the capex costs (columns) against the energy generation (line) across the different tidal range schemes. Our analysis shows that the Severn Tidal Bar (8000MW) scheme has the greatest level of generation (25,692 GWh/year), benefitting from a large basin area and length of barrage allowing space for a greater number of turbines to be installed which maximises the installed capacity.

[20] The combined scheme (5700MW) comprises of Severn Lagoon (2000MW), Severn Lagoon (500MW), North Wales Lagoon (2500MW) and Mersey Estuary (700MW)

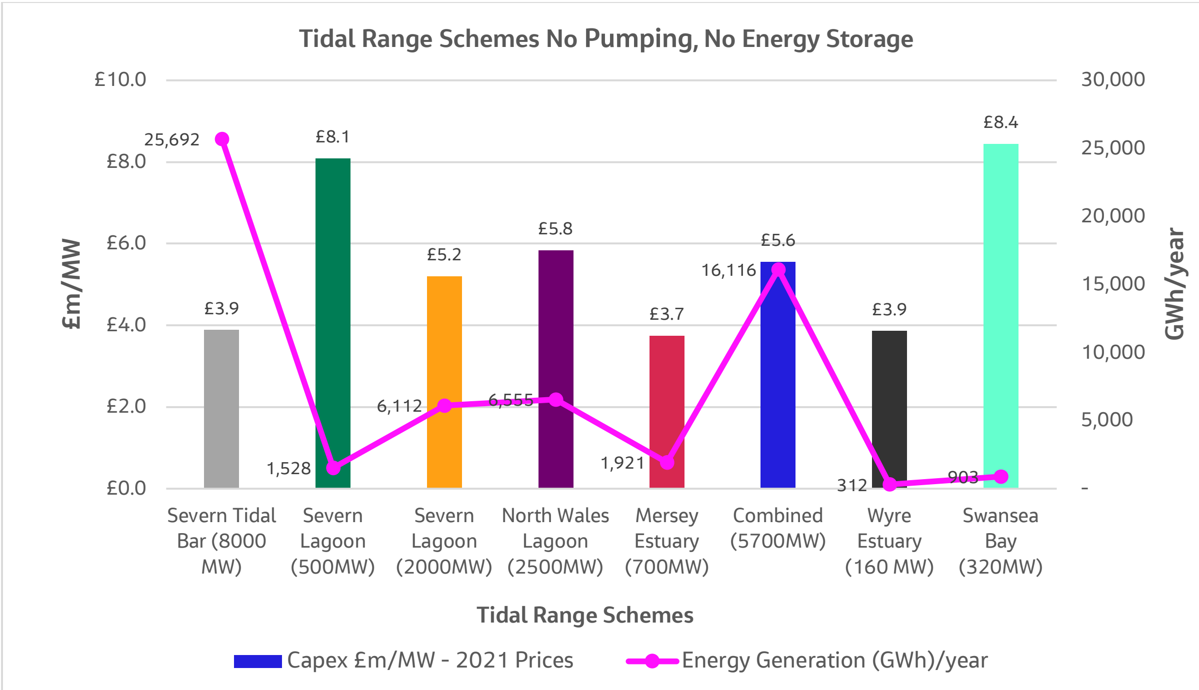

Figure 6-1 Tidal Range No Pumping No Energy Storage Schemes - Capex (£/MW 2021 Prices) and Energy Generation (GWh/year)

6.4.2.1.1 No Energy Storage - LCoE Results

Dividing the discounted costs by the discounted generation, provides the LCoE (£/MWh) which is the measure of the average cost per MWh generated for each tidal range scheme over the financial appraisal period.

Figure 6-2 presents the LCoE (£/MWh) for the commercial pilot, FOAK and NOAK tidal range schemes in 2021 prices. Our analysis demonstrates that there is a large variance in LCoE across schemes, £175/MWh-£432/MWh at commercial pilot, £114/MWh- £278/MWh at FOAK stage and between £98/MWh-£239/MWh at NOAK stage.

The higher LCoE at commercial pilot reflects a position of early stage development for tidal range, and thus has been calculated using a hurdle rate applicable to a pilot tidal stream project. During the FOAK and NOAK stages, tidal range transitions from controlled environments to be deployed at full scale, such that once tidal range projects have matured to NOAK developments, it would then be appropriate to utilise a hurdle rate similar to that to large hydro.

Whilst the LCoE falls as tidal range advances through the technology readiness framework, another inherent observation is that there are significant differences in levelised cost across tidal range schemes. The Severn Tidal Bar (8000MW) and the Mersey Estuary (700MW) are considered the most cost efficient schemes, with an LCoE of £98/MWh and £111/MWh respectively at NOAK stage. In contrast, the Swansea Bay (320MW) scheme drives the highest levelised cost with a value of £432/MWh at commercial pilot stage, reducing to £239/MWh at NOAK stage, yet this value is still £27/MWh higher than the next most expensive scheme, Severn Lagoon (500MW).

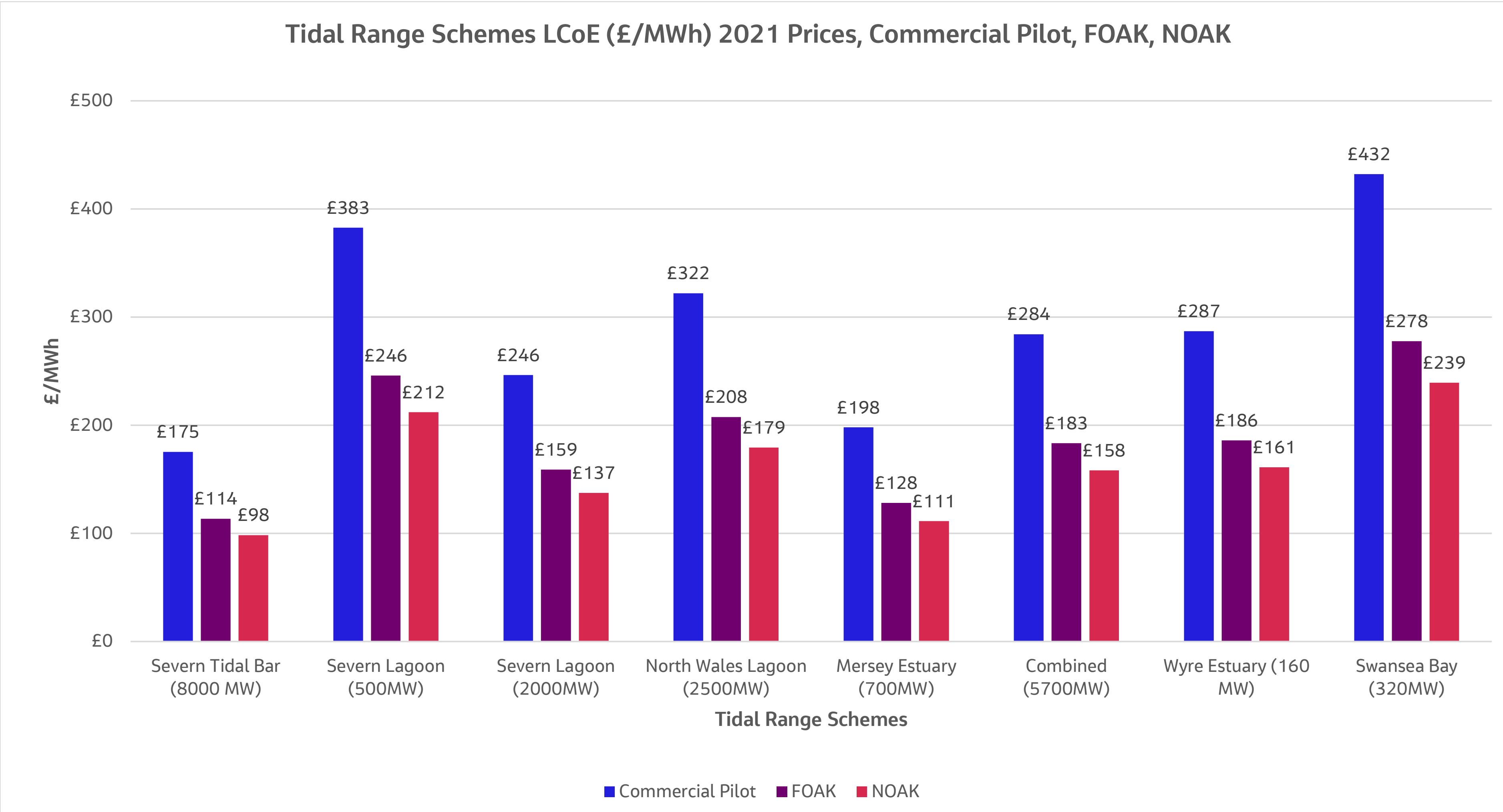

Figure 6-2 LCoE: No Pumping, No Energy Storage (2021 Prices) – Commercial Pilot. FOAK, NOAK
Source: Jacobs Analysis, hurdle rate at 9.4%, 6.3% and 5.4% for Commercial Pilot, FOAK, NOAK

6.4.2.2 Co-Located Storage

Table 6-9 presents a summary of energy generation and capital and operational costs across the different tidal range schemes. The co-located storage cost includes additional battery and hydrogen storage infrastructure which is not required under the no storage scheme arrangement. For a more detailed breakdown of the capex and opex components and energy outputs across each tidal range scheme, please refer to Appendix A.2.2.

Table 6-9 Tidal Range Schemes No Pumping Co-Located Storage - Energy Generation and Scheme Costs (2021 Prices)

Scheme	Energy Generation (GWh)/year	Total Capex (£m)	Capex (£m/MW)	Opex (£/MW/year)	Plant Replacement Costs (£m)*
Severn Tidal Barrage – (8000MW)	20,927	£41,746	£5.2	£65,226	£11,771
Severn Lagoon (500MW)	1,203	£4,989	£10.0	£124,727	£736
Severn Lagoon (2000MW)	4,987	£13,409	£6.7	£83,808	£2,943
North Wales Lagoon (2500MW)	5,364	£17,488	£7.0	£87,441	£3,678
Mersey Estuary (700MW)	1,586	£3,394	£4.8	£60,611	£1,030
Combined (5700MW)	13,140	£39,281	£6.9	£86,142	£8,387
Wyre Estuary (160 MW)	253	£809	£5.1	£63,205	£235
Swansea Bay (320MW)	735	£3,178	£9.9	£124,131	£471
*Plant replacement costs are assumed to be incurred every 40 years.					

Figure 6-3 compares the capex costs against the energy generation across the different tidal range schemes. Consistent with the pattern outlined in no storage tidal scheme arrangement, the Severn Tidal Bar (8000MW) scheme has the greatest level of generation (20,927 GWh/year), owing to its high installed capacity relative to comparator schemes. The Mersey Estuary (700MW) has the lowest cost of capital (£4.8m/MW) closely followed by the Wyre Estuary (160MW) at £5.1m/MW.

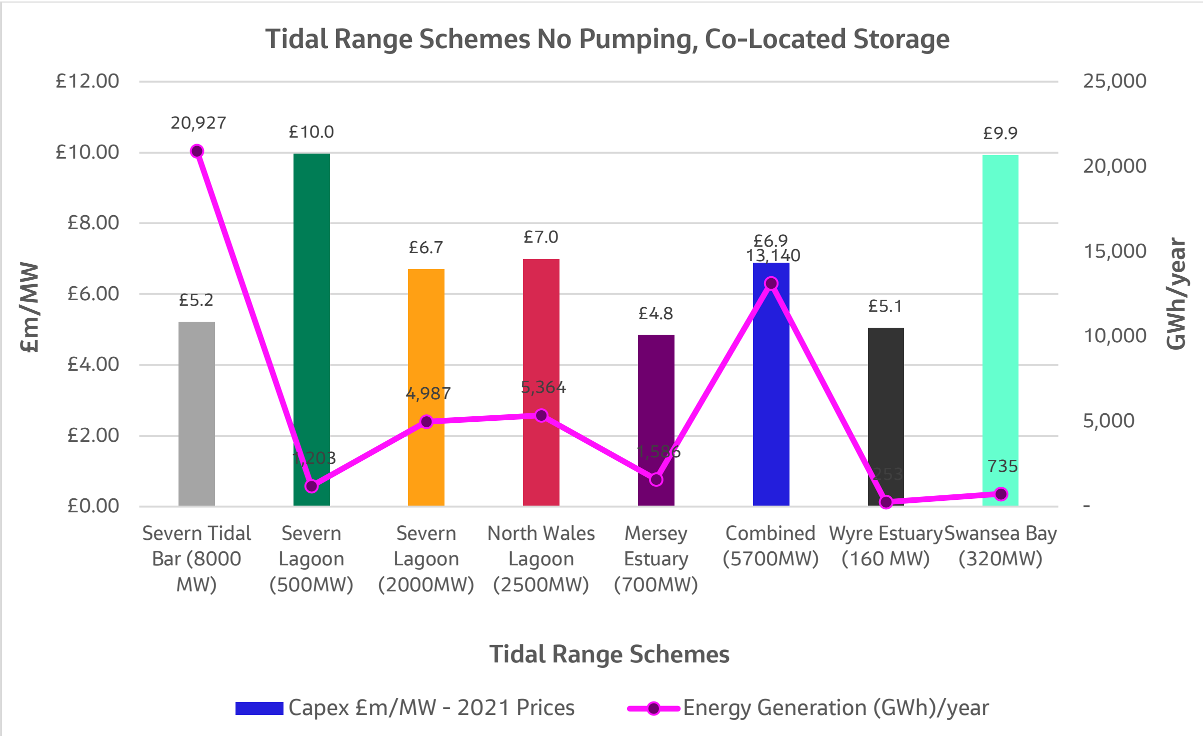

Figure 6-3 Tidal Range No Pumping Co-Located Storage Schemes - Capex (£/MWh 2021 Prices) and Energy Generation (GWh/year)

6.4.2.2.1 Co-Located Storage – LCoE Results

Figure 6-4 presents the LCoE (£/MWh) for the commercial pilot, FOAK and NOAK tidal range schemes in 2021 prices. At the early stage of tidal range development, our analysis demonstrates that the LCoE ranges from £289/MWh for Severn Tidal Bar (8000MW) to £625/MWh for the Swansea Bay (320MW), with the combined (5700MW) tidal range scheme at £432/MWh. At FOAK and NOAK stages, the LCoE is between £186-£401/MWh and £161-£345/MWh respectively recognising the greater technology maturity and lower associated risks as tidal range advances through to full scale deployment.

Relative to the no storage tidal scheme arrangement (Section 6.4.2.1), the increase in LCoE is primarily driven through the introduction of energy storage costs reflected through the requirement for battery and hydrogen under the co-located scheme arrangement.

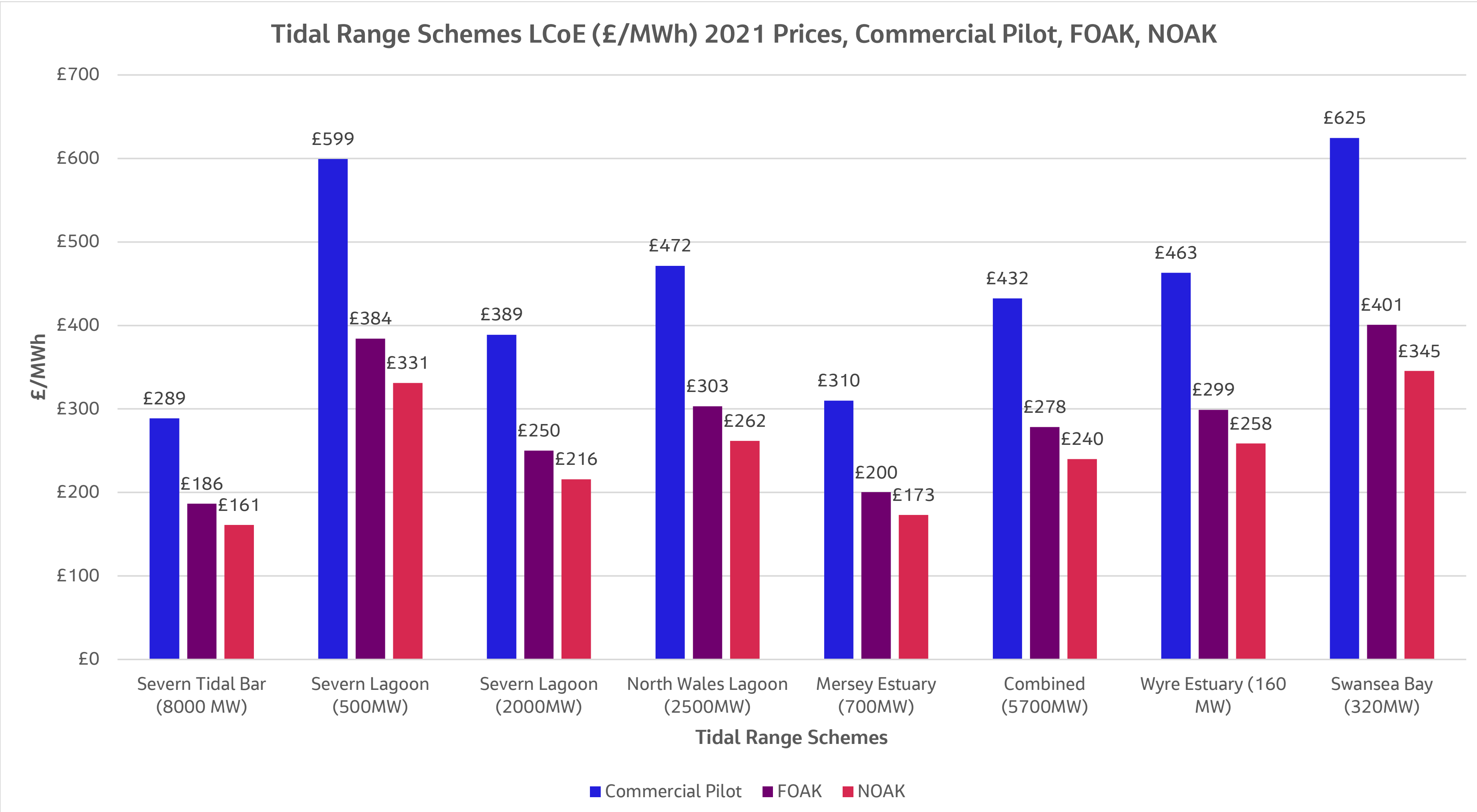

Figure 6-4 LCoE: No Pumping, Co-Located Storage (2021 Prices) – Commercial Pilot. FOAK, NOAK
Source: Jacobs Analysis, hurdle rate at 9.4%, 6.3% and 5.4% for Commercial Pilot, FOAK, NOAK

6.4.2.3 Grid Balancing Storage

Table 6-10 presents a summary of energy generation and capital and operational costs across the different tidal range schemes. This scenario utilises integrated grid-based energy system storage from other intermittent renewables such as wind and solar, with that of tidal. For further details on the various capex and opex components and energy outputs across each tidal range scheme, please refer to Appendix A.2.3.

Table 6-10 Tidal Range Schemes No Pumping Grid Balancing Storage - Energy Generation and Scheme Costs

Scheme	Energy Generation (GWh)/year	Total Capex (£m)	Capex (£m/MW)	Opex (£/MW/year)	Plant Replacement Costs (£m)*
Severn Tidal Barrage – (8000MW)	25,692	36,694	£4.6	£57,331	£11,771
Severn Lagoon (500MW)	1,528	4,463	£8.9	£111,567	£736
Severn Lagoon (2000MW)	6,112	11,803	£5.9	£73,770	£2,943
North Wales Lagoon (2500MW)	6,555	16,355	£6.5	£81,776	£3,678
Mersey Estuary (700MW)	1,921	3,115	£4.5	£55,625	£1,030
Combined (5700MW)	16,116	35,736	£6.3	£78,368	£8,387
Wyre Estuary (160 MW)	312	730	£4.6	£57,038	£235
Swansea Bay (320MW)	903	2,927	£9.1	£114,350	£471
*Plant replacement costs are assumed to be incurred every 40 years.					

Figure 6-5 compares the capex costs against the energy generation across the different tidal range schemes. In line with the pattern displayed across other tidal scheme arrangements, our analysis shows that the highest energy generation can be achieved at the Severn Tidal Barrage (8000MW) with an estimated 25,692 GWh/year. The lowest capital cost per installed capacity is estimated at £4.5m/MW under the Mersey Estuary (700MW) scheme.

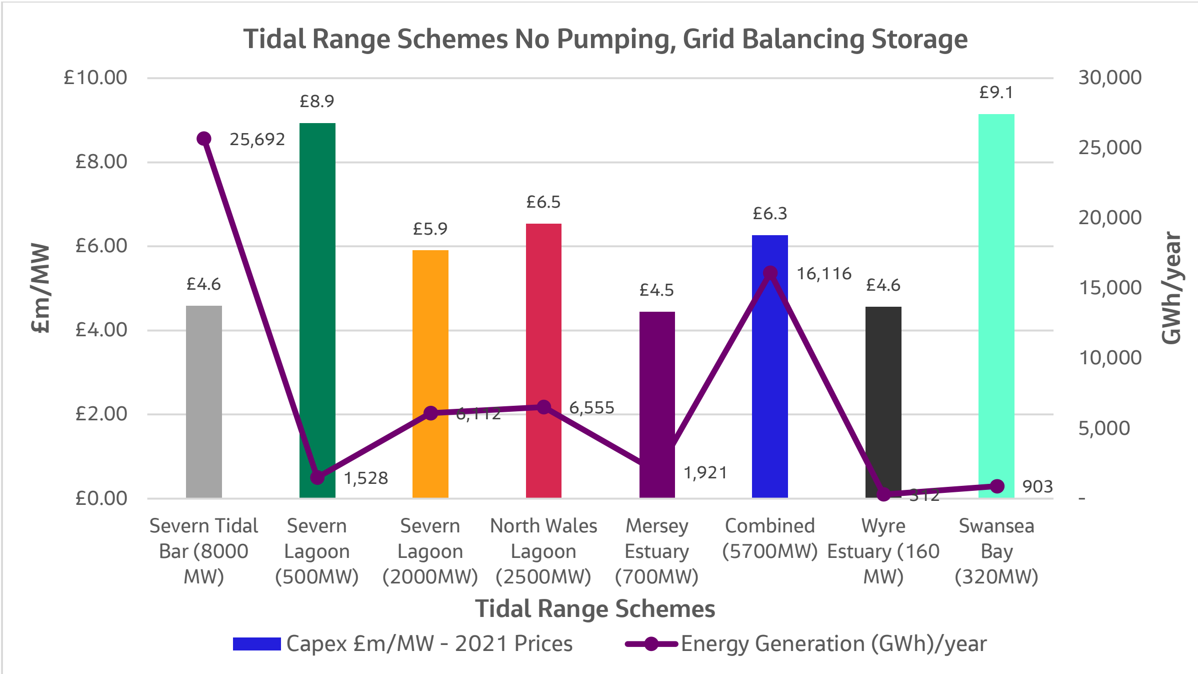

Figure 6-5 Tidal Range No Pumping Grid Balancing Storage Schemes - Capex (£/MWh 2021 Prices) and Energy Generation (GWh/year)

6.4.2.3.1 Grid Balancing Storage - LCoE Results

The LCoE (£/MWh) for the commercial pilot, FOAK and NOAK tidal range schemes in 2021 prices is outlined in Figure 6-6. Our analysis demonstrates that across tidal range schemes, the LCoE ranges from £207-£468£/MWh at commercial pilot, £134-£301 £/MWh at FOAK and £116-£259 £/MWh at NOAK stages.

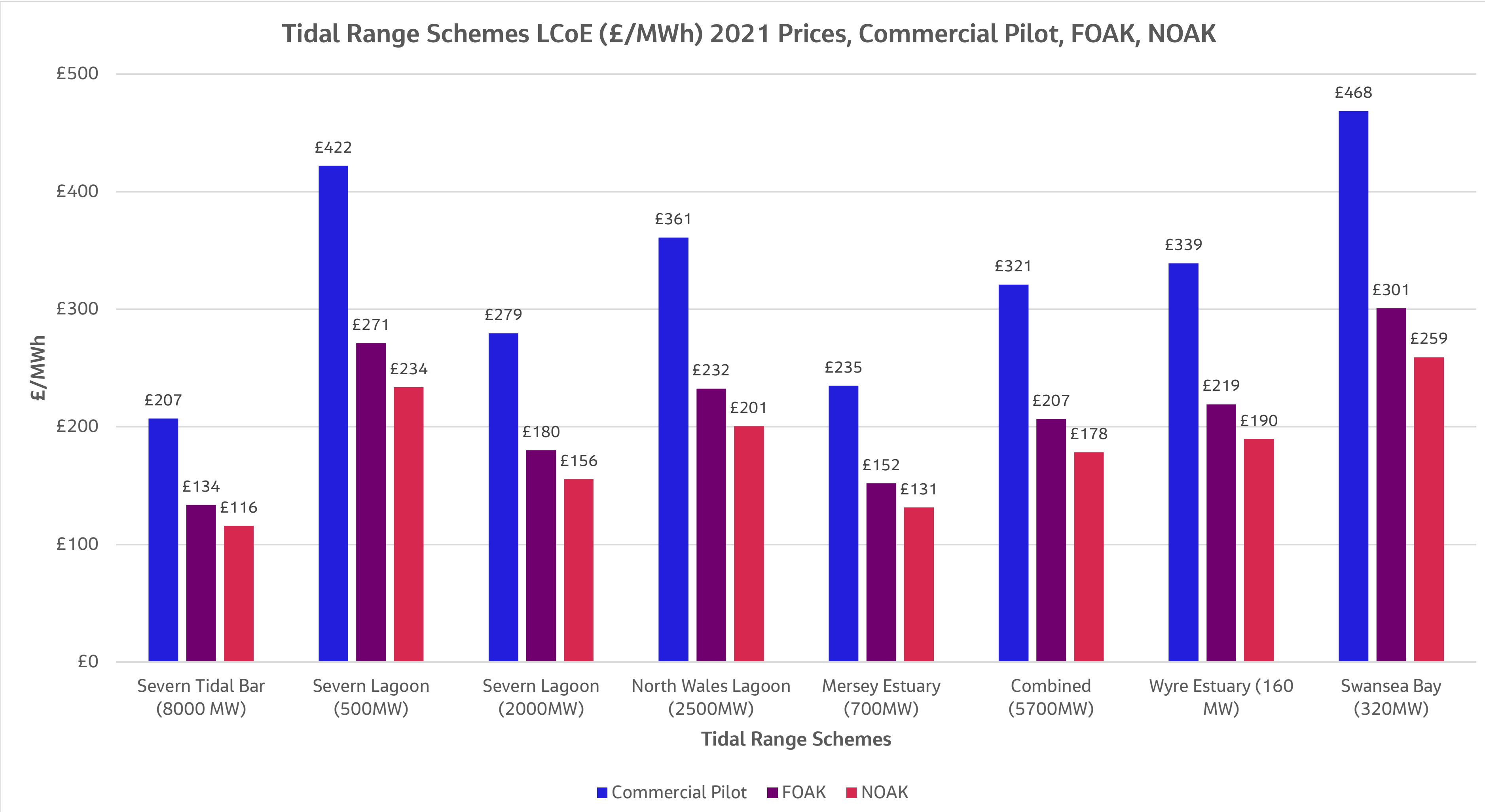

Figure 6-6 LCoE: No Pumping, Grid Balancing Storage (2021 Prices) – Commercial Pilot. FOAK, NOAK
Source: Jacobs Analysis, hurdle rate at 9.4%, 6.3% and 5.4% for Commercial Pilot, FOAK, NOAK

6.4.3 Enhanced Tidal Turbine Technologies - with Pumping

6.4.3.1 No Energy Storage with Pumping

Energy generation, capital and operational costs are calculated across no energy storage with pumping tidal schemes. A summary of the energy outputs and total costs uplifted to 2021 prices are displayed in Table 6-11. For a more detailed breakdown of the capex and opex components and energy outputs across each tidal range scheme, please refer to Appendix A.2.4

Table 6-11 Tidal Range Schemes with Pumping No Energy Storage - Energy Generation and Scheme Costs

Scheme	Energy Generation (GWh)/year	Total Capex (£m)	Capex (£m/MW)	Opex (£/MW/year)	Plant Replacement Costs (£m)*
Severn Tidal Barrage – (8000MW)	27,936	£31,053	£3.9	£48,517	£11,771
Severn Lagoon (500MW)	1,637	£4,045	£8.1	£101,122	£736
Severn Lagoon (2000MW)	6,550	£10,393	£5.2	£64,957	£2,943
North Wales Lagoon (2500MW)	7,173	£14,593	£5.8	£72,963	£3,678
Mersey Estuary (700MW)	2,144	£2,622	£3.7	£46,812	£1,030
Combined (5700MW)	17,504	£31,652	£5.6	£69,412	£8,387
Wyre Estuary (160 MW)	358	£617	£3.9	£48,225	£235
Swansea Bay (320MW)	960	£2,702	£8.4	£105,536	£471
*Plant replacement costs are assumed to be incurred every 40 years.					

Figure 6-7 compares the capex costs against the energy generation across the different tidal range schemes under the with pumping no energy storage specification. Our analysis demonstrates that the Severn Tidal Bar (8000MW) scheme has the greatest level of generation (27,936GWh/year), owing to its high installed capacity relative to comparator schemes. The lowest per MW cost of capital is calculated at £3.7m/MW under the Mersey Estuary (700MW).

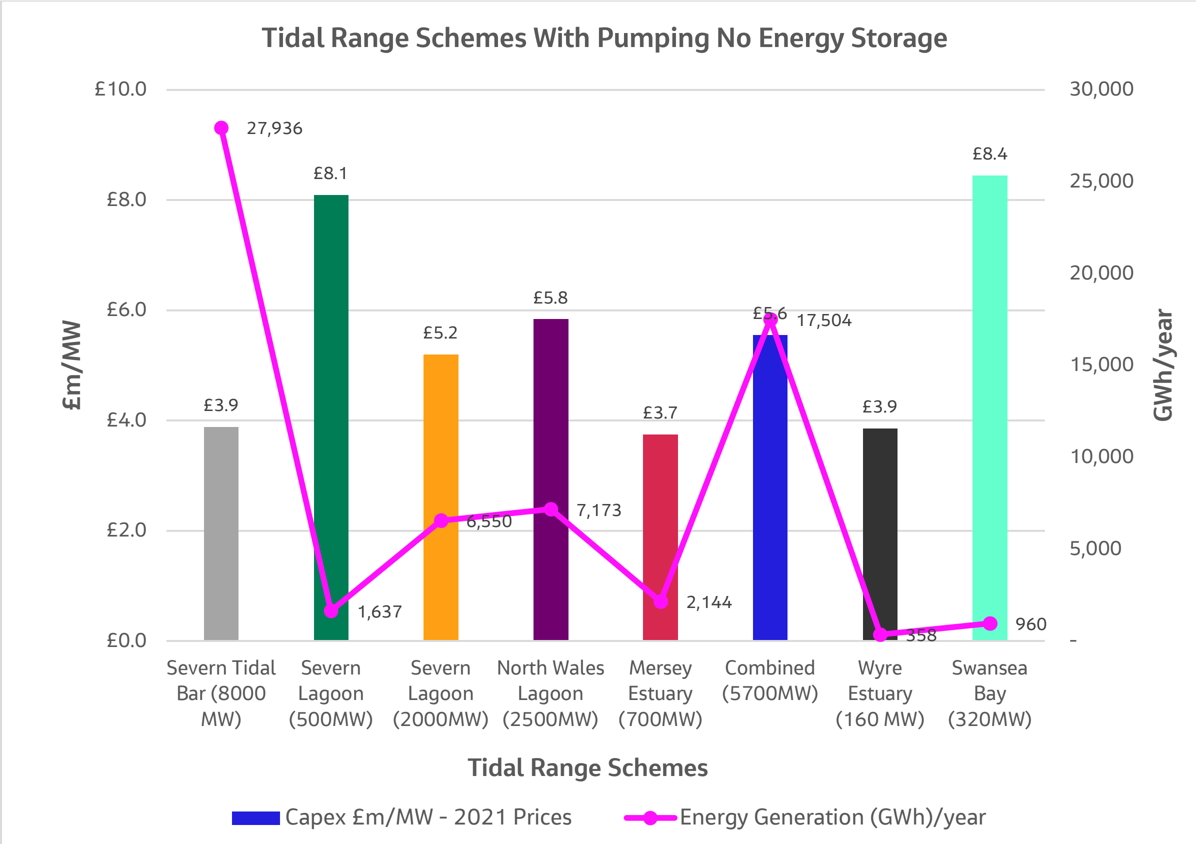

Figure 6-7 With Pumping No Energy Storage Discounted Generation & Costs: Commercial Pilot, FOAK, NOAK (2021 Prices)

6.4.3.1.1 No Energy Storage – LCoE Results

Figure 6-8 presents the LCoE (£/MWh) for the commercial pilot, FOAK and NOAK tidal range schemes in 2021 prices. Our analysis demonstrates that there is significant variation in the LCoE across schemes, £161/MWh- £407/MWh at commercial pilot, £104/MWh- £261/MWh at FOAK stage and between £90/MWh-£225/MWh at NOAK stage.

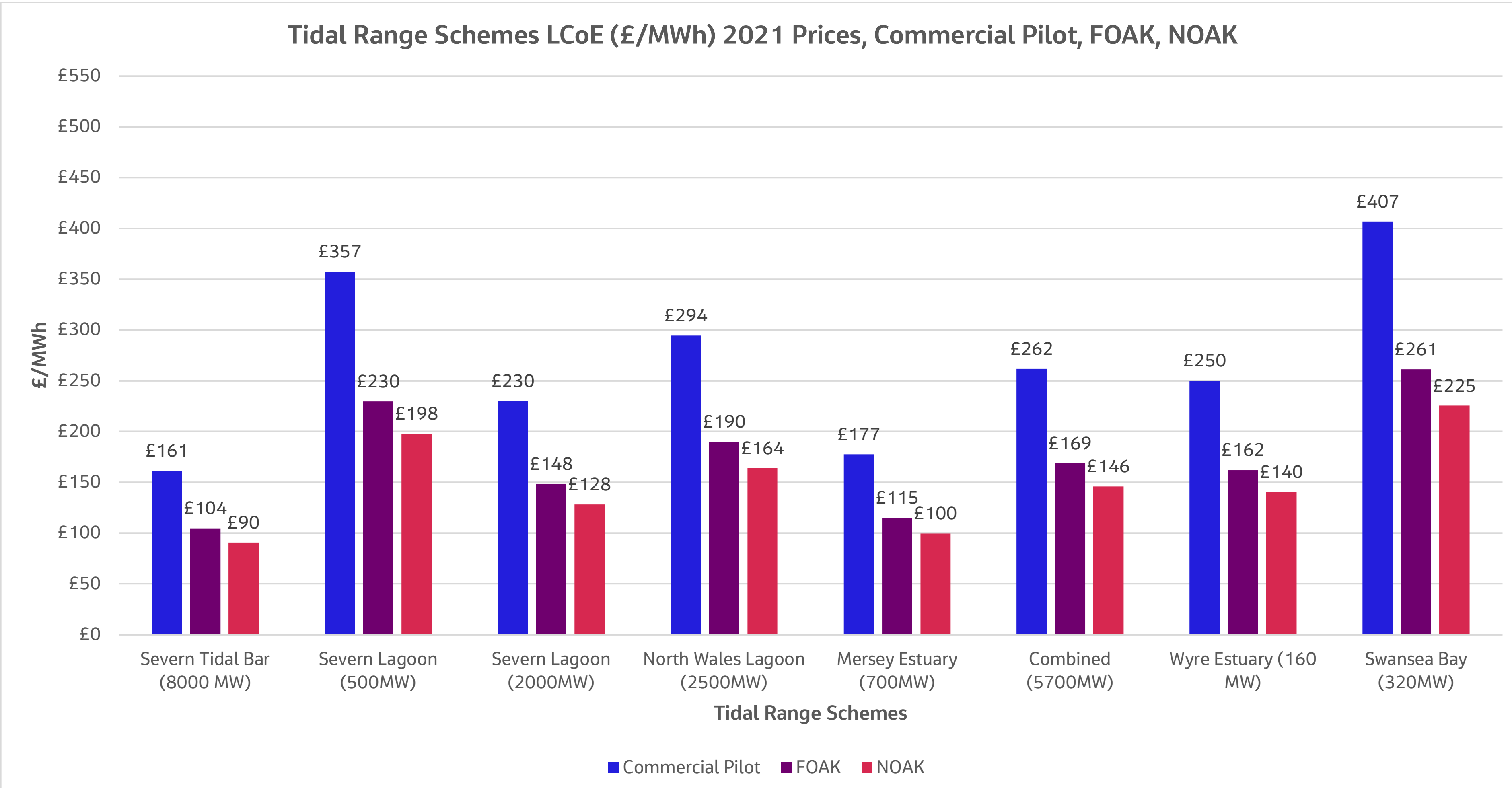

Figure 6-8 LCoE: No Energy Storage with Pumping (2021 Prices) – Commercial Pilot. FOAK, NOAK

Source: Jacobs Analysis, hurdle rate at 9.4%, 6.3% and 5.4% for Commercial Pilot, FOAK, NOAK

6.4.3.2 Co-Located Storage with Pumping

The co-located storage with pumping includes additional battery and hydrogen storage infrastructure which is not required under the no storage scheme arrangement. The figures within Table 6-12 should not be compared directly with other technology LCoE as such technologies do not account for storage.

Further details on the capex and opex costs across each tidal scheme is provided in Appendix A.2.5

Table 6-12 Tidal Range Schemes with Pumping Co-Located Storage - Energy Generation and Scheme Costs

Scheme	Energy Generation (GWh)/year	Total Capex (£m)	Capex (£m/MW)	Opex (£/MW/year)	Plant Replacement Costs (£m)*
Severn Tidal Barrage – (8000MW)	23,063	£41,398	£5.2	£64,682	£11,771
Severn Lagoon (500MW)	1,342	£4,908	£9.8	£122,692	£736
Severn Lagoon (2000MW)	5,362	£13,382	£6.7	£83,636	£2,943
North Wales Lagoon (2500MW)	5,933	£17,622	£7.0	£88,109	£3,678
Mersey Estuary (700MW)	1,788	£3,451	£4.9	£61,627	£1,030
Combined (5700MW)	14,425	£39,363	£6.9	£86,321	£8,387
Wyre Estuary (160 MW)	290	£819	£5.1	£63,984	£235
Swansea Bay (320MW)	777	£3,195	£10.0	£124,806	£471
*Plant replacement costs are assumed to be incurred every 40 years.					

Figure 6-9 compares the capex costs against the energy generation across the different tidal range schemes. Our analysis shows that for the co-located storage with pumping tidal schemes, the highest energy generation of 23,063 GWh/year could be achieved at the Severn Tidal Barrage (8000MW), with the lowest capex per installed capacity at the Mersey Estuary (1000MW) at £6.70m/MW. The lowest annual generation is attributed to the Wyre Estuary (160MW) at 290 GWh/year with the highest capital costs of £10.0m/MW under the Swansea Bay (320MW) scheme.

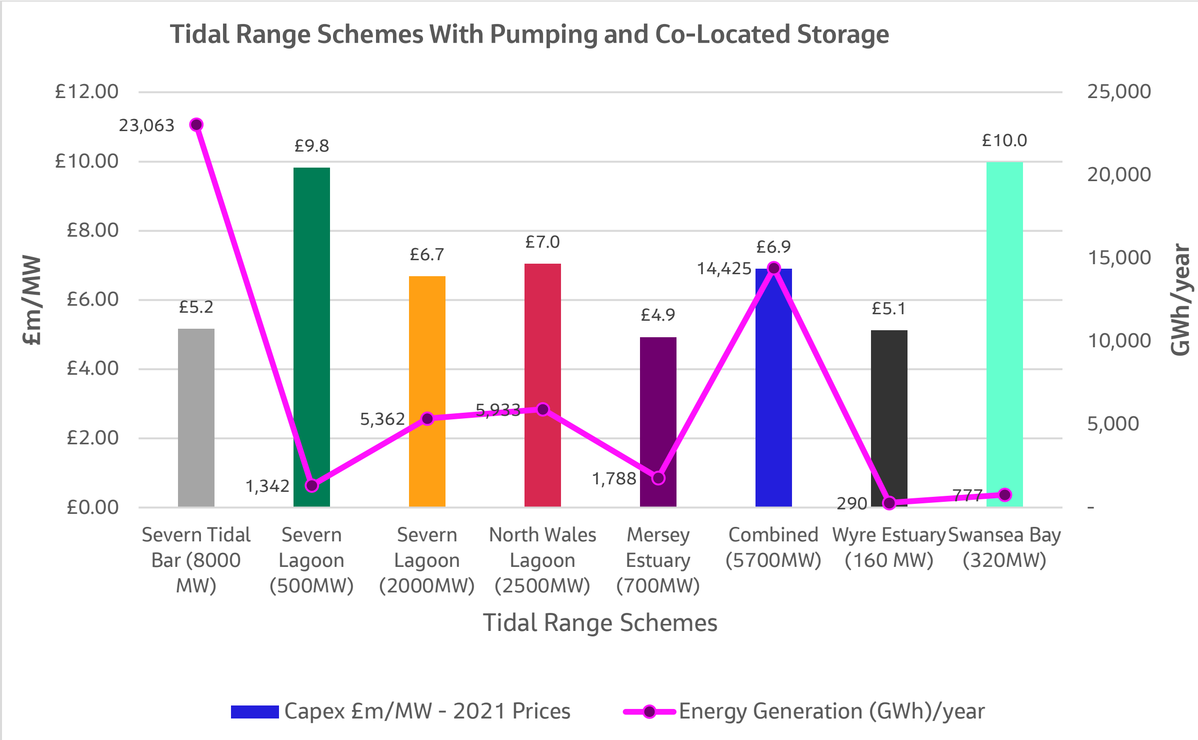

Figure 6-9 Tidal Range With Pumping Co-Located Storage Schemes - Capex (£/MW 2021 Prices) and Energy Generation (GWh/year)

6.4.3.2.1 Co – Located Storage: LCoE Results

Figure 6-10 presents the LCoE (£/MWh) for the commercial pilot, FOAK and NOAK tidal range schemes in 2021 prices. Our analysis demonstrates that across tidal range schemes, the LCoE ranges from £260-£594 £/MWh at commercial pilot, £168-£381 £/MWh at FOAK and £145-£328 £/MWh at NOAK stages.
The higher LCoE relative to the no energy storage scheme arrangement (Section 6.4.3.1) is mainly associated with an increase in energy storage requirements and associated infrastructure.

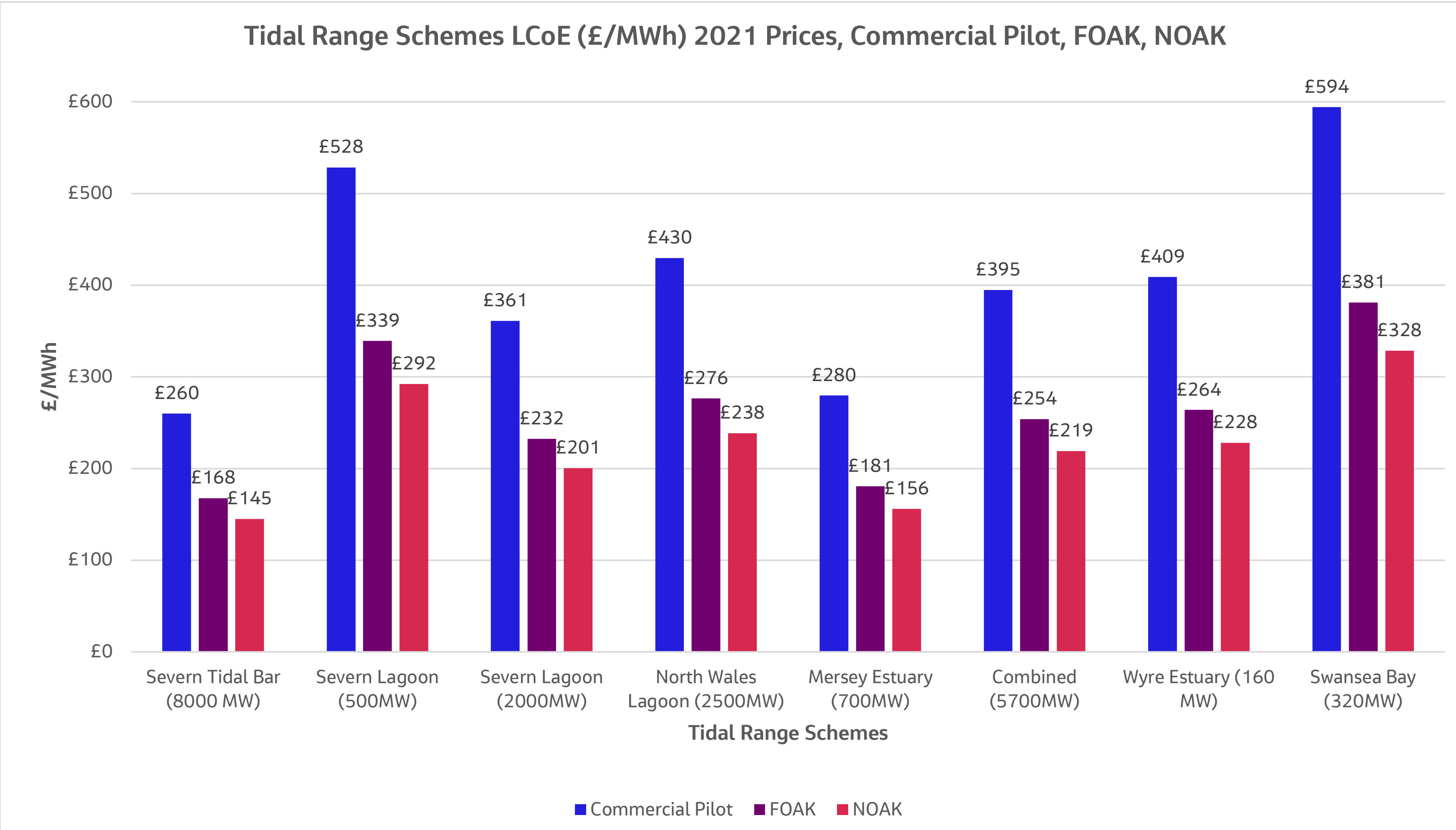

Figure 6-10 LCoE: Co-Located Storage with Pumping (2021 Prices) – Commercial Pilot. FOAK, NOAK

Source: Jacobs Analysis, hurdle rate at 9.4%, 6.3% and 5.4% for Commercial Pilot, FOAK, NOAK

6.4.3.3 Grid Balancing Storage with Pumping

Energy generation, capital and operational costs have been derived for the grid balancing storage with pumping schemes. This scenario utilises integrated grid-based energy system storage from other intermittent renewables such as wind and solar, with that of tidal. The figures within Table 6-13 should not be compared directly with other technology LCoE as such technologies do not account for storage.

For further details on the specific cost components across tidal range schemes, please refer to Appendix A.2.6

Table 6-13 Tidal Range Schemes With Pumping Grid Balancing Storage - Energy Generation and Scheme Costs

Scheme	Energy Generation (GWh)/year	Total Capex (£m)	Capex (£m/MW)	Opex (£/MW/year)	Plant Replacement Costs (£m)*
Severn Tidal Barrage – (8000MW)	27,936	£36,515	£4.6	£57,052	£11,771
Severn Lagoon (500MW)	1,637	£4,426	£8.9	£110,658	£736
Severn Lagoon (2000MW)	6,550	£11,783	£5.9	£73,645	£2,943
North Wales Lagoon (2500MW)	7,173	£16,444	£6.6	£82,222	£3,678
Mersey Estuary (700MW)	2,144	£3,156	£4.5	£56,362	£1,030
Combined (5700MW)	17,504	£35,811	£6.3	£78,531	£8,387
Wyre Estuary (160 MW)	358	£735	£4.6	£57,440	£235
Swansea Bay (320MW)	960	£2,935	£9.2	£114,662	£471
*Plant replacement costs are assumed to be incurred every 40 years.					

Figure 6-11 maps the energy generation against capex costs across tidal range schemes under the grid balancing storage with pumping specification. Consistent with the findings across other tidal scheme arrangements, our analysis shows that the greatest energy outputs can be achieved under the Severn Tidal Bar (8000MW) estimated at 27,936 GWh/year with the smallest energy generation expected under the Wyre Estuary (160MW) at 358 GWh/year.

The lowest capital cost per installed capacity is estimated at £4.5m/MW under the Mersey Estuary (700MW) scheme with the highest capital costs generated under the Swansea Bay (320MW) scheme, estimated at £9.2m/MW.

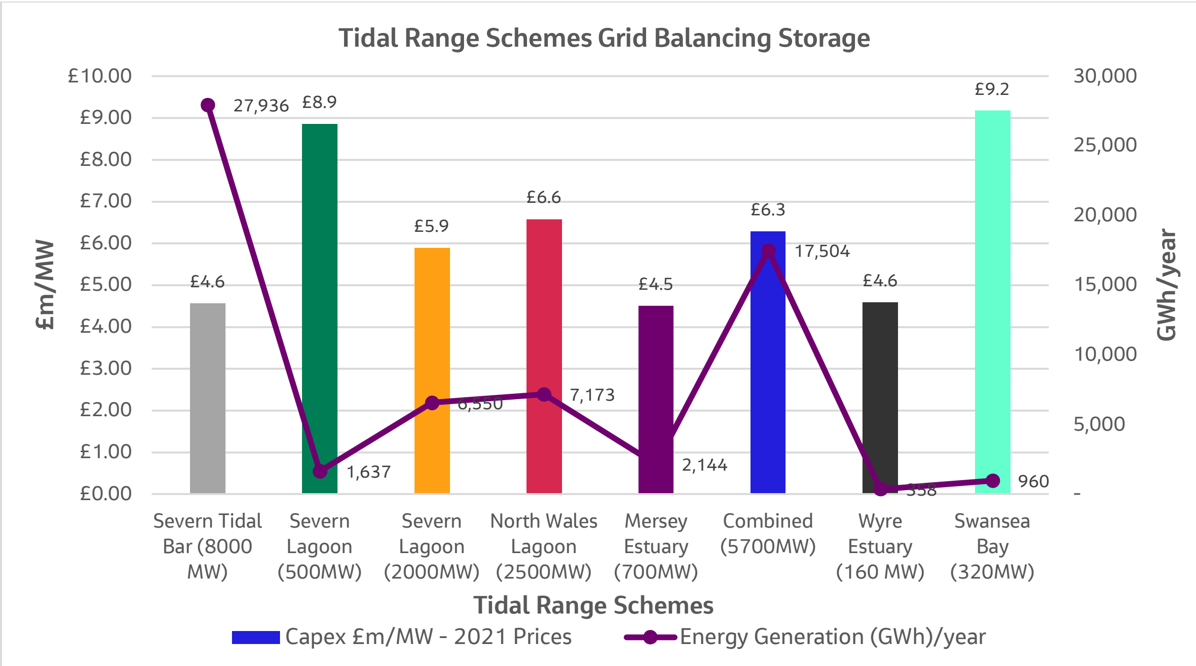

Figure 6-11 Tidal Range With Pumping Grid Balancing Storage Schemes - Capex (£/MW 2021 Prices) and Energy Generation (GWh/year)

6.4.3.3.1 Grid Balancing Storage – LCoE Results

The LCoE (£/MWh) for the commercial pilot, FOAK and NOAK tidal range schemes in 2021 prices is outlined in Figure 6-12 analysis demonstrates that across tidal range schemes, the LCoE ranges from £189-£442 £/MWh at commercial pilot, £122-£284 £/MWh at FOAK and £106-£244 £/MWh at NOAK stages.

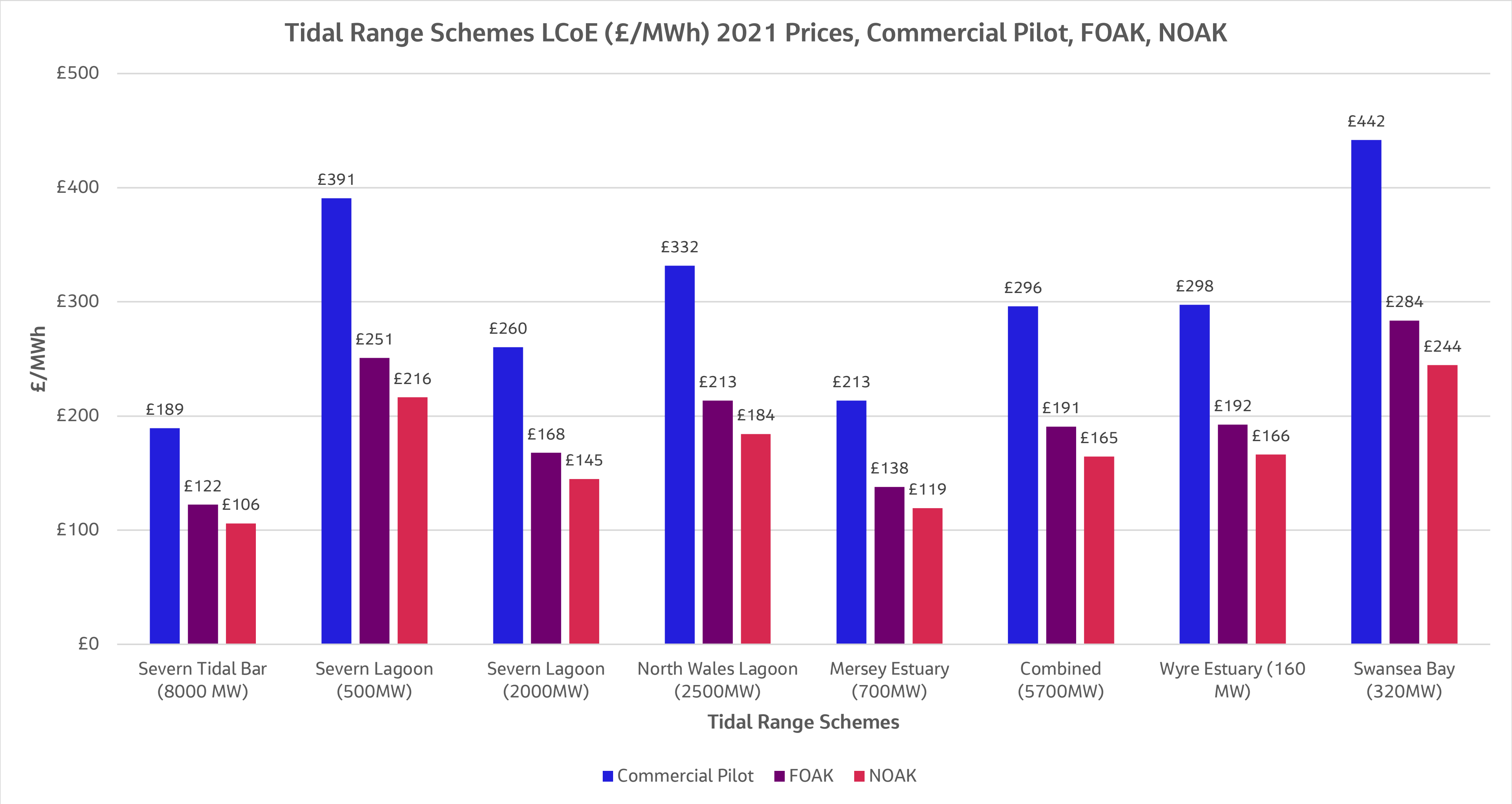

Figure 6-12 LCoE: Grid Balancing Storage with Pumping (2021 Prices) – Commercial Pilot. FOAK, NOAK
Source: Jacobs Analysis, hurdle rate at 9.4%, 6.3% and 5.4% for Commercial Pilot, FOAK, NOAK

6.4.4 Enhanced Tidal Turbine Technologies Summary

The main conclusions of the enhanced tidal turbine technologies LCoE analysis can be summarised as follows:

- Economies of scale for tidal schemes is evident where the level of construction (which is a function of barrage length) is minimised in proportion to basin area and amount of retained water which maximise the potential energy captured.
- This translates into a lower LCoE compared to tidal range schemes with a longer barrage length that scales up construction costs to reach seabed depths where generation assets can be installed. The area of basin is fundamental to the optimal hold level which maximises the level of retained water and increases the energy generation capability.
- The storage solutions have a higher LCoE than the non-storage solution due to an increase in infrastructure costs. As other technologies do not include storage costs in their assessments, the tidal range figures without storage costs should be used when comparing across technologies.
- The LCoE is very sensitive to the designated hurdle rate and is a critical parameter in evaluating the viability of tidal range in the low carbon generation mix to meet the UK's net zero targets. Higher LCoEs are expected at commercial pilot stage as the lack of technology maturity increases the level of construction and operational risk with investors needing to factor in large contingencies, raising hurdle rates and t increasing the cost of capital.
- When comparing conventional bulb turbines to enhanced turbine technologies across each scenario under a given hurdle rate, enhanced tidal turbines demonstrate a lower LCoE. This is driven by an expected lower caissons costs and higher efficiency levels for VLH turbines which supports lower capex costs and greater load factors. However, given that enhanced tidal turbines are yet to be deployed in their intended operating environment, this conclusion cannot be fully verified as of yet.

6.5 Comparing No Storage with Contracts for Difference

The cost effectiveness of our tidal range schemes can be evaluated through comparing the levelised cost of no storage scenario against the contracts for difference (CfD) values for tidal stream.

The contracts for difference (CfD) scheme was introduced in 2014 and is the UK Government's key framework for assessing the financial viability of low carbon electricity generation. CfDs are a contractual mechanism designed to incentive investment in renewable energy projects at the least cost to the consumer.

Developers are paid a flat indexed rate for the electricity they produce over a defined period; the difference between the 'strike price' (a price for electricity reflecting the cost of investing in a particular low carbon technology) and the 'reference price' (a measure of the average market price for electricity in the GB market).

At the time of writing this report, there have been six CfD rounds. Whilst currently there has been no CfD allocation to tidal range, tidal stream has featured in the latest CfD rounds under the following strike prices:

- Tidal Stream Strike Price CfD Round 5[21] - £198.00 (2012 prices)
- Tidal Stream Administrative Strike Price CfD Round 6 - £261.00 (2012 prices)[22]

The administrative strike price is the maximum strike price applicable to a technology under a CfD allocation round. Allocation Round 6 is due to open in March 2024. At the time of writing, the latest guidance indicates that tidal stream has a hurdle rate of 9.4%[23], in line with our assumptions for a VLH commercial pilot.

For comparative purposes, the following sub-sections therefore analyse the LCOE of conventional and enhanced tidal turbines against the tidal stream CfD strike prices at commercial pilot stage only.

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[21] DESNZ (2023) Contracts for Difference Allocation Round 5 Results

[22] DESNZ (2023): Contracts for Difference: Administrative Strike Prices for CfD Allocation Round 6

[23] DESNZ (2023) Generation Cost Report, Annex A Additional Estimates and Key Assumptions (updated 16.10.23)

6.5.1 Conventional Bulb Turbine Technologies

Figure 6-13 evaluates the LCoE for conventional bulb turbine technologies under no pumping and no energy storage relative to the CfD Round 5 strike price and CfD Round 6 administrative strike price for tidal stream.

Our analysis demonstrates that the Severn Tidal Bar (8000MW) is the only tidal scheme that is estimated to have a lower LCoE than the current CfD Round 5 and Administrative Strike Price Round 6. The Mersey Estuary (700MW) and Severn Lagoon (2000MW) are expected to have a lower LCOE than the Round 6 Administrative Strike Price. All other tidal range schemes are considered to be of higher cost than the Cfd Round 5 & Round 6 strike prices.

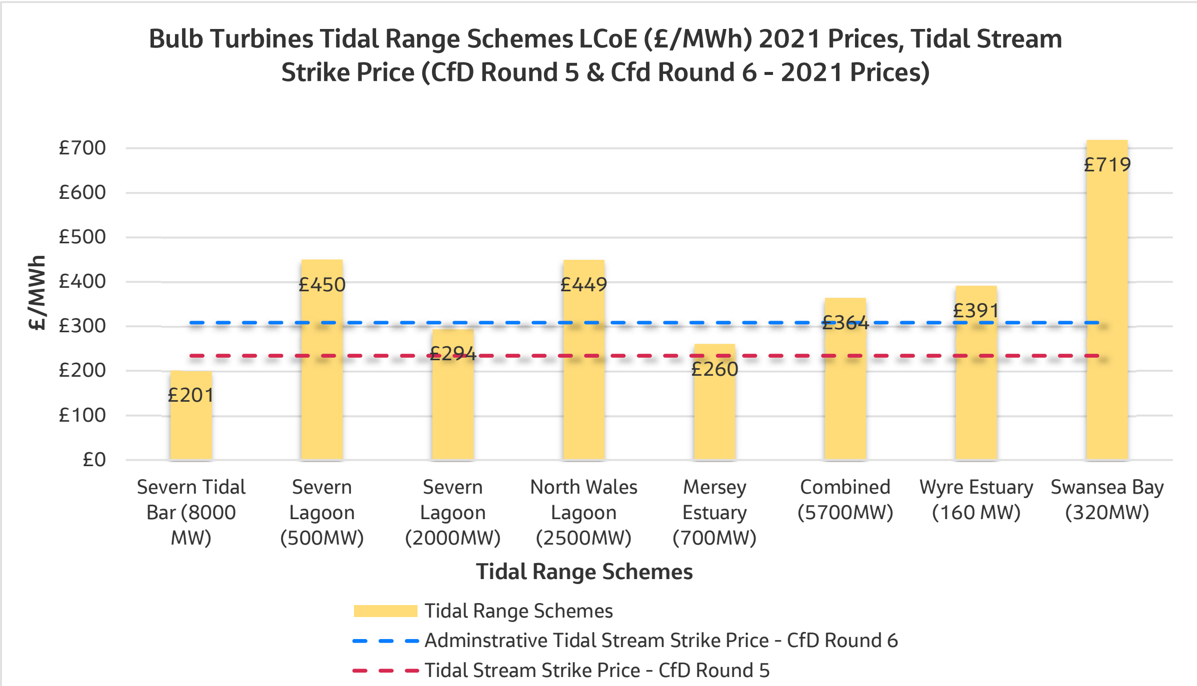

Figure 6-13 Conventional Bulb Turbines Technologies LCoEs & CfD Strike Prices for Commercial Pilot stage
Source: Jacobs Analysis, DESNZ CfD Round 5 & Round 6 Reports, hurdle rate at 9.4%

6.5.2 Enhanced Tidal Range Technologies

Figure 6-14 assesses the LCoE for enhanced tidal range technologies against the CfD Round 5 & CfD Round 6 strike prices under no pumping no energy storage scheme arrangement for VLH turbines. CfD Round 5 & CfD Round 6 prices have been uplifted to 2021 prices for comparative purposes.

Based on our financial analysis, the LCoE for the Mersey Estuary (700MW) and Severn Tidal Bar (8000MW) would be lower than the current CfD Round 5 and Administrative Strike Price Round 6. Our findings also show that the Severn Lagoon (2000MW), the Wyre Estuary (160MW) and Combined 5700MW schemes have a lower LCoE than the CfD Round 6 Administrative Strike Price.

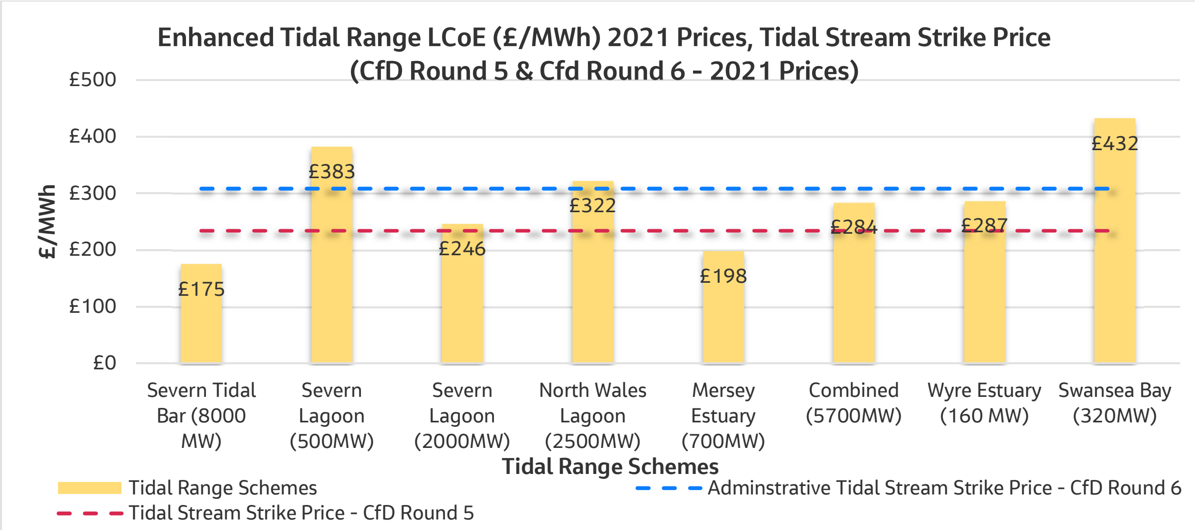

Figure 6-14 Enhanced Tidal Range Technologies LCoEs & CfD Strike Prices for Commercial Pilot stage
Source: Jacobs Analysis, DESNZ CfD Round 5 & Round 6 Reports, hurdle rate at 9.4%

6.5.3 NOAK Projects

On the assumption that enhanced tidal turbines successfully move through the technology readiness framework, reaching full scale deployment with the cost of capital falling hurdle rate of 5.4%, Figure 6-15 below outlines the potential LCoE figures at NOAK stage in relative to the current tidal strike price. Similarly, conventional bulb turbines LCoE are also compared at NOAK stage against tidal stream CfD.

At NOAK stage, our analysis demonstrates that the Severn Tidal Bar (8000MW), Severn Lagoon (2000MW), Mersey Estuary (700MW), Combined (5700MW) and Wyre Estuary (160MW) would have a lower LCoE than the tidal stream CfD strike prices for both the conventional and enhanced tidal turbines.

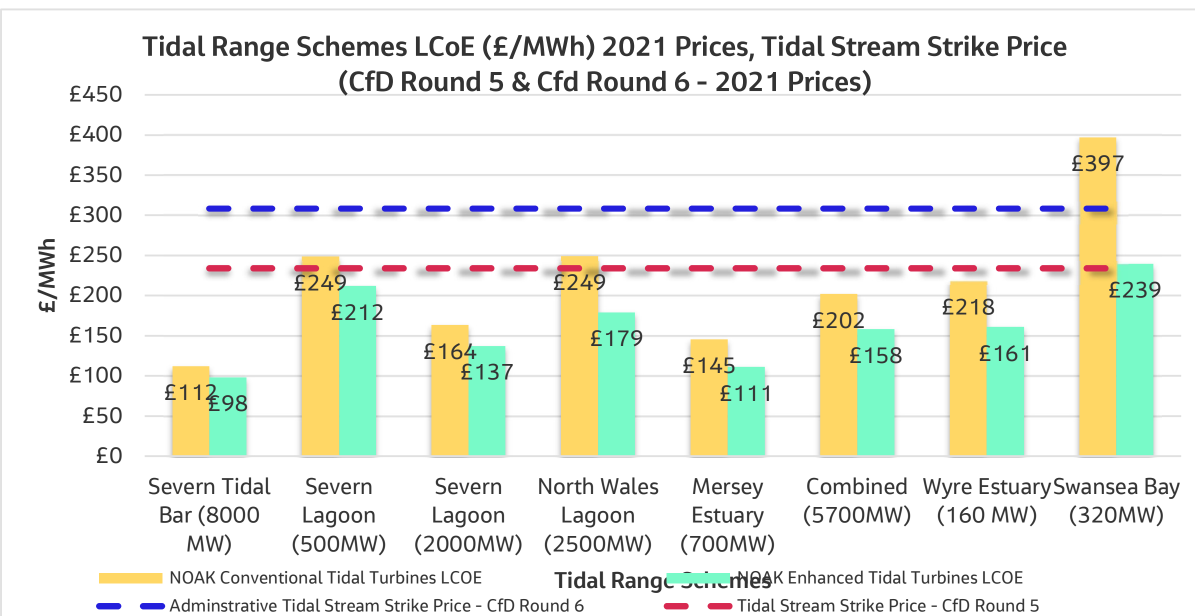

Figure 6-15 Conventional & Enhanced Tidal Range Technologies LCoEs & CfD Strike Prices for Commercial Pilot stage
Source: Jacobs Analysis, Conventional & Enhanced Tidal Range Technologies, hudrle rate 5.4%. DESNZ CfD Round 5 & Round 6 Reports, hurdle rate at 9.4%

6.6 Wider Considerations

6.6.1 Additional Benefits of Tidal Range

Tidal range possesses unique advantages relative to other renewables in terms of its high levels of predictability and operational capability, whilst also providing wider benefits such as coastal protection and habitat mitigation, particularly against sea level rise. Providing coastal protection is particularly important given that only £5.2bn of flood management funding in the UK has been secured between 2021-2027[24], with a 40% cut in the number of properties protected from flooding and 500 of 2,000 new flood defence projects abandoned[25].

Further, the localised nature of potential tidal range schemes reduces the need for extensive grid connections and infrastructure that other renewables such as offshore wind require. Within this context, tidal range generation could support local consumption patterns, increasing grid flexibility and resource utilisation.

These factors are not able to be fully captured within the LCoE, therefore when evaluating tidal range generation contribution to the UK's low carbon generation, it is important to consider both the financial and non-financial aspects of tidal range. A holistic approach can support the development of sustainable, secure and resilient energy systems that utilises renewable generation which considers the long term benefits for both society and the environment in conjunction with the financial feasibility.

[24] Department for Environment, Food & Rural Affairs (2023) – Funding for Flood and Coastal Erosion Risk Management

[25] The Guardian (2023) – 'Flood protection plans for English homes cut by 40%'

7. Comparison with Alternative Generation Options

A comparison of the estimated LCoE of tidal range, as determined under this study, has been made with the LCoE of alternative types of renewable and low-carbon generation, such as tidal range, offshore floating wind and nuclear, based on existing levelised costs published by DESNZ in their Electricity Generation Cost Reports[26], uplifted as necessary to 2021 prices.

7.1 LCoE of Tidal Range Generation

From the foregoing analyses, we have derived a set of tables giving the LCoE for the tidal range schemes investigated under this study, using different hurdle rates depending on whether they are developed as Pilot, FOAK or NOAK schemes, in line with the approach adopted by DESNZ in their Electricity Generation Cost reports. This has enabled the LCoE of tidal range schemes to be compared directly with other generation technologies, using a similar consistent approach.

7.1.1 Tidal Range LCoE – Commercial Pilot

The levelised costs of generation determined for Commercial Pilot tidal range schemes (uplifted to 2021 prices) using a hurdle rate of 9.4%, as recommended by DESNZ for tidal stream projects, assuming conventional bulb turbine technologies, are presented in Figure 7-1 and Table 7-1 below:

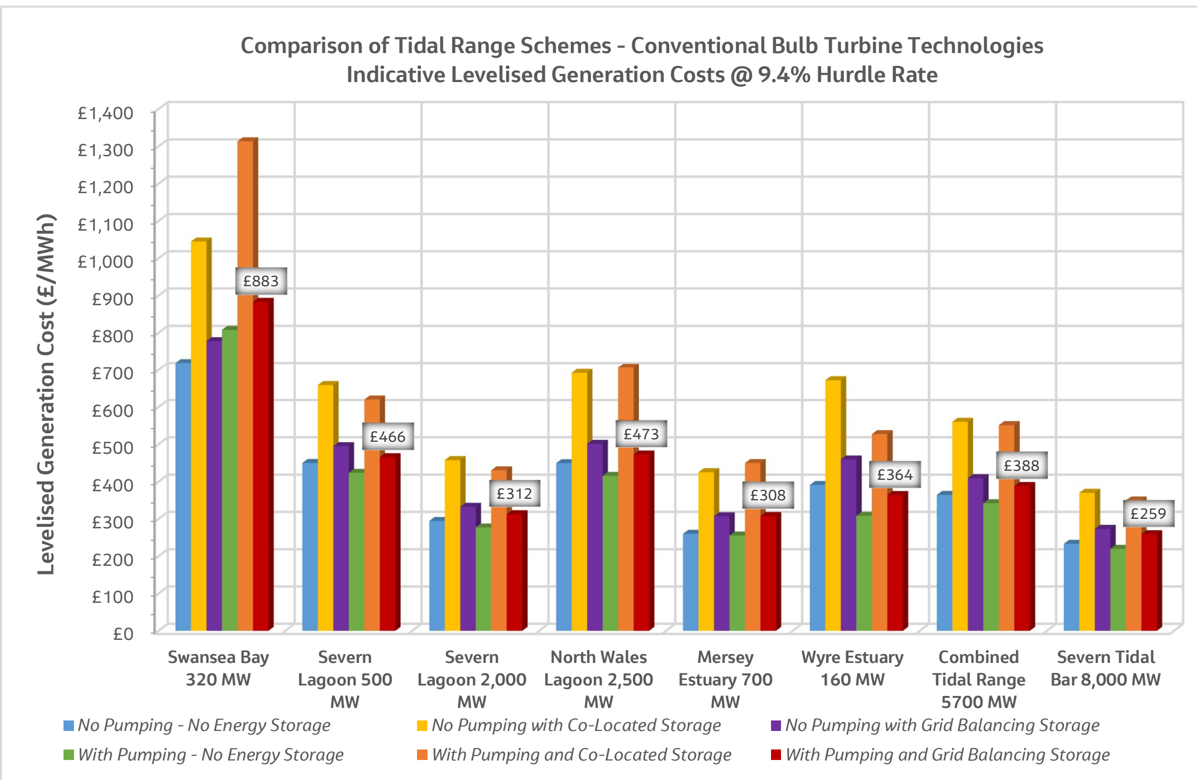

Figure 7-1 Comparison of Tidal Range Pilot Schemes (conventional technologies)

[26] DESNZ/BEIS Electricity Generation Cost Reports 2016, 2021, 2023.

Table 7-1 Conventional Tidal Range Technologies (Commercial Pilot)

LCoE Costs (£/MWh)	Swansea Lagoon 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Estuary Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£719	£450	£294	£449	£260	£391	£364	£233
Co-Located Storage	£1,045	£659	£458	£692	£425	£672	£560	£370
Grid Storage	£778	£495	£332	£501	£307	£459	£409	£273
With Pumping								
No Energy Storage	£808	£424	£277	£415	£255	£308	£342	£220
Co-Located Storage	£1,313	£620	£430	£706	£450	£527	£551	£349
Grid Storage	£883	£466	£312	£473	£308	£364	£388	£259

The levelised costs of generation determined for Commercial Pilot tidal range schemes (uplifted to 2021 prices) using a hurdle rate of 9.4%, as recommended by DESNZ for tidal stream projects, assuming enhanced turbine technologies, are presented in Figure 7-2 and **Error! Not a valid bookmark self-reference.** below:

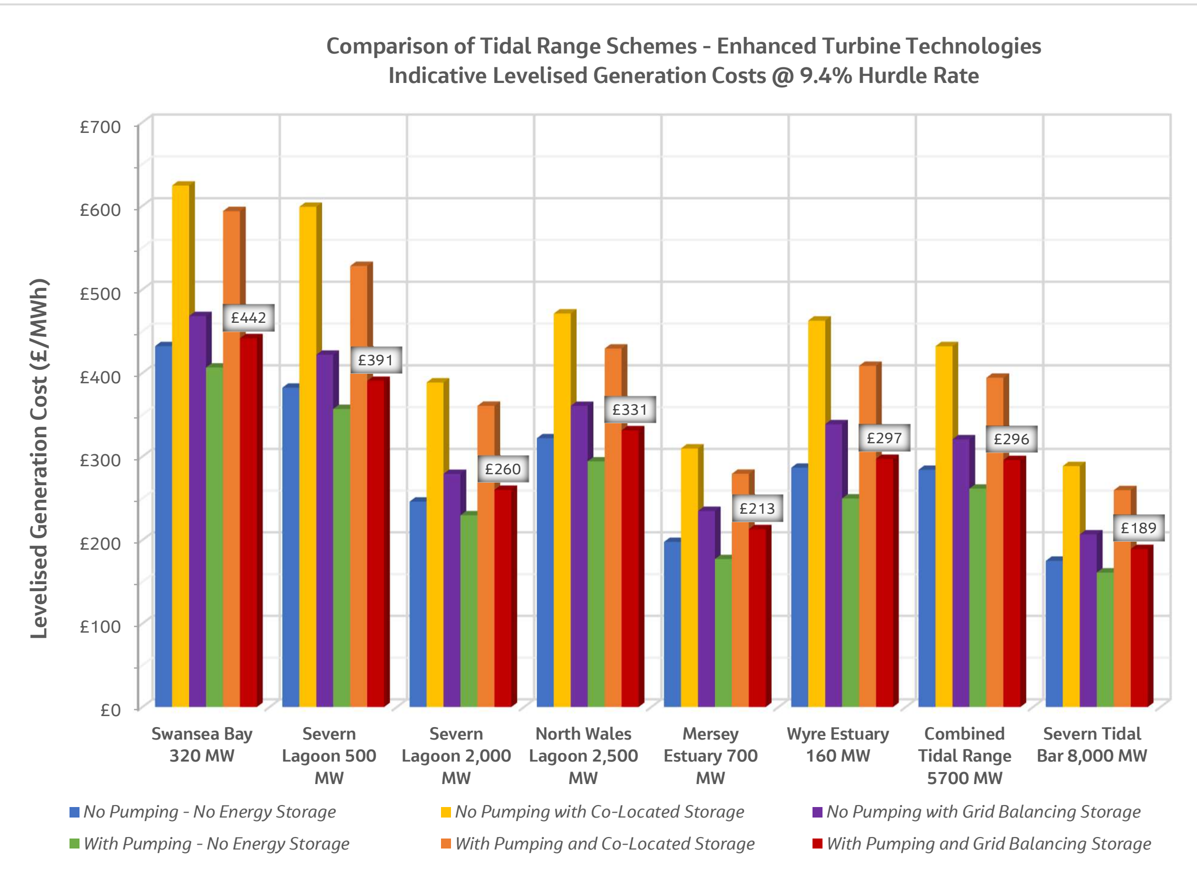

Figure 7-2 Comparison of Tidal Range Pilot Schemes (enhanced technologies)

Table 7-2 LCoE – Enhanced Tidal Range Technologies (Commercial Pilot)

LCoE Costs (£/MWh)	Swansea Lagoon 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Estuary Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£432	£382	£246	£322	£198	£287	£284	£175
Co-Located Storage	£624	£599	£389	£471	£310	£463	£432	£289
Grid Storage	£468	£422	£279	£361	£235	£339	£321	£207
With Pumping								
No Energy Storage	£407	£357	£230	£294	£177	£250	£262	£161
Co-Located Storage	£594	£528	£361	£429	£279	£409	£394	£260
Grid Storage	£442	£391	£260	£331	£213	£297	£296	£189

7.1.2 Tidal Range LCoE – First of a Kind (FOAK)

The levelised costs of generation determined for FOAK tidal ranges schemes, using a hurdle rate of 6.3%, as recommended by DESNZ for large solar deployment, assuming conventional bulb turbine technologies, are shown in Figure 7-3 and Table 7-3 below:

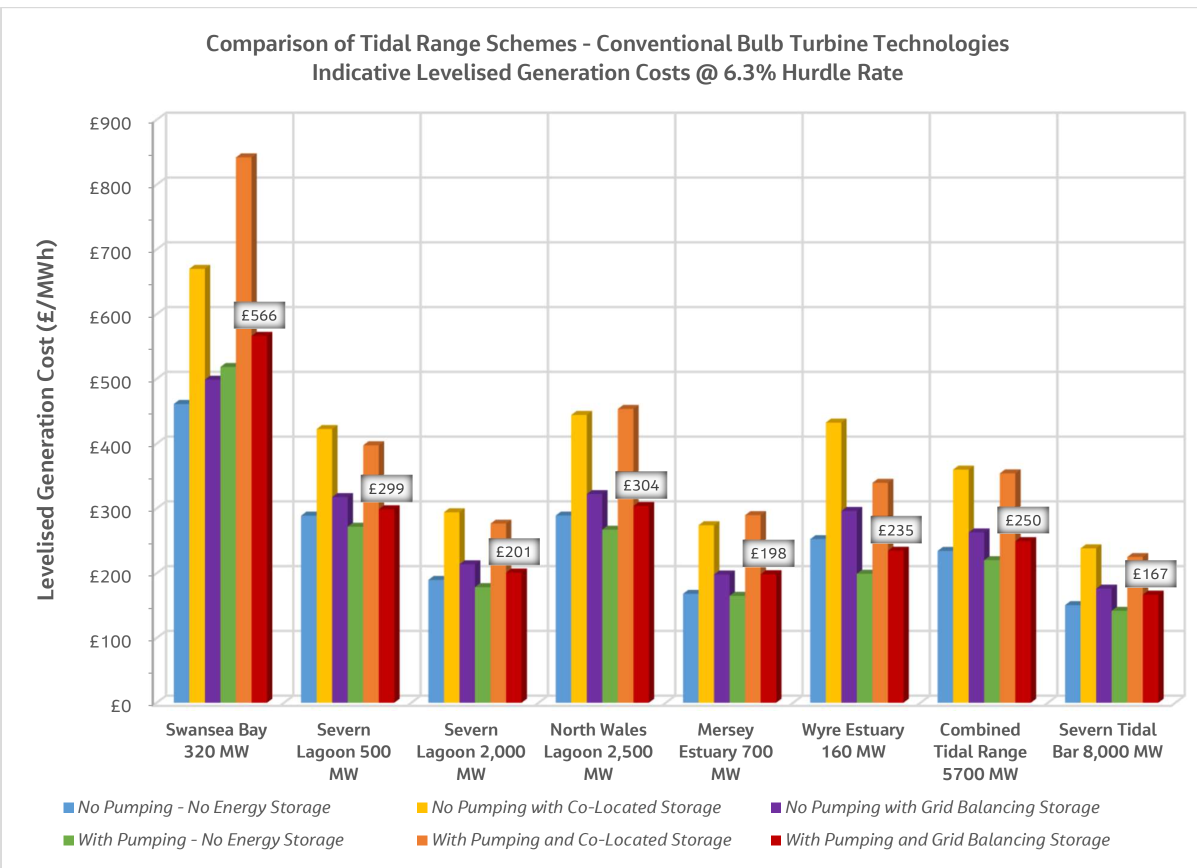

Figure 7-3 Comparison of Tidal Range FOAK Schemes (conventional technologies)

Table 7-3 LCoE – Conventional Tidal Range Technologies (FOAK)

LCoE Costs (£/MWh)	Swansea Lagoon 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Estuary Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£461	£289	£190	£289	£168	£253	£234	£151
Co-Located Storage	£670	£422	£294	£444	£274	£433	£360	£238
Grid Storage	£499	£317	£214	£322	£198	£296	£263	£176
With Pumping								
No Energy Storage	£518	£272	£178	£267	£165	£199	£220	£142
Co-Located Storage	£842	£397	£276	£453	£290	£339	£354	£225
Grid Storage	£566	£299	£201	£304	£198	£235	£250	£167

The levelised costs of generation determined for FOAK tidal ranges schemes, using a hurdle rate of 6.3%, as recommended by DESNZ for large solar deployment, assuming enhanced turbine technologies, are shown in Figure 7-4 and **Error! Not a valid bookmark self-reference.** below:

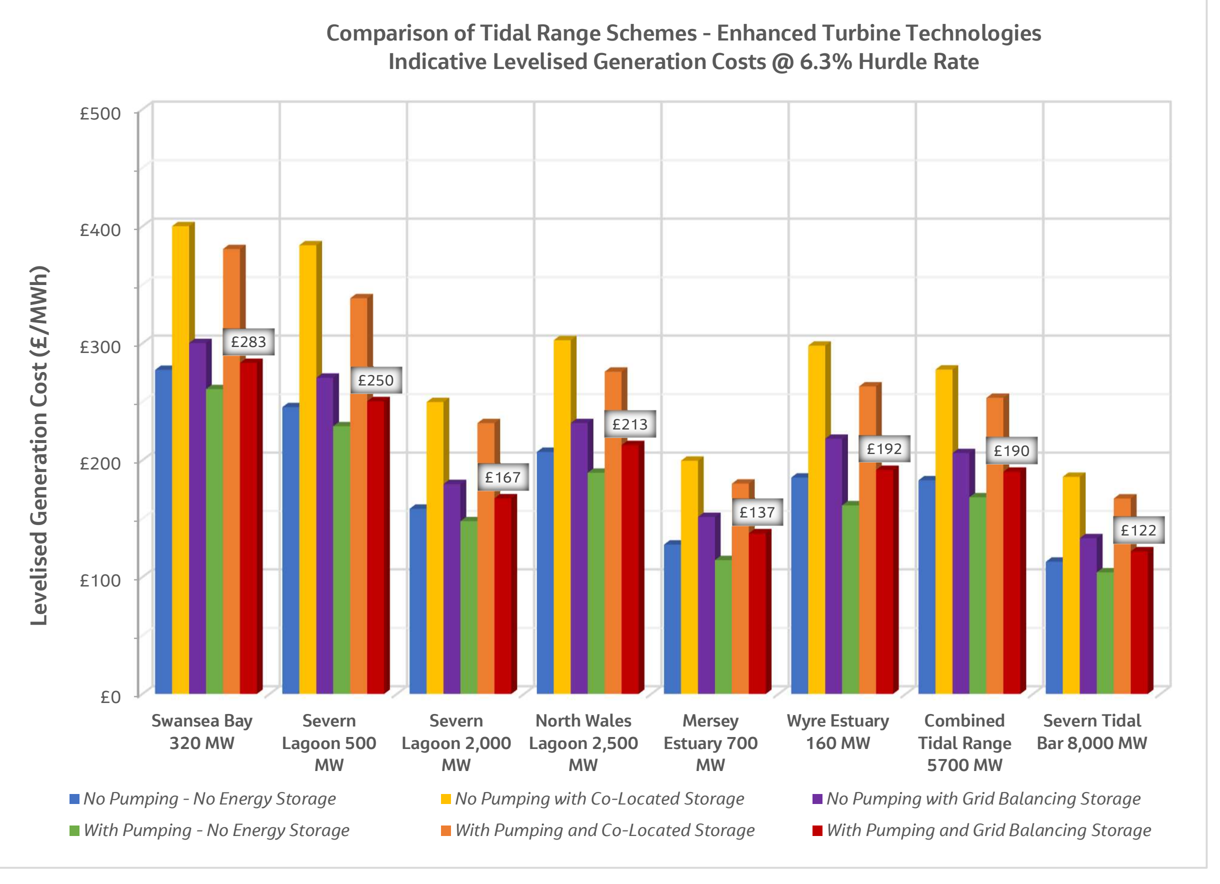

Figure 7-4 Comparison of Tidal Range Pilot FOAK schemes (enhanced technologies)

Table 7-4 LCoE – Enhanced Tidal Range Technologies (FOAK)

LCoE Costs (£/MWh)	Swansea Lagoon 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Estuary Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£277	£245	£158	£207	£128	£185	£183	£113
Co-Located Storage	£400	£384	£250	£303	£200	£298	£278	£186
Grid Storage	£300	£271	£180	£232	£151	£218	£206	£133
With Pumping								
No Energy Storage	£261	£229	£148	£189	£115	£161	£168	£104
Co-Located Storage	£381	£338	£232	£276	£180	£263	£253	£167
Grid Storage	£283	£250	£167	£213	£137	£192	£190	£122

7.1.3 Tidal Range LCoE – Nth of a Kind (NOAK)

The levelised costs of generation determined for NOAK tidal ranges schemes using a hurdle rate of 5.4%, as recommended by DESNZ for large scale hydro, assuming conventional bulb turbine technologies, are presented in Figure 7-5 and Table 7-5 below:

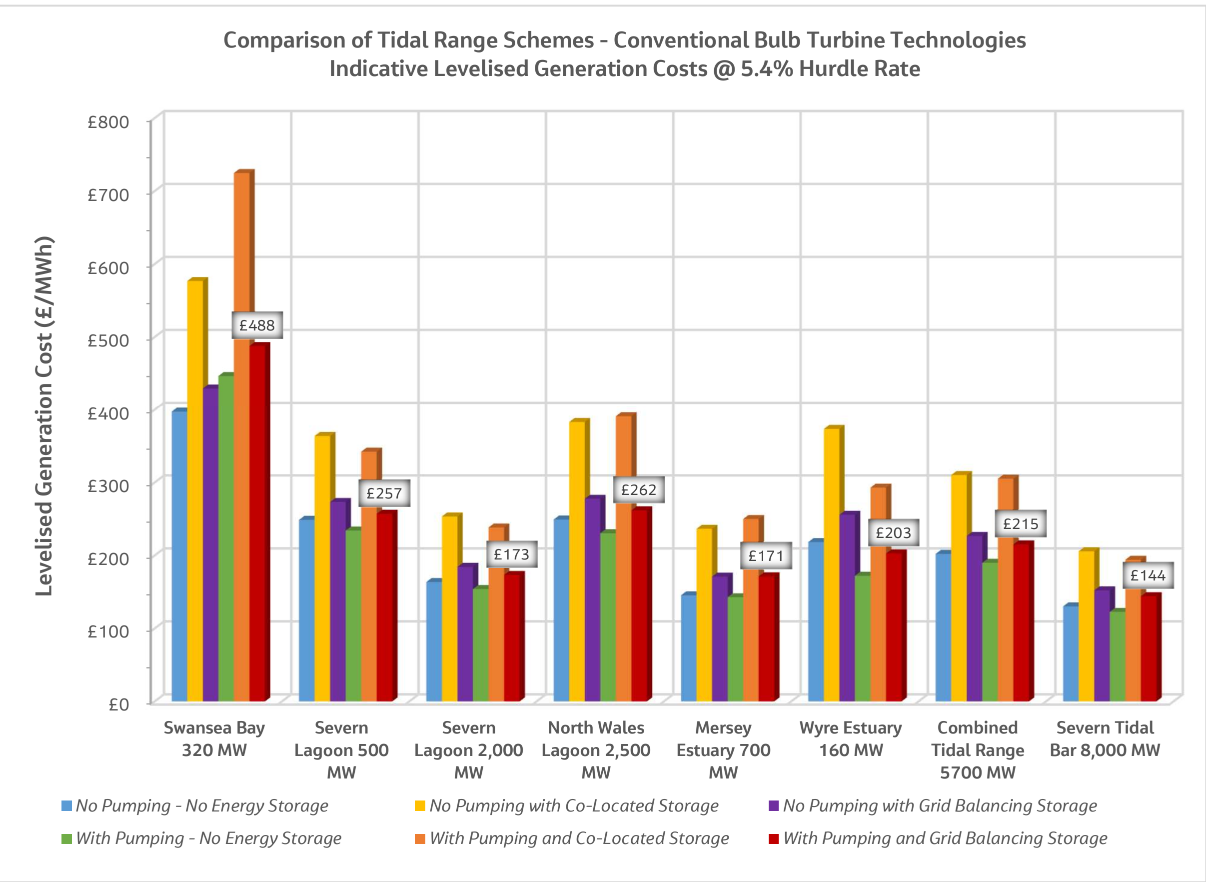

Figure 7-5 Comparison of Tidal Range NOAK Schemes (conventional technologies)

Table 7-5 LCoE – Conventional Tidal Range Technologies (NOAK)

LCoE Costs (£/MWh)	Swansea Lagoon 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Estuary Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£397	£249	£164	£249	£145	£218	£202	£130
Co-Located Storage	£577	£364	£253	£383	£236	£373	£310	£206
Grid Storage	£429	£273	£184	£278	£171	£256	£227	£152
With Pumping								
No Energy Storage	£446	£234	£154	£230	£143	£172	£190	£123
Co-Located Storage	£725	£342	£238	£391	£250	£293	£305	£194
Grid Storage	£488	£257	£173	£262	£171	£203	£215	£144

The levelised costs of generation determined for NOAK tidal ranges schemes using a hurdle rate of 5.4%, as recommended by DESNZ for large scale hydro, assuming enhanced turbine technologies, are presented in Figure 7-6 and **Error! Not a valid bookmark self-reference.** below:

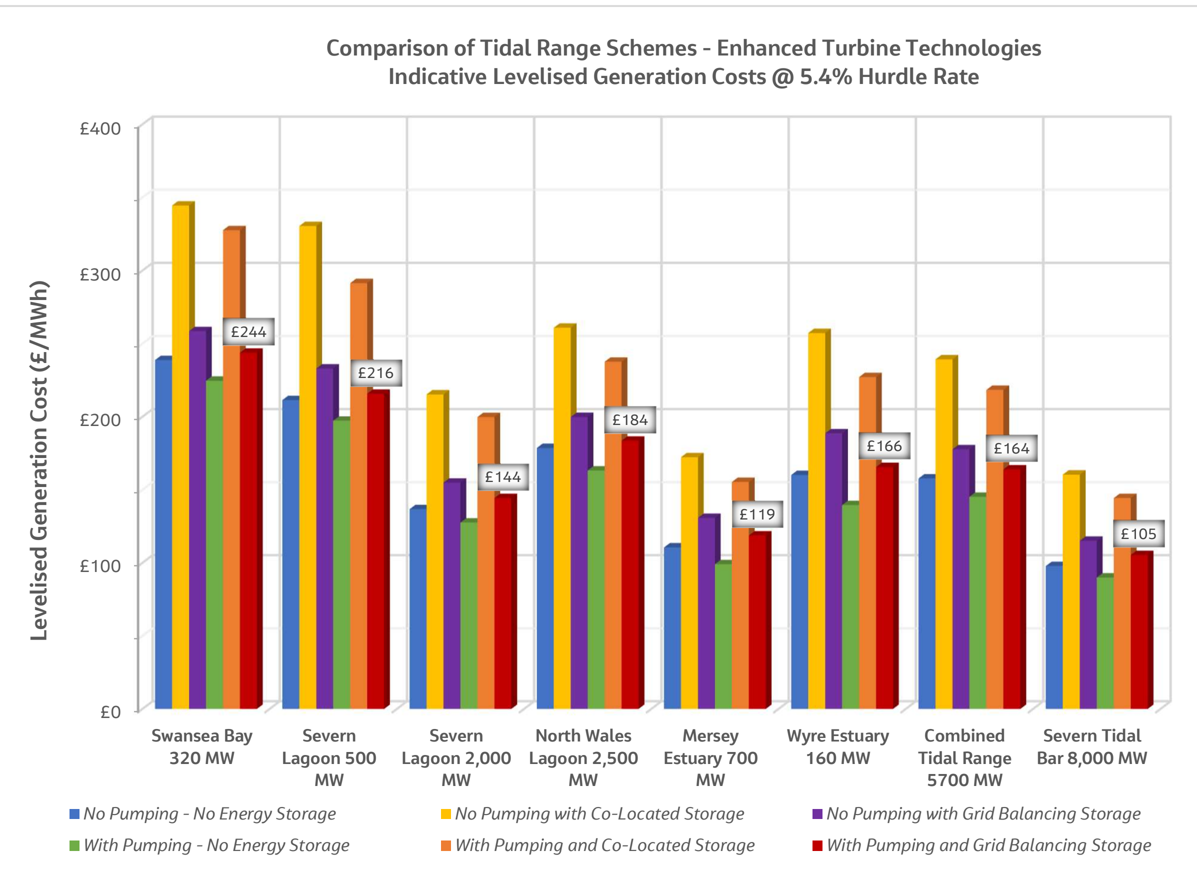

Figure 7-6 Comparison of Tidal Range NOAK Schemes (enhanced technologies)

Table 7-6 LCoE – Enhanced Tidal Range Technologies (NOAK)

LCoE Costs (£/MWh)	Swansea Lagoon 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Estuary Tidal Bar 8,000 MW
No Pumping								
No Energy Storage	£239	£211	£137	£179	£111	£160	£158	£98
Co-Located Storage	£345	£330	£215	£261	£172	£257	£239	£160
Grid Storage	£259	£233	£155	£200	£131	£189	£178	£115
With Pumping								
No Energy Storage	£225	£197	£128	£163	£99	£140	£145	£90
Co-Located Storage	£328	£291	£200	£238	£155	£227	£218	£144
Grid Storage	£244	£216	£144	£184	£119	£166	£164	£105

7.1.4 LCoE Correlation of Tidal Range Schemes with Different Basin Areas

These analyses show there is a distinct correlation between the LCoE of tidal ranges schemes and the area of their estuary/lagoon basin area as shown in Figure 7-7. This can be attributed to the energy output being proportional to the impounded area of the basin and hence its storage volume. This demonstrates that, unlike wind or solar, tidal range schemes exhibit major economies of scale, such that schemes with large basin areas can achieve an LCoE of about half that of schemes with much smaller areas.

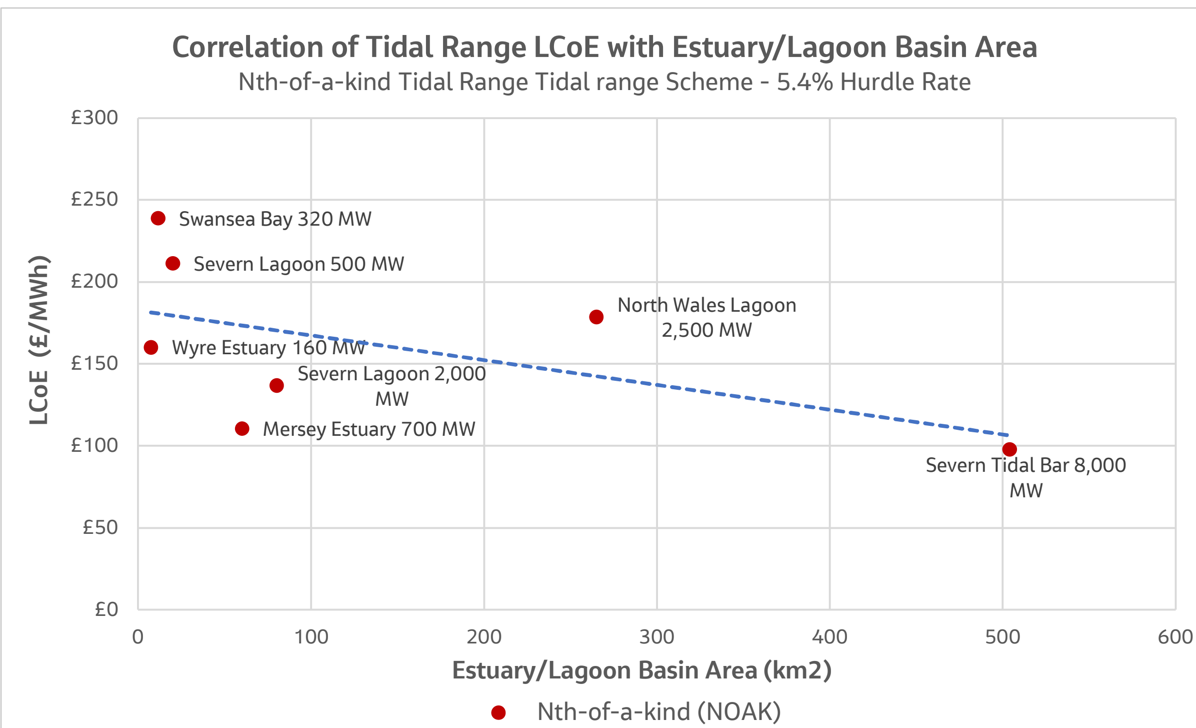

Figure 7-7 Correlation of Tidal Range Schemes with Different Basin Areas

Also note that tidal estuary schemes can also achieve a significantly lower LCoE compared to tidal lagoon schemes, with a similar basin area, due to the longer barrage length needed by lagoon schemes. However, this needs to be weighed up against the potentially greater environmental and other impacts of constructing barrages across major estuaries.

7.2 LCoE of Tidal Stream Generation

The levelised costs of generation for Pilot, FOAK and NOAK tidal stream schemes published in the DESNZ 2023 Generation Costs Report, including transmission TNUoS charges, are presented in Table 7-7.

Table 7-7 Tidal Stream LCoE

Levelised cost breakdown	Units	Demonstrator (Pilot)	First of a Kind (FOAK)	Nth of a Kind (NOAK)
Pre-development costs	£/MWh	£38	£16	£6
Construction costs	£/MWh	£294	£135	£86
Fixed O&M costs	£/MWh	£111	£52	£34
Variable O&M costs	£/MWh	£0	£0	£0
Fuel costs	£/MWh	£0	£0	£0
Carbon costs	£/MWh	£0	£0	£0
CO2 Transport and Storage	£/MWh	£0	£0	£0
Decommissioning and waste	£/MWh	<1	<1	<1
Steam Revenue	£/MWh	£0	£0	£0
Additional Costs	£/MWh	£0	£0	£0
Tidal Stream LCoE	£/MWh	£444	£203	£126
Transmission TNUoS Charges	**Units**	**Northern Scotland**	**Northern Scotland**	**Northern Scotland**
Year-Round Shared Element	£/kW/yr	£20.3	£20.3	£20.3
Load Factor	%	30%	30%	30%
Year-Round Not Shared Element	£/kW/yr	£17.2	£17.2	£17.2
Adjustment Tariff	£/kW/yr	-£0.9	-£0.9	-£0.9
Offshore Substation Tariff	£/kW/yr	£8.4	£8.4	£8.4
Offshore Circuit Tariff	£/kW/yr	£23.0	£23.0	£23.0
Total TNUoS Tariff	£/kW/yr	£53.8	£53.8	£53.8
Transmission TNUoS	£/MWh	£6	£6	£6
Total LCoE (inc. Transmission)	£/MWh	£450	£209	£132

Source: DESNZ Electricity Generation Costs 2023 and ESO TNUoS Tariffs 2023

7.3 LCoE of Floating Offshore Wind Generation

The levelised costs of generation for Pilot, FOAK and NOAK floating offshore wind, published in the DESNZ 2023 Generation Costs Report, including transmission TNUoS charges, are presented in

Table 7-8 below:

Table 7-8 Floating Offshore Wind LCoE

Levelised cost breakdown	Units	Demonstrator (Pilot)	First of a Kind (FOAK)	Nth of a Kind (NOAK)
Pre-development costs	£/MWh	£8	£4	£3
Construction costs	£/MWh	£88	£52	£45
Fixed O&M costs	£/MWh	£23	£19	£16
Variable O&M costs	£/MWh	£0	£0	£0
Fuel costs	£/MWh	£0	£0	£0
Carbon costs	£/MWh	£0	£0	£0
CO2 Transport and Storage	£/MWh	£0	£0	£0
Decommissioning and waste	£/MWh	<1	<1	<1
Steam Revenue	£/MWh	£0	£0	£0
Additional Costs	£/MWh	£0	£0	£0
Offshore Floating Wind LCoE	£/MWh	£119	£76	£64
Transmission TNUoS Charges	**Units**	**Northern Scotland**	**Northern Scotland**	**Northern Scotland**
Year-Round Shared Element	£/kW/yr	£20.3	£20.3	£20.3
Load Factor	%	34%	34%	34%
Year-Round Not Shared Element	£/kW/yr	£17.2	£17.2	£17.2
Adjustment Tariff	£/kW/yr	-£0.9	-£0.9	-£0.9
Offshore Substation Tariff	£/kW/yr	£25.2	£25.2	£25.2
Offshore Circuit Tariff	£/kW/yr	£69.0	£69.0	£69.0
Total TNUoS Tariff	£/kW/yr	£117.4	£117.4	£117.4
Transmission TNUoS	£/MWh	£13	£13	£13
Total LCoE (inc. Transmission)	£/MWh	£132	£89	£77

Source: DESNZ Electricity Generation Costs 2023 and ESO TNUoS Tariffs 2023

7.4 LCoE of Large Scale Nuclear

The most recent levelised cost of energy published by DESNZ (BEIS) was in their 2016 Generation Cost Report (cost base 2014) and thus we have referred to the 2021 Lazards energy generation cost report to provide a more recent estimate for the LCoE of large nuclear. While the LCoE published by both DESNZ and Lazards for 2014 are very similar, according to Lazards, there has been a marked increase in the LCoE between 2014 and 2021, as shown in Figure 7-8 below.

Thus, we have utilised the Lazards 2021 estimate for the LCoE of large nuclear for our generation comparison with other renewables. This increased generation cost for nuclear (2021) is also in line with the recently reported increases in the construction cost for nuclear in the UK.

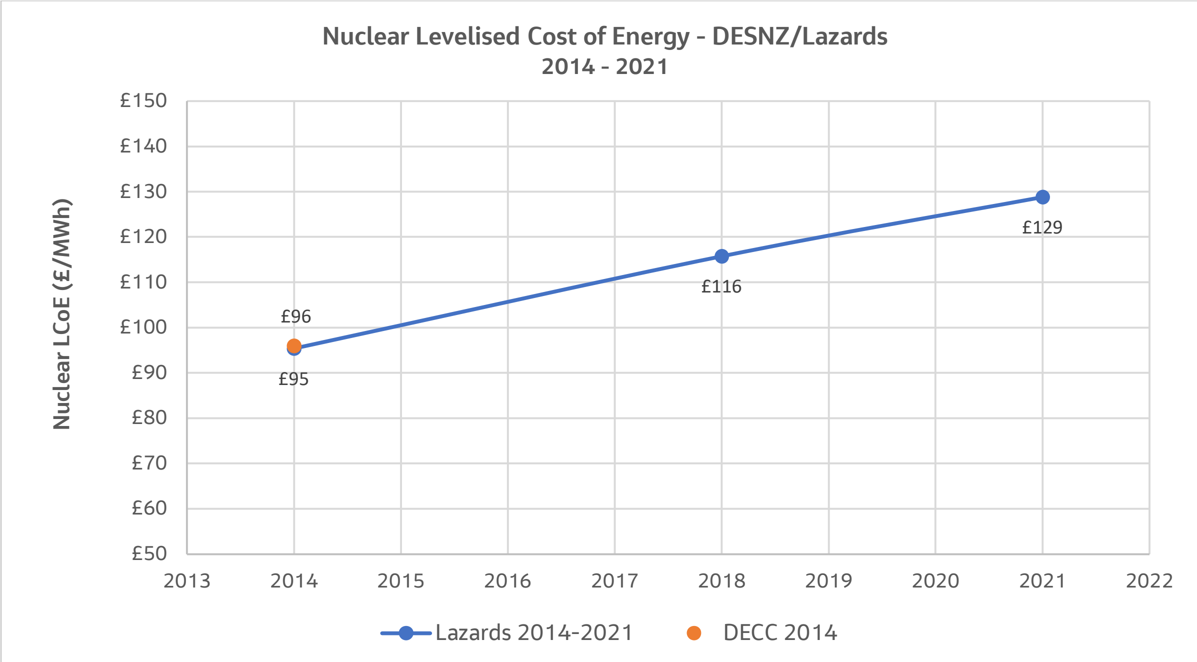

Figure 7-8 Nuclear Levelised Cost of Energy (DESNZ/Lazards)

The levelised costs of generation published in the DECC/BEIS 2016 Generation Costs Report (2014 base date) and more recent levelised costs published by Lazards (2021), including transmission TNUoS charges, are presented in Table 7-9 below.

Table 7-9 Large Scale Nuclear LCoE (DESNZ/Lazards)

Levelised cost breakdown	Units	DECC/BEIS 2014	Lazards – uplifted to 2021
Pre-development costs	£/MWh	£7	£9
Construction costs	£/MWh	£66	£89
Fixed O&M costs	£/MWh	£11	£15
Variable O&M costs	£/MWh	£5	£7
Fuel costs	£/MWh	£5	£7
Carbon costs	£/MWh	£0	£0
CO2 Transport and Storage	£/MWh	£0	£0
Decommissioning and waste	£/MWh	£2	£3
Steam Revenue	£/MWh	£0	£0
Additional Costs	£/MWh	£0	£0
Generation LCoE	£/MWh	£96	£129

Transmission TNUoS Charges	Units	Somerset & Wessex	Somerset & Wessex
Peak Element	£/kW/yr	-£0.8	-£0.8
Year-Round Shared Element	£/kW/yr	-£2.6	-£2.6

Load Factor	%	£0.7	£0.7
Year-Round Not Shared Element	£/kW/yr	£0.0	£0.0
Adjustment Tariff	£/kW/yr	-£0.9	-£0.9
Onshore Substation Tariff	£/kW/yr	£0.3	£0.3
Onshore circuit Tariff	£/kW/yr	£0.0	£0.0
Offshore Substation Tariff	£/kW/yr	£0.0	£0.0
Offshore Circuit Tariff	£/kW/yr	£0.0	£0.0
Total TNUoS Tariff	£/kW/yr	-£3.3	-£3.3
Transmission TNUoS	£/MWh	-£0.4	-£0.4
Total LCoE (inc. Transmission)	£/MWh	£96	£128

7.5 Tidal Range Development Pathway - Excluding Energy Storage

From the foregoing, a set of levelised costs of generation have been presented for a selection of potential tidal range schemes, that have been investigated under this study. We have then attempted to draw up a notional tidal range development pathway comprising a set of projects implemented between 2030 and 2040, under the DESNZ development readiness categories of Pilot, FOAK and NOAK, with associated hurdle rates reflecting technology readiness, for the case with and without energy storage.

This notional development pathway has been drawn up as follows:

- Pilot Development (2030) comprising schemes in the range 100 MW to 500 MW;
- FOAK Development (2035) comprising schemes in the range 500 MW to 2,500 MW;
- NOAK Development (2040) comprising schemes over 2,500 MW.

The LCOE of this notional tidal development pathway has then been compared with the LCoEs of other renewable and low-carbon technologies at a similar DESNZ readiness level, except for nuclear where a fixed LCoE has been assumed, based on the recent Lazards data.

The LCoEs of this notional tidal range development pathway has been compared with other renewable and low-carbon technologies, without energy storage, as set out in in Table 7-10 below.

Table 7-10 LCoE Comparison excluding Energy Storage

Tidal Range - Current Technologies	Hurdle Rate:	9.4%	6.3%	5.4%
Levelised cost breakdown	**Units**	**2030 (Pilot)**	**2035 (FOAK)**	**2040 (NOAK)**
Swansea Bay 320 MW	£/MWh	£719		
Severn Lagoon 500 MW	£/MWh	£424		
Wyre Estuary 160 MW	£/MWh	£308		
Severn Lagoon 2,000 MW	£/MWh		£178	
North Wales Lagoon 2,500 MW	£/MWh		£267	
Mersey Estuary 700 MW	£/MWh		£165	
Severn Tidal Bar 8,000 MW	£/MWh			£123
Mean LCoE	£/MWh	£484	£204	£123

Tidal Range - Enhanced Technologies	Hurdle Rate:	9.4%	6.3%	5.4%
Levelised cost breakdown	Units	2030 (Pilot)	2035 (FOAK)	2040 (NOAK)
Swansea Bay 320 MW	£/MWh	£407		
Severn Lagoon 500 MW	£/MWh	£357		
Wyre Estuary 160 MW	£/MWh	£297		
Severn Lagoon 2,000 MW	£/MWh		£148	
North Wales Lagoon 2,500 MW	£/MWh		£189	
Mersey Estuary 700 MW	£/MWh		£115	
Severn Tidal Bar 8,000 MW	£/MWh			£90
Mean LCoE	£/MWh	£353	£151	£90

LCoE Generation Comparison		Without Energy Storage for Grid Balancing		
Levelised cost breakdown	Units	2030 (Pilot)	2035 (FOAK)	2040 (NOAK)
Tidal Stream (DESNZ)	£/MWh	£450	£209	£132
Tidal Range - Current Technologies	£/MWh	£484	£204	£123
Tidal Range - Enhanced Technologies	£/MWh	£353	£151	£90
Floating Offshore Wind (DESNZ)	£/MWh	£132	£89	£77
Nuclear (DESNZ/Lazards)	£/MWh	£128	£128	£128

This analysis shows that while a Pilot tidal range development by 2030, utilising a hurdle rate of 9.4%, has a similar LCoE to tidal stream generation, the tidal range LCoE reduces noticeably for a First-of-a-kind (FOAK) development by 2035, utilising a hurdle rate of 6.3%, and further still for an Nth-of-a-kind (FOAK) development by 2040, utilising a hurdle rate of 5.4%.

This demonstrates that tidal range has the potential to achieve an LCoE approaching, or even less than, that of nuclear in the longer term.

The LCoE comparison between tidal stream, tidal range, floating offshore wind and nuclear, excluding system balancing costs, is presented in Figure 7-9 below.

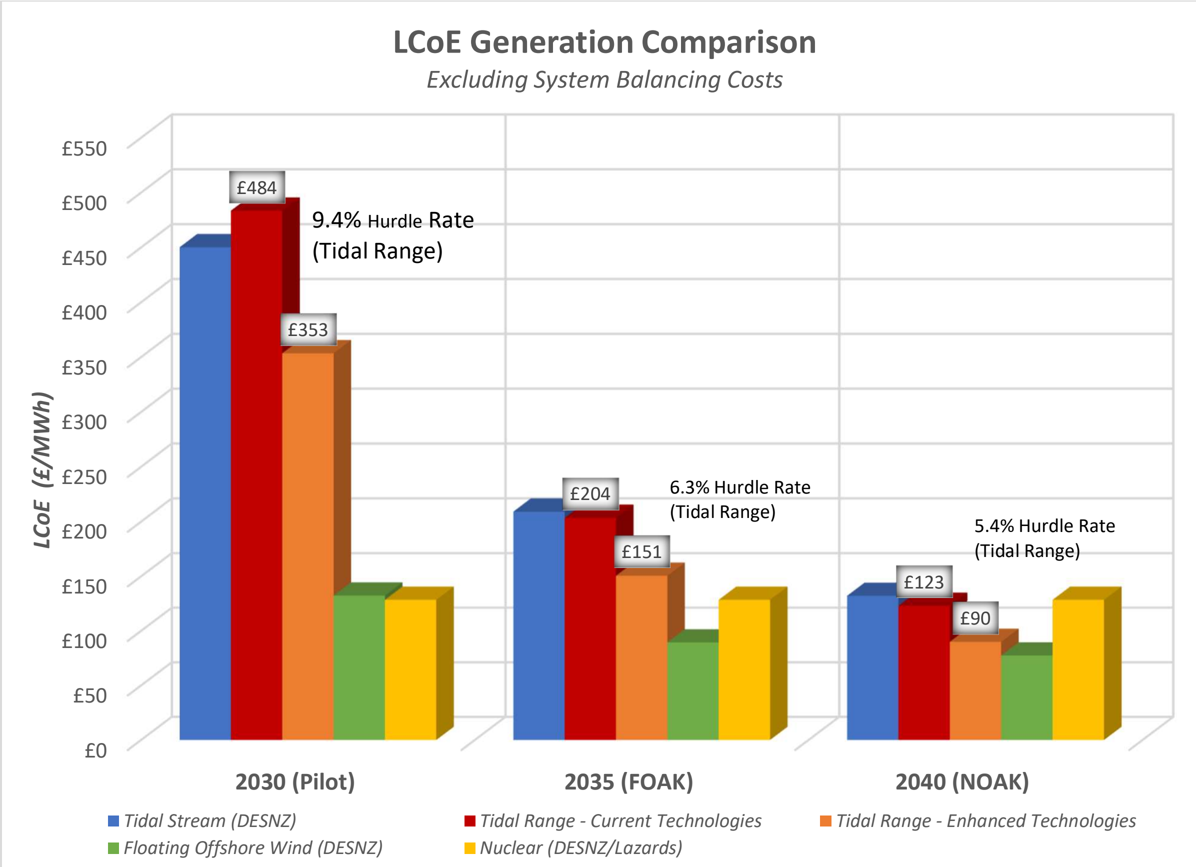

Figure 7-9 LCoE Generation Comparison – Excluding System Balancing Costs

7.6 Tidal Range Development Pathway - Including Energy Storage

A similar LCoE comparison of this notional tidal range development pathway has been carried, but this time for the case including grid-located energy storage for load balancing, as set out in in Table 7-11 below.

Table 7-11 LCoE Comparison including Energy Storage

Tidal Range - Current Technologies	Hurdle Rate:	9.4%	6.3%	5.4%
Levelised cost breakdown	**Units**	**2030 (Pilot)**	**2035 (FOAK)**	**2040 (NOAK)**
Swansea Bay 320 MW	£/MWh	£778		
Severn Lagoon 500 MW	£/MWh	£466		
Wyre Estuary 160 MW	£/MWh	£364		
Severn Lagoon 2,000 MW	£/MWh		£201	
North Wales Lagoon 2,500 MW	£/MWh		£304	
Mersey Estuary 700 MW	£/MWh		£198	
Severn Tidal Bar 8,000 MW	£/MWh			£144
Mean LCoE	£/MWh	£536	£234	£144

Tidal Range - Enhanced Technologies	Hurdle Rate:	9.4%	6.3%	5.4%
Levelised cost breakdown	**Units**	**2030 (Pilot)**	**2035 (FOAK)**	**2040 (NOAK)**
Swansea Bay 320 MW	£/MWh	£442		
Severn Lagoon 500 MW	£/MWh	£391		
Wyre Estuary 160 MW	£/MWh	£297		
Severn Lagoon 2,000 MW	£/MWh		£167	
North Wales Lagoon 2,500 MW	£/MWh		£213	
Mersey Estuary 700 MW	£/MWh		£137	
Severn Tidal Bar 8,000 MW	£/MWh			£105
Mean LCoE	£/MWh	£376	£173	£105

LCoE Energy Storage	Hurdle Rate:	9.4%	6.3%	5.4%
Levelised cost breakdown	**Units**	**2030 (Pilot)**	**2035 (FOAK)**	**2040 (NOAK)**
Tidal Stream	£/MWh	£31.1	£20.6	£18.1
Floating Wind	£/MWh	£30.6	£20.3	£17.8
Nuclear	£/MWh	£0.9	£0.6	£0.5

LCoE Generation Comparison		With Energy Storage for Grid Balancing		
Levelised cost breakdown	**Units**	**2030 (Pilot)**	**2035 (FOAK)**	**2040 (NOAK)**
Tidal Stream (DESNZ)	£/MWh	£481	£230	£150
Tidal Range - Current Technologies	£/MWh	£536	£234	£144
Tidal Range - Enhanced Technologies	£/MWh	£376	£173	£105
Floating Offshore Wind (DESNZ)	£/MWh	£163	£110	£95
Nuclear (DESNZ/Lazards)	£/MWh	£129	£129	£129

The LCoE comparison between tidal stream, tidal range, floating offshore wind and nuclear, including system balancing costs, is presented in Figure 7-100 below.

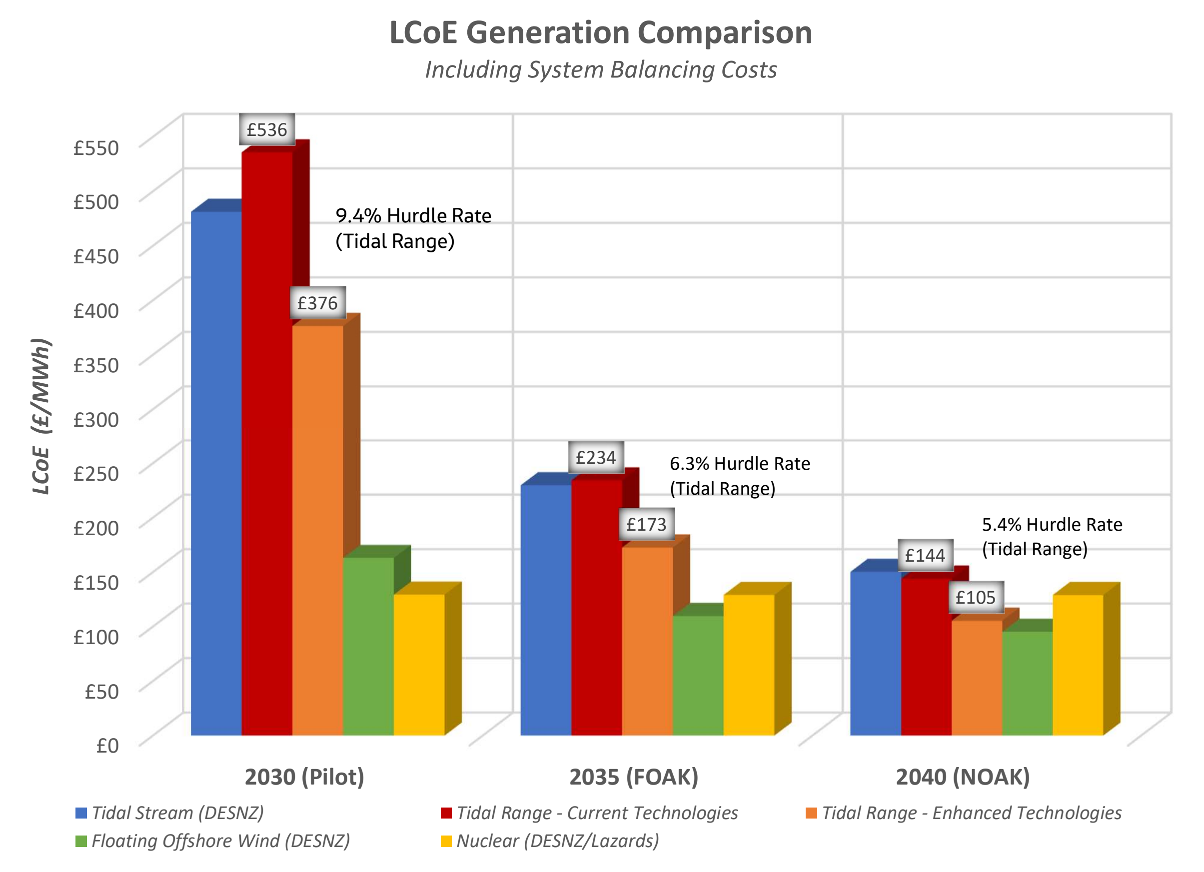

Figure 7-10 LCoE Generation Comparison – Including System Balancing Costs

This shows that tidal range also has the potential to achieve an LCoE approaching, or even less than, that of nuclear in the longer term, for the case including grid-based energy storage for load balancing.

This is an important finding as it demonstrates that tidal range generation, utilising both short duration and long duration grid-based storage, could provide flexible generation to the grid at a competitive cost, not only across the daily tidal cycle, including between spring and neap tides, but also during extended periods when there may be either a surplus or deficit of intermittent renewables generation.

7.7 System LCoE – ESO Future Energy Scenarios 2050

As assessment has also been made of the impact of tidal range on the overall LCoE of the GB power system, based on the forecast generation mix for 2050, as set out in National Grid ESO's latest future energy scenarios (FES 2023), using our in-house GB load dispatch model. For this analysis we have taken the forecast tidal (marine) installed capacity for 2050, as set out in FES 2023, and compared the resulting LCoE for these scenarios (with the forecast tidal capacity in place for 2050), with a variant of these scenarios, assuming this tidal capacity is replaced with the equivalent nuclear generation.

This comparative analysis has been carried out for both the FES Consumer Transformation Scenario, that includes a total tidal (marine) installed capacity of 5,600 MW by 2050, and the FES System Transformation Scenario, that includes a total tidal (marine) installed capacity of 8,250 MW by 2050.

7.7.1 FES Consumer Transformation Scenario – 5,000 MW Tidal Range

Using our in-house generation load dispatch model of the GB power system, we have simulated the FES 2023 Consumer Transformation Scenario to determine the incremental energy storage needed, over a six year period of simulation (2015-2020), for balancing up to 5,000 MW of tidal range capacity. A snap-shot of this simulation, covering the critical period of low wind generation in January 2015, is shown in Figure 7-11 below.

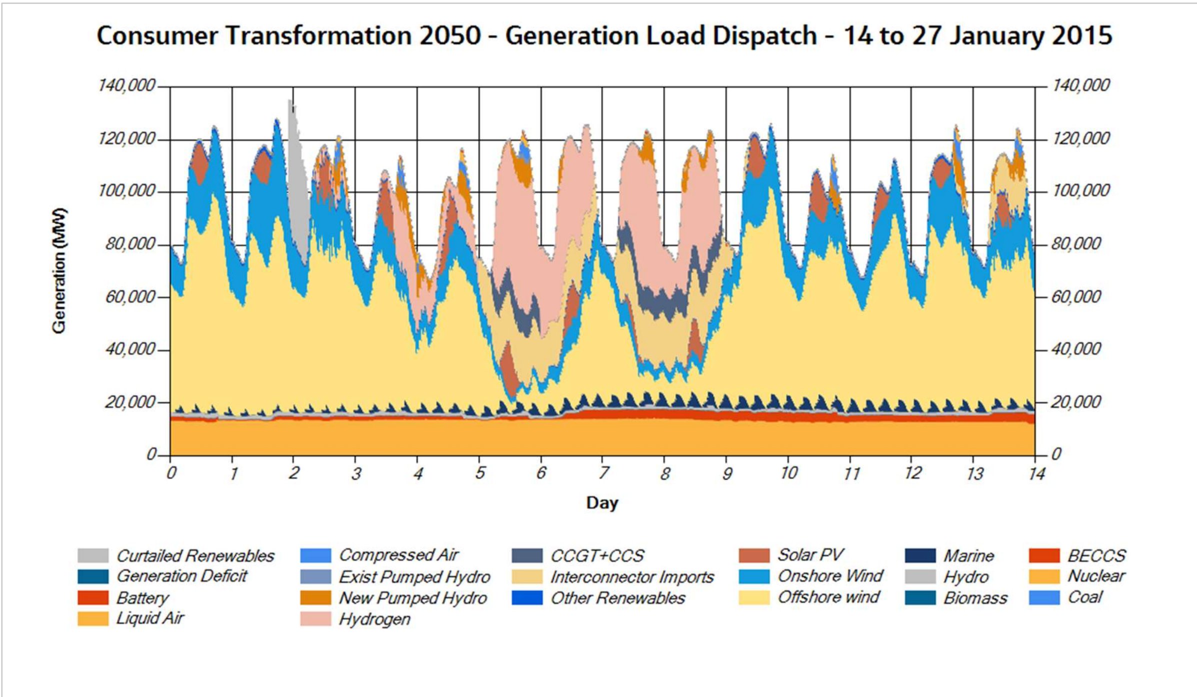

Figure 7-11 Generation Load Dispatch in 2050 – 5,000 MW Tidal Range

The above figure shows how tidal range can assist, by providing more predictable generation over such periods, thus reducing the required energy storage capacity that would otherwise be required for balancing the forecast wind capacity. Note that for this scenario, the tidal range capacity was assumed to made up from tidal lagoon schemes in the Severn Estuary and North Wales totalling 5,000 MW, with the remaining 600 MW made up by tidal stream and/or wave. Note also the generation spread in Figure 7-10, provided by the group of tidal range schemes. From this, the total NPV cost (based on the whole life costs of all generation and energy storage assets for this scenario) together with the NPV of the annual energy generated over the period of simulation (2015-2020), was determined to produce an indicative system LCoE for that scenario.

The generation mix for the FES Consumer Transformation scenario in 2050 is presented in Figure 7-12 below. This show that 2.1% of generation is provided by marine (tidal) generation, with 14.1% provided by nuclear.

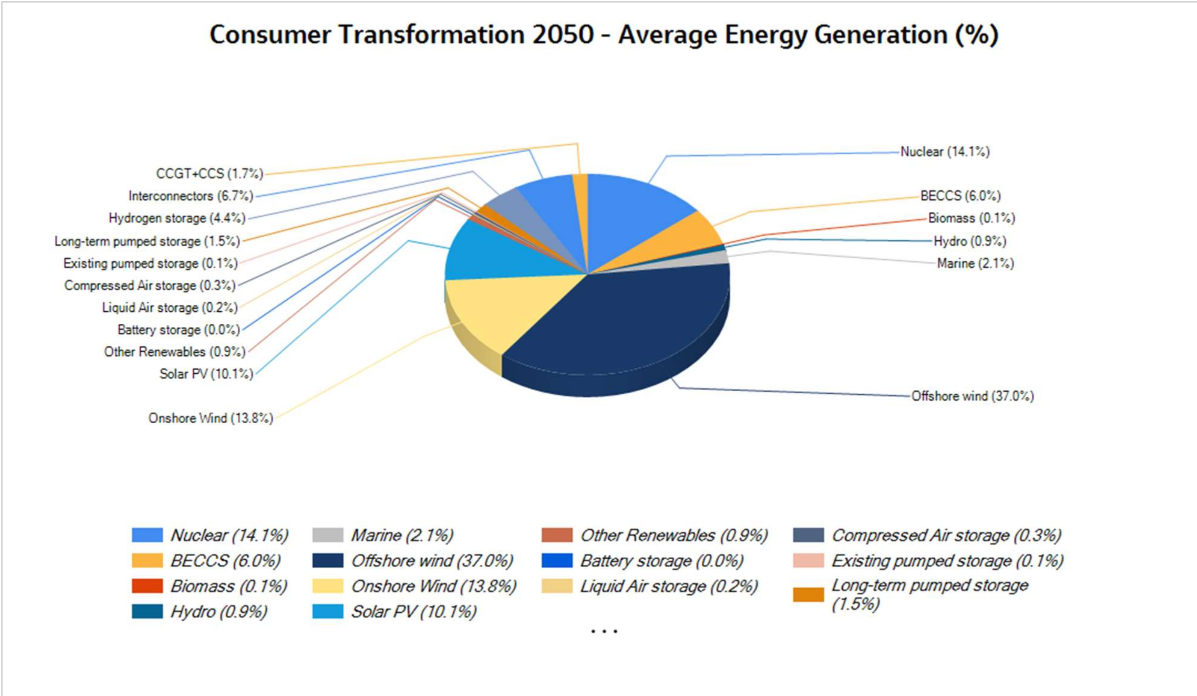

Figure 7-12 Energy Generation Mix in 2050 - 5,700 MW Tidal Range

A similar simulation was then carried out, but this time substituting the original 5,000 MW of tidal generation with an equivalent 2,400 MW of nuclear generation capacity, to derive a system LCoE for each of these configurations, as shown in Table 7-12 below.

Table 7-12 System LCoE - FES 2023 Consumer Transformation Scenario

Year 2050	5,000 MW Tidal Range FOAK		5,000 MW Tidal Range NOAK		2,400 MW Equivalent Nuclear	
Generation Category	NPV Cost (£m)	NPV Energy (GWh)	NPV Cost (£m)	NPV Energy (GWh)	NPV Cost (£m)	NPV Energy (GWh)
Nuclear	£117,967	746,224	£117,967	746,224	£146,782	928,129
BECCS	£130,660	453,906	£130,660	453,906	£130,660	453,906
Hydro	£2,133	23,547	£2,133	23,547	£2,133	23,547
Tidal	£44,216	242,414	£29,707	279,971	£3,086	29,084
Offshore wind	£278,648	3,892,382	£278,648	3,892,382	£278,648	3,884,836
Onshore Wind	£67,807	1,364,084	£67,807	1,364,084	£67,807	1,361,668
Solar PV	£64,862	1,091,179	£64,862	1,091,179	£64,862	1,090,390
Battery Storage	£559	651	£559	651	£559	599
Liquid Air Storage	£6,759	15,258	£6,759	15,258	£6,759	14,127
Compressed Air Storage	£5,175	22,644	£5,175	22,644	£5,175	19,433
Pumped Hydro	£20,490	202,252	£20,490	202,252	£20,490	197,553
Hydrogen Storage	£115,159	435,187	£115,159	435,187	£112,711	445,686

Year 2050	5,000 MW Tidal Range FOAK		5,000 MW Tidal Range NOAK		2,400 MW Equivalent Nuclear	
Interconnectors	£53,016	506,559	£53,016	506,559	£52,535	496,771
CCGT+CCS	£44,456	170,407	£44,456	170,407	£44,164	166,236
Total System	£951,908	9,166,693	£937,399	9,204,250	£936,371	9,111,964
LCoE (£/MWh)		£103.8		£101.8		£102.8

7.7.2 FES System Transformation Scenario – 8,000 MW Tidal Range

A further set of simulations, using our in-house generation load dispatch model, was then carried out for the FES 2023 System Transformation Scenario, but now assuming up to 8,000 MW of tidal range capacity installed, with the remaining 250 MW made up by tidal stream and/or wave. A snap-shot of this simulation, covering the critical period of low wind generation in January 2015, is shown in Figure 7-13 below.

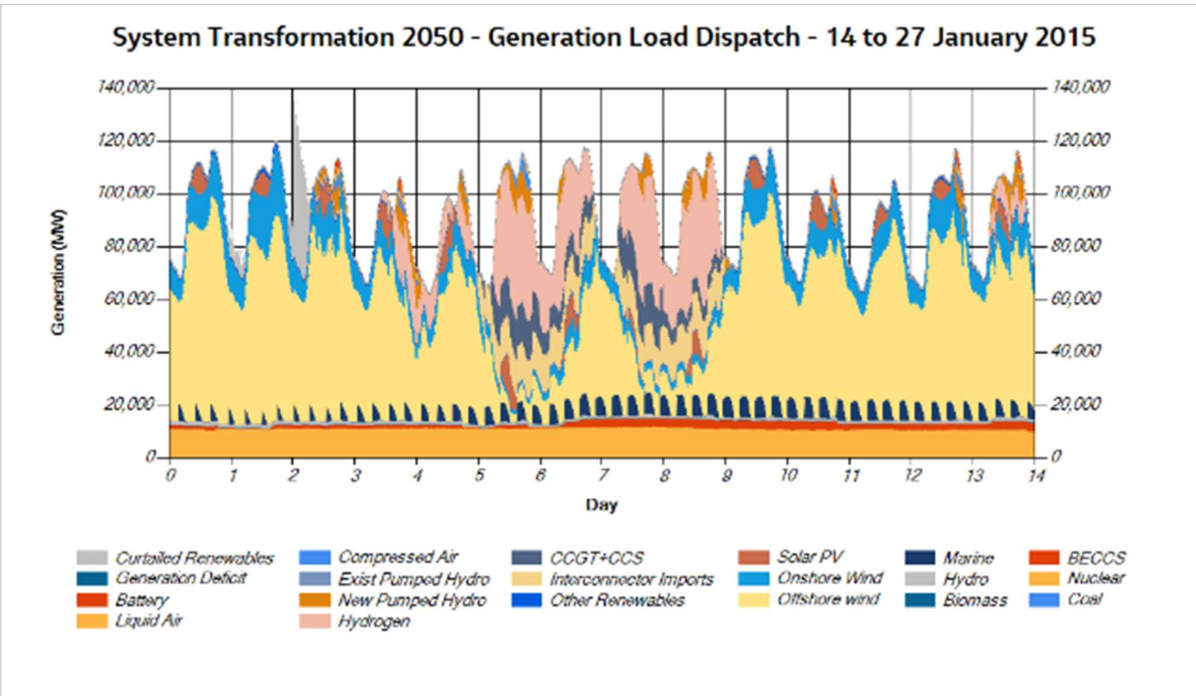

Figure 7-13 Generation Load Dispatch in 2050 – 8,000 MW Tidal Range

The generation mix for the FES System Transformation scenario in 2050 is presented in Figure 7-14 below. This show that 3.7% of generation is provided by marine (tidal) generation, with 12.4% provided by nuclear.

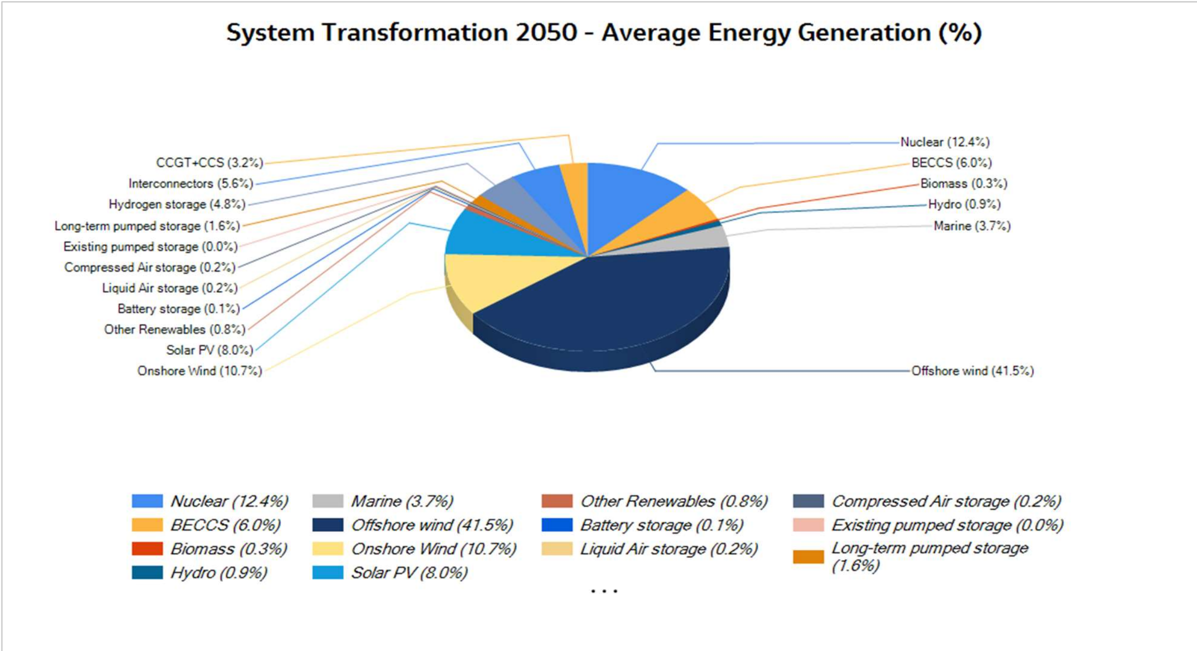

Figure 7-14 Energy Generation Mix in 2050 – 8,000 MW Tidal Range

Note that for this scenario, the tidal range capacity was assumed to be provided by the Severn Estuary Tidal bar (SETB) scheme. Note also the narrower generation spread in Figure 7-12, provided by the SETB scheme. As before, the total NPV cost (based on the whole life costs of all generation and energy storage assets for this scenario) together with the NPV of the annual energy generated over the period of simulation (2015-2020), was then determined to produce an indicative system LCoE for that scenario.

A similar simulation was then carried out, but this time substituting the original 8,000 MW of tidal generation with an equivalent 3,800 MW of nuclear generation capacity, to derive a system LCoE for each of these configurations, as shown in Table 7-13 below.

Table 7-13 System LCoE - FES 2023 System Transformation Scenario

Year 2050	8,000 MW Tidal Range FOAK		8,000 MW Tidal Range NOAK		3,800 MW Equivalent Nuclear	
Generation Category	NPV Cost (£m)	NPV Energy (GWh)	NPV Cost (£m)	NPV Energy (GWh)	NPV Cost (£m)	NPV Energy (GWh)
Nuclear	£84,108	532,053	£84,108	532,053	£129,733	820,484
BECCS	£121,751	422,884	£121,751	422,884	£121,751	422,884
Hydro	£974	10,754	£974	10,754	£974	10,754
Tidal	£65,152	399,594	£43,773	461,502	£1,179	12,436
Offshore wind	£298,834	4,106,094	£298,834	4,106,094	£298,834	4,110,035
Onshore Wind	£42,353	842,369	£42,353	842,369	£42,353	843,188
Solar PV	£43,349	744,735	£43,349	744,735	£43,349	745,625
Battery Storage	£6,005	9,570	£6,005	9,570	£3,021	4,138
Liquid Air Storage	£5,048	12,140	£5,048	12,140	£5,048	10,300

Year 2050	8,000 MW Tidal Range FOAK		8,000 MW Tidal Range NOAK		3,800 MW Equivalent Nuclear	
Compressed Air Storage	£3,882	17,006	£3,882	17,006	£3,882	14,027
Pumped Hydro	£20,113	194,029	£20,113	194,029	£20,113	192,332
Hydrogen Storage	£100,275	436,630	£100,275	436,630	£96,937	434,207
Interconnectors	£37,018	359,406	£37,018	359,406	£37,328	365,711
CCGT+CCS	£75,185	292,479	£75,185	292,479	£75,344	294,752
Total System	£904,048	8,379,743	£882,669	8,441,650	£879,848	8,280,873
LCoE (£/MWh)		£107.9		£104.6		£106.3

7.7.3 Comparison of Overall System LCoE – FES 2023 Scenarios

Indicative LCoEs for the two FES 2023 scenarios analysed (for year 2050), for the cases with the forecast tidal capacity, compared with the equivalent nuclear capacity, are presented in Figure 7-15 below. These are for both the First of a kind (FOAK) and Nth of a kind (NOAK) tidal range developments at their respective hurdle rates, using DESNZ technology specific hurdle rates for the other generation technologies, at a 2021 price base.

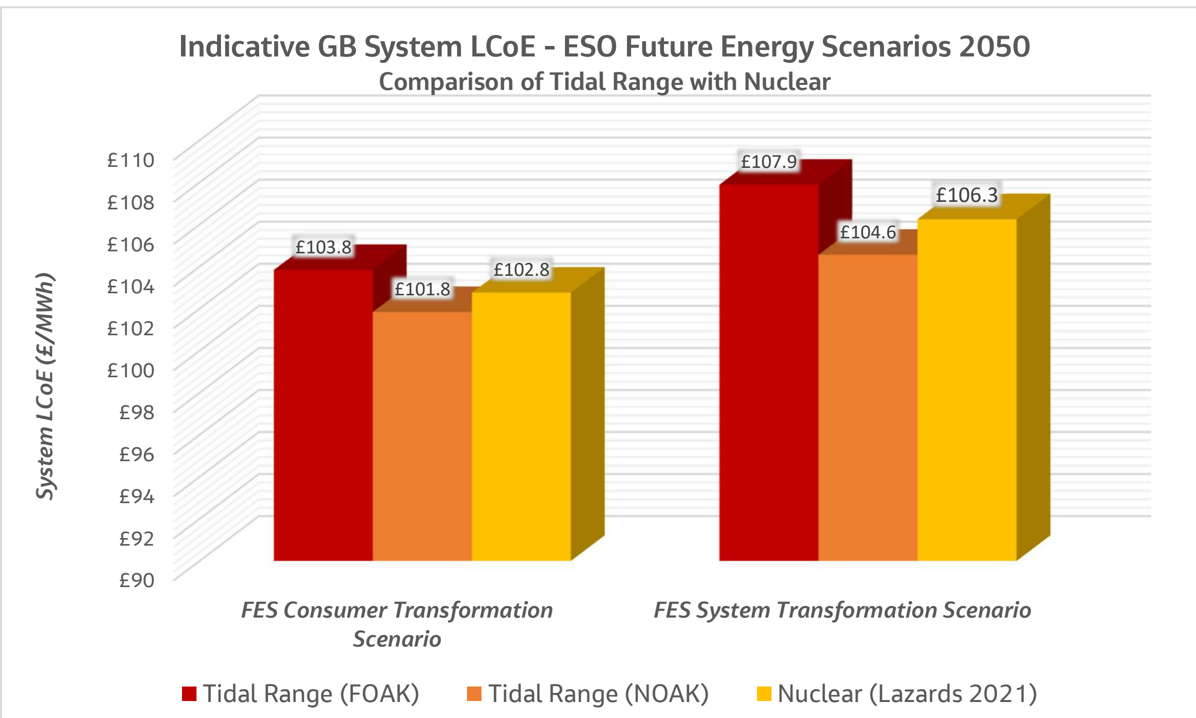

Figure 7-15 Indicative GB System LCoE – FES 2050 Generation Comparison

This figure gives the range of system LCoEs that could be expected with FOAK and NOAK tidal range schemes developed by 2050, compared with the system LCoE with an equivalent capacity of nuclear generation, based on Lazards recent Levelised Cost of Energy Report (2023).

This analysis thus shows that the LCoE for tidal range is thus comparable to that for the equivalent nuclear capacity, for both the Consumer Transformation and System Transformation scenarios, with the LCoE for FOAK tidal range being just higher, and the LCoE for NOAK tidal range being just lower, than that for the equivalent nuclear generation capacity.

8. Summary & Conclusions

8.1 Summary

To summarise, this study has comprised the following:

- Zero-D tidal range power modelling to estimate the potential energy outputs at alternative tidal estuary and tidal lagoon sites, for different modes of tidal operation and for alternative tidal turbine technologies;
- Estimation of the necessary energy storage requirements, comprising both short duration and long duration energy storage, needed to maximise the utilisation of the energy generated by tidal range schemes;
- Development of generic cost functions used for the estimation of high-level capital and operating costs for alternative tidal range sites, on a consistent basis;
- Utilisation of technology specific 'CfD' hurdle rates, as published by DESNZ, to determine the LCoE for the forecast generation mix by 2050 and adopting a sliding scale hurdle rate for tidal range, assuming that pilot tidal range schemes would have a similar hurdle rate as tidal stream and that Nth-of-a-kind (NOAK) tidal range schemes could achieve a similar hurdle rate to that of large hydro;
- Estimation of indicative levelised costs of energy (LCoE) for alternative tidal range sites, including comparison with the LCoE of other renewal and low carbon generation, as well as an assessment of the impact of tidal range on the overall system LCoE based on the forecast generation mix for 2050, as set out in National Grid ESO's latest future energy scenarios (FES 2023);
- Energy system modelling of the GB power system, to estimate the potential contribution of tidal range generation to the overall system, for comparison with other renewal and low carbon generation types, including identification of the required level of energy storage needed for grid load balancing;
- Estimation of the impact that tidal range could have on the overall levelised cost of generation of the GB power system, compared to an equivalent capacity of nuclear generation.

8.2 Conclusions

The conclusions of the study can be summarised as follows:

- Zero-D tidal range modelling is appropriate for the assessment of the long term energy output of tidal range schemes, utilising extended tidal gauge records over several years to take account of the seasonal and annual variation in tidal cycles;
- Energy outputs from the Zero-D model can be validated by calibration with the energy outputs from the outputs of a hydrodynamic 2-D model derived over a common period;
- Optimising 'hold' levels for tidal range schemes (above the minimum turbine operating head) can increase tidal energy output by up to 20%;
- Applying sluicing flows, once the net head across the tidal barrage has reduced to below the minimum turbine head, can increase energy output by a further 10%;
- Introducing pumping, after the 'hold' level has been achieved, can increase energy output still further by up to about another 10%, although pumping may need to be 'capped' to avoid the level in the tidal basin exceeding natural high tide levels;
- Some form of energy storage will be required, not only for balancing the twice daily tidal cycle, but also the longer weekly cycle between spring tides and neap tides. In addition, if pumping is to be utilised, further short-term storage may also be required to avoid placing excessive stress on the grid;
- Energy storage could be applied in two ways, either by introducing co-located energy storage at each tidal range site or by utilising integrated grid storage. Our analyses have shown that as grid-based energy storage can also be used to balance wind and solar, this would require approximately 60% of that required for the equivalent dedicated co-located storage;

- Unlike wind or solar, tidal range schemes exhibit major economies of scale, such that schemes with large basin areas can achieve an LCoE of about half that of schemes with much smaller areas;
- Tidal estuary schemes can also achieve a lower LCoE, compared to tidal lagoon schemes, with a similar basin area, due to the longer barrage length needed for lagoon schemes;
- Based on our findings, there are a number of potential tidal range schemes that are estimated to have a lower levelised cost than the current CfD Round 5 and Administrative Strike Price Round 6 for tidal stream at the commercial pilot hurdle rate;
- These analyses have used DESNZ technology specific hurdle rates, which support traditional financing routes for Contracts-for-Difference (CfD) funded projects
- The LCoE is very sensitive to the designated hurdle rate and is a critical parameter in evaluating the viability of tidal range in the low carbon generation mix to meet the UK's net zero targets. The appropriate hurdle rate should be proportionate to the level of technology readiness and reflective of the project specific risks against alternative renewable investments.
- Relative to other low carbon generation sources, there are significant advantages to tidal range such as its high level of predictability, operational capability and the ability to act as a flood barrier which are not able to be fully captured within the LCOE metric.
- When evaluating tidal range generation contribution to the UK's low carbon generation, it is therefore important to consider both the financial and non-financial aspects of tidal range.
- Tidal Range generation using existing Bulb Turbine technology can achieve an LCoE similar to that of nuclear (for NOAK case) in the long term;
- Using VLH turbines the LCoE can be reduced further below that of nuclear and approaching that of floating offshore wind (for NOAK case) in the long term;
- By adopting a whole system approach, utilising grid connected storage together with demand management measures, it would be possible to provide effectively firm tidal energy generation at an LCoE similar to that of nuclear;
- This demonstrates that Tidal Range has a clear case for inclusion in the overall renewable generation mix needed to achieve the UK's net zero targets.

Appendix A. Supporting Information

A.1 Tidal Range Schemes Detailed Costs – Based on the earlier SETS Report using conventional turbine technology

A.1.1 No Pumping with No Energy Storage

Table A-1 Tidal Range No Pumping No Energy Storage Schemes: Design Specification & Costs (2010 prices, undiscounted)

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Total Installed Capacity (MW)	320	500	2,000	2,500	700	160	5,700	8,000
Number of Units	24	42	168	210	57	12	477	672
Unit Installed Capacity (MW)	13.33	11.90	11.90	11.90	12.28	13.33		11.90
Area of basin (km2)	8.5	20.0	80.0	265.0	60.0	7.4	425.0	504.0
Length of Barrage (km)	9.5	10.9	19.5	34.9	1.7	0.4	67.0	18.5
Number of 40m Power Caissons	8	14	56	70	19	4	159	224
Length of Power Caissons (km)	0.32	0.56	2.24	2.80	0.76	0.16	6.36	8.96
Mean Power Caisson Height (m)	25.0	28.4	29.3	26.0	24.0	25.0		26.0
Power Caisson cost per km (£m/km)	£431	£489	£505	£448	£413	£431		£448
Power Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Power Caisson cost (£m)	£186	£370	£1,526	£1,693	£424	£93	4,012	£5,416
Length of Plain Caissons (km)	9.18	10.34	17.26	32.10	0.94	0.24	61	9.54
Mean Plain Caisson Height (m)	20.0	25.8	24.2	24.0	12.0	20.0		16.0
Plain Caisson cost per km (£m/km)	£61.1	£78.8	£73.9	£73.3	£36.6	£61.1		£49

Tidal Range Levelised Cost of Energy Study

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Plain Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Plain Caisson cost (£m)	£757	£1,100	£1,722	£3,176	£47	£20	£6,044	£629
Navigation Lock (£m)	£100	£100	£200	£200	£200	£50	£700	£2,400
Buildings & site costs (17%)	£174	£261	£574	£844	£112	£27	£1,792	£1,407
Civils Sub Total (£m)	£1,217	£1,831	£4,022	£5,913	£782	£190	£12,549	£9,853
M&E plant unit cost (£m/MW)	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20		£1.20
Estimated M&E cost (£m)	£384	£600	£2,400	£3,000	£840	£192	£6,840	£9,600
Preconstruction cost (£m)	£24	£36	£96	£134	£24	£6	£291	£292
Engineering & Contingency	£480	£729	£1,927	£2,674	£487	£115	£5,817	£5,836
Environmental cost (£m)	£139.9	£210.6	£462.6	£680.0	£90.0	£21.8	£1,443.1	£1,133.1
Total Installed Cost (£m)	£2,245	£3,407	£8,908	£12,401	£2,223	£524	£26,940	£26,713
Installed Cost per MW (£m/MW)	£7.02	£6.81	£4.45	£4.96	£3.18	£3.28	£4.73	£3.34
Construction Period (years)	8	8	8	8	8	8		8
Annual O&M cost (£m/year)	£28	£43	£111	£155	£28	£7	£337	£334
Annual energy output (GWh)	553	1,341	5,365	4,893	1,518	238	13,117	23,583
Load Factor (%)	20%	31%	31%	22%	25%	17%	26%	34%
Project Life (years)	80	80	80	80	80	80		80

A.1.2 No Pumping with Co-Located Storage

Table A-2 Tidal Range No Pumping Co-Located Storage Schemes: Design Specification & Costs (2010 prices, undiscounted)

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Total Installed Capacity (MW)	320	500	2,000	2,500	700	160	5,700	8,000
Number of Units	24	42	168	210	57	12	477	672
Unit Installed Capacity (MW)	13.33	11.90	11.90	11.90	12.28	13.33		11.90
Area of basin (km2)	11.5	20.0	80.0	265.0	60.0	7.4	425.0	504.0
Length of Barrage (km)	9.5	11.2	19.5	34.9	1.7	0.4	67.30	18.5
Number of 40m Power Caissons	8	14	56	70	19	4	159	224
Length of Power Caissons (km)	0.32	0.56	2.24	2.80	0.76	0.16	6.36	8.96
Mean Power Caisson Height (m)	25.0	28.4	29.3	26.0	24.0	25.0		26.0
Power Caisson cost per km (£m/km)	£431	£489	£505	£448	£413	£431		£448
Power Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Power Caisson cost (£m)	£186	£370	£1,526	£1,693	£424	£93	4,012	£5,416
Length of Plain Caissons (km)	9.18	10.64	17.26	32.10	0.94	0.24	61	9.54
Mean Plain Caisson Height (m)	20.0	25.8	24.2	24.0	12.0	20.0		16.0
Plain Caisson cost per km (£m/km)	£61.1	£78.8	£73.9	£73.3	£36.6	£61.1		£49
Plain Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Plain Caisson cost (£m)	£757	£1,132	£1,722	£3,176	£47	£20	£6,076	£629
Navigation Lock (£m)	£100	£100	£200	£200	£200	£50	£700	£2,400
Buildings & site costs (17%)	£174	£267	£574	£844	£112	£27	£1,797	£1,407

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Civils Sub Total (£m)	£1,217	£1,868	£4,022	£5,913	£782	£190	£12,586	£9,853
Battery storage capacity (MW)	218	318	1,273	1,344	347	106	3,282	5,133
Battery storage requirement (MWh)	872	1,272	5,092	5,376	1,388	424	13,128	20,532
Hydrogen storage capacity (MW)	82	163	654	739	217	38	1,773	2,602
Hydrogen storage requirement (MWh)	7,872	15,648	62,784	70,944	20,832	3,648	170,208	249,792
Total Energy Storage costs (£m)	£352	£566	£2,269	£2,454	£665	£169	£5,955	£9,107
M&E plant unit cost (£m/MW)	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20		£1.20
Estimated M&E cost (£m)	£384	£600	£2,400	£3,000	£840	£192	£6,840	£9,600
Preconstruction cost (£m)	£24	£37	£96	£134	£24	£6	£291	£292
Engineering & Contingency	£480	£740	£1,927	£2,674	£487	£115	£5,828	£5,836
Environmental cost (£m)	£139.9	£214.9	£462.6	£680.0	£90.0	£21.8	£1,447.4	£1,133.1
Total Installed Cost (£m)	£2,597	£4,027	£11,177	£14,855	£2,889	£693	£32,948	£35,821
Installed Cost per MW (£m/MW)	£8.12	£8.05	£5.59	£5.94	£4.13	£4.33	£5.78	£4.48
Construction Period (years)	8	8	8	8	8	8		8
Annual O&M cost (£m/year)	£32	£50	£140	£186	£36	£9	£412	£448
Annual energy output (GWh)	440	1,082	4,329	3,805	1,205	183	10,421	18,757
Load Factor (%)	16%	25%	25%	17%	20%	13%	21%	27%
Project Life (years)	80	80	80	80	80	80		80

A.1.3 No Pumping with Grid Balancing Storage

Table A-3 Tidal Range No Pumping Grid Balancing Storage Schemes: Design Specification & Costs (2010 prices, undiscounted)

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Total Installed Capacity (MW)	320	500	2,000	2,500	700	160	5,700	8,000
Number of Units	24	42	168	210	57	12	477	672
Unit Installed Capacity (MW)	13.33	11.90	11.90	11.90	12.28	13.33		11.90
Area of basin (km2)	11.5	20.0	80.0	265.0	60.0	7.4	425.0	504.0
Length of Barrage (km)	9.5	11.2	19.5	34.9	1.7	0.4	67.30	18.5
Number of 40m Power Caissons	8	14	56	70	19	4	159	224
Length of Power Caissons (km)	0.32	0.56	2.24	2.80	0.76	0.16	6.36	8.96
Mean Power Caisson Height (m)	25.0	28.4	29.3	26.0	24.0	25.0		26.0
Power Caisson cost per km (£m/km)	£431	£489	£505	£448	£413	£431		£448
Power Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Power Caisson cost (£m)	£186	£370	£1,526	£1,693	£424	£93	4,012	£5,416
Length of Plain Caissons (km)	9.18	10.64	17.26	32.10	0.94	0.24	61	9.54
Mean Plain Caisson Height (m)	20.0	25.8	24.2	24.0	12.0	20.0		16.0
Plain Caisson cost per km (£m/km)	£61.1	£78.8	£73.9	£73.3	£36.6	£61.1		£49
Plain Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Plain Caisson cost (£m)	£757	£1,132	£1,722	£3,176	£47	£20	£6,076	£629
Navigation Lock (£m)	£100	£100	£200	£200	£200	£50	£700	£2,400
Buildings & site costs (17%)	£174	£267	£574	£844	£112	£27	£1,797	£1,407

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Civils Sub Total (£m)	£1,217	£1,868	£4,022	£5,913	£782	£190	£12,586	£9,853
Battery storage capacity (MW)	96	150	600	750	210	48	1,710	2,400
Battery storage requirement (MWh)	384	600	2,400	3,000	840	192	6,840	9,600
Hydrogen storage capacity (MW)	60	94	375	469	131	30	1,069	1,500
Hydrogen storage requirement (MWh)	5,760	9,000	36,000	45,000	12,600	2,880	102,600	144,000
Total Energy Storage costs (£m)	£184	£288	£1,150	£1,438	£403	£92	£3,278	£4,600
M&E plant unit cost (£m/MW)	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20		£1.20
Estimated M&E cost (£m)	£384	£600	£2,400	£3,000	£840	£192	£6,840	£9,600
Preconstruction cost (£m)	£24	£37	£96	£134	£24	£6	£291	£292
Engineering & Contingency	£480	£740	£1,927	£2,674	£487	£115	£5,828	£5,836
Environmental cost (£m)	£139.9	£214.9	£462.6	£680.0	£90.0	£21.8	£1,447.4	£1,133.1
Total Installed Cost (£m)	£2,429	£3,748	£10,058	£13,838	£2,626	£616	£30,270	£31,314
Installed Cost per MW (£m/MW)	£7.59	£7.50	£5.03	£5.54	£3.75	£3.85	£5.31	£3.91
Construction Period (years)	8	8	8	8	8	8		8
Annual O&M cost (£m/year)	£30	£47	£126	£173	£33	£8	£378	£391
Annual energy output (GWh)	553	1,341	5,365	4,893	1,518	238	13,117	23,583
Load Factor (%)	20%	31%	31%	22%	25%	17%	26%	34%
Project Life (years)	80	80	80	80	80	80		80

A.1.4 Pumping with No Energy Storage

Table A-4 Tidal Range Pumping No Energy Storage Schemes: Design Specification & Costs (2010 prices, undiscounted)

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Total Installed Capacity (MW)	320	500	2,000	2,500	700	160	5,700	8,000
Number of Units	24	42	168	210	57	12	477	672
Unit Installed Capacity (MW)	13.33	11.90	11.90	11.90	12.28	13.33		11.90
Area of basin (km2)	11.5	20.0	80.0	265.0	60.0	7.4	425.0	504.0
Length of Barrage (km)	9.5	10.9	19.5	34.9	1.7	0.4	67.0	18.5
Number of 40m Power Caissons	8	14	56	70	19	4	159	224
Length of Power Caissons (km)	0.32	0.56	2.24	2.80	0.76	0.16	6.36	8.96
Mean Power Caisson Height (m)	25.0	28.4	29.3	26.0	24.0	25.0		26.0
Power Caisson cost per km (£m/km)	£431	£489	£505	£448	£413	£431		£448
Power Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Power Caisson cost (£m)	£186	£370	£1,526	£1,693	£424	£93	4,012	£5,416
Length of Plain Caissons (km)	9.18	10.34	17.26	32.10	0.94	0.24	61	9.54
Mean Plain Caisson Height (m)	20.0	25.8	24.2	24.0	12.0	20.0		16.0
Plain Caisson cost per km (£m/km)	£61.1	£78.8	£73.9	£73.3	£36.6	£61.1		£49
Plain Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Plain Caisson cost (£m)	£757	£1,100	£1,722	£3,176	£47	£20	£6,044	£629
Navigation Lock (£m)	£100	£100	£200	£200	£200	£50	£700	£2,400
Buildings & site costs (17%)	£174	£261	£574	£844	£112	£27	£1,792	£1,407

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Civils Sub Total (£m)	£1,217	£1,831	£4,022	£5,913	£782	£190	£12,549	£9,853
M&E plant unit cost (£m/MW)	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20		£1.20
Estimated M&E cost (£m)	£384	£600	£2,400	£3,000	£840	£192	£6,840	£9,600
Preconstruction cost (£m)	£24	£36	£96	£134	£24	£6	£291	£292
Engineering & Contingency	£480	£729	£1,927	£2,674	£487	£115	£5,817	£5,836
Environmental cost (£m)	£139.9	£210.6	£462.6	£680.0	£90.0	£21.8	£1,443.1	£1,133.1
Total Installed Cost (£m)	£2,245	£3,407	£8,908	£12,401	£2,223	£524	£26,940	£26,713
Installed Cost per MW (£m/MW)	£7.02	£6.81	£4.45	£4.96	£3.18	£3.28	£4.73	£3.34
Construction Period (years)	8	8	8	8	8	8		8
Annual O&M cost (£m/year)	£28	£43	£111	£155	£28	£7	£337	£334
Annual energy output (GWh)	492	1,425	5,701	5,292	1,546	302	13,964	24,268
Load Factor (%)	18%	33%	33%	24%	25%	22%	28%	35%
Project Life (years)	80	80	80	80	80	80		80

A.1.5 Pumping with Co-Located Storage

Table A-5 Tidal Range Pumping Co-Located Storage Schemes: Design Specification & Costs (2010 prices, undiscounted)

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Total Installed Capacity (MW)	320	500	2,000	2,500	700	160	5,700	8,000
Number of Units	24	42	168	210	57	12	477	672
Unit Installed Capacity (MW)	13.33	11.90	11.90	11.90	12.28	13.33		11.90
Area of basin (km2)	11.5	20.0	80.0	265.0	60.0	7.4	425.0	504.0
Length of Barrage (km)	9.5	11.2	19.5	34.9	1.7	0.4	67.30	18.5
Number of 40m Power Caissons	8	14	56	70	19	4	159	224
Length of Power Caissons (km)	0.32	0.56	2.24	2.80	0.76	0.16	6.36	8.96
Mean Power Caisson Height (m)	25.0	28.4	29.3	26.0	24.0	25.0		26.0
Power Caisson cost per km (£m/km)	£431	£489	£505	£448	£413	£431		£448
Power Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Power Caisson cost (£m)	£186	£370	£1,526	£1,693	£424	£93	4,012	£5,416
Length of Plain Caissons (km)	9.18	10.64	17.26	32.10	0.94	0.24	61	9.54
Mean Plain Caisson Height (m)	20.0	25.8	24.2	24.0	12.0	20.0		16.0
Plain Caisson cost per km (£m/km)	£61.1	£78.8	£73.9	£73.3	£36.6	£61.1		£49
Plain Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Plain Caisson cost (£m)	£757	£1,132	£1,722	£3,176	£47	£20	£6,076	£629
Navigation Lock (£m)	£100	£100	£200	£200	£200	£50	£700	£2,400
Buildings & site costs (17%)	£174	£267	£574	£844	£112	£27	£1,797	£1,407

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Civils Sub Total (£m)	£1,217	£1,868	£4,022	£5,913	£782	£190	£12,586	£9,853
Battery storage capacity (MW)	255	336	1,345	1,811	435	120	3,927	5,093
Battery storage requirement (MWh)	1,020	1,344	5,380	7,244	1,740	480	15,708	20,372
Hydrogen storage capacity (MW)	89	146	582	706	207	34	1,641	2,113
Hydrogen storage requirement (MWh)	8,544	14,016	55,872	67,776	19,872	3,264	157,536	202,848
Total Energy Storage costs (£m)	£404	£567	£2,266	£2,957	£755	£181	£6,546	£8,471
M&E plant unit cost (£m/MW)	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20		£1.20
Estimated M&E cost (£m)	£384	£600	£2,400	£3,000	£840	£192	£6,840	£9,600
Preconstruction cost (£m)	£24	£37	£96	£134	£24	£6	£291	£292
Engineering & Contingency	£480	£740	£1,927	£2,674	£487	£115	£5,828	£5,836
Environmental cost (£m)	£139.9	£214.9	£462.6	£680	£90	£22	£1,447	£1,133
Total Installed Cost (£m)	£2,649	£4,027	£11,174	£15,358	£2,979	£705	£33,538	£35,184
Installed Cost per MW (£m/MW)	£8.28	£8.05	£5.59	£6.14	£4.26	£4.40	£5.88	£4.40
Construction Period (years)	8	8	8	8	8	8		8
Annual O&M cost (£m/year)	£33	£50	£140	£192	£37	£9	£419	£440
Annual energy output (GWh)	357	1,150	4,602	3,852	1,175	237	10,779	19,910
Load Factor (%)	13%	26%	26%	18%	19%	17%	22%	28%
Project Life (years)	80	80	80	80	80	80		80

A.1.6 Pumping with Grid Balancing Storage

Table A-6 Tidal Range Pumping with Grid Balancing Storage Schemes: Design Specification & Costs (2010 prices, undiscounted)

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Total Installed Capacity (MW)	320	500	2,000	2,500	700	160	5,700	8,000
Number of Units	24	42	168	210	57	12	477	672
Unit Installed Capacity (MW)	13.33	11.90	11.90	11.90	12.28	13.33		11.90
Area of basin (km2)	11.5	20.0	80.0	265.0	60.0	7.4	425.0	504.0
Length of Barrage (km)	9.5	11.2	19.5	34.9	1.7	0.4	67.30	18.5
Number of 40m Power Caissons	8	14	56	70	19	4	159	224
Length of Power Caissons (km)	0.32	0.56	2.24	2.80	0.76	0.16	6.36	8.96
Mean Power Caisson Height (m)	25.0	28.4	29.3	26.0	24.0	25.0		26.0
Power Caisson cost per km (£m/km)	£431	£489	£505	£448	£413	£431		£448
Power Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Power Caisson cost (£m)	£186	£370	£1,526	£1,693	£424	£93	4,012	£5,416
Length of Plain Caissons (km)	9.18	10.64	17.26	32.10	0.94	0.24	61	9.54
Mean Plain Caisson Height (m)	20.0	25.8	24.2	24.0	12.0	20.0		16.0
Plain Caisson cost per km (£m/km)	£61.1	£78.8	£73.9	£73.3	£36.6	£61.1		£49
Plain Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Plain Caisson cost (£m)	£757	£1,132	£1,722	£3,176	£47	£20	£6,076	£629
Navigation Lock (£m)	£100	£100	£200	£200	£200	£50	£700	£2,400
Buildings & site costs (17%)	£174	£267	£574	£844	£112	£27	£1,797	£1,407

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Civils Sub Total (£m)	£1,217	£1,868	£4,022	£5,913	£782	£190	£12,586	£9,853
Battery storage capacity (MW)	112	158	634	1,011	263	54	2,066	2,381
Battery storage requirement (MWh)	449	634	2,536	4,042	1,053	217	8,265	9,525
Hydrogen storage capacity (MW)	65	84	334	448	125	27	991	1,218
Hydrogen storage requirement (MWh)	6,252	8,061	32,037	42,991	12,019	2,577	95,108	116,938
Total Energy Storage costs (£m)	£209	£286	£1,140	£1,715	£457	£96	£3,598	£4,238
M&E plant unit cost (£m/MW)	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20		£1.20
Estimated M&E cost (£m)	£384	£600	£2,400	£3,000	£840	£192	£6,840	£9,600
Preconstruction cost (£m)	£24	£37	£96	£134	£24	£6	£291	£292
Engineering & Contingency	£480	£740	£1,927	£2,674	£487	£115	£5,828	£5,836
Environmental cost (£m)	£140	£215	£463	£680	£90	£22	£1,447	£1,133
Total Installed Cost (£m)	£2,454	£3,746	£10,048	£14,116	£2,680	£620	£30,590	£30,952
Installed Cost per MW (£m/MW)	£7.67	£7.49	£5.02	£5.65	£3.83	£3.87	£5.37	£3.87
Construction Period (years)	8	8	8	8	8	8		8
Annual O&M cost (£m/year)	£31	£47	£126	£176	£34	£8	£382	£387
Annual energy output (GWh)	492	1,425	5,701	5,292	1,546	302	13,964	24,268
Load Factor (%)	18%	33%	33%	24%	25%	22%	28%	35%
Project Life (years)	80	80	80	80	80	80		80

A.2 Tidal Range Schemes Detailed Costs – Based on the earlier SETS Report using enhanced turbine technology

A.2.1 No Pumping with No Energy Storage

Table A-7 Tidal Range No Pumping No Energy Storage Schemes: Design Specification & Costs (2010 prices, undiscounted)

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Total Installed Capacity (MW)	320	500	2,000	2,500	700	160	5,700	8,000
Number of Units	36	60	240	300	84	18	684	960
Unit Installed Capacity (MW)	8.89	8.33	8.33	8.33	8.33	8.89		8.33
Area of basin (km2)	11.5	20.0	80.0	265.0	60.0	7.4	425.0	504.0
Length of Barrage (km)	9.5	10.9	19.5	34.9	1.7	0.4	67.0	18.5
Number of 40m Power Caissons	12	20	80	100	28	6	228	320
Length of Power Caissons (km)	0.48	0.80	3.20	4.00	1.12	0.24	9.12	12.80
Mean Power Caisson Height (m)	25.0	28.4	29.3	26.0	24.0	25.0		26.0
Power Caisson cost per km (£m/km)	£269	£306	£316	£280	£258	£269		£280
Power Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Power Caisson cost (£m)	£174	£330	£1,363	£1,512	£391	£87	3,596	£4,838
Length of Plain Caissons (km)	9.02	10.10	16.30	30.90	0.58	0.16	58	5.70
Mean Plain Caisson Height (m)	20.0	25.8	24.2	24.0	12.0	20.0		16.0
Plain Caisson cost per km (£m/km)	£61.1	£78.8	£73.9	£73.3	£36.6	£61.1		£49
Plain Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Plain Caisson cost (£m)	£744	£1,074	£1,626	£3,057	£29	£13	£5,787	£376

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Navigation Lock (£m)	£100	£100	£200	£200	£200	£50	£700	£2,400
Buildings & site costs (17%)	£170	£251	£531	£795	£103	£25	£1,680	£1,269
Civils Sub Total (£m)	£1,188	£1,755	£3,721	£5,564	£723	£175	£11,763	£8,883
M&E plant unit cost (£m/MW)	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20		£1.20
Estimated M&E cost (£m)	£384	£600	£2,400	£3,000	£840	£192	£6,840	£9,600
Preconstruction cost (£m)	£24	£35	£92	£128	£23	£6	£279	£277
Engineering & Contingency	£472	£707	£1,836	£2,569	£469	£110	£5,581	£5,545
Environmental cost (£m)	£136.6	£201.9	£427.9	£639.9	£83.1	£20.2	£1,352.7	£1,021.5
Total Installed Cost (£m)	£2,204	£3,299	£8,477	£11,901	£2,138	£503	£25,815	£25,327
Installed Cost per MW (£m/MW)	£6.89	£6.60	£4.24	£4.76	£3.05	£3.15	£4.53	£3.17
Construction Period (years)	8	8	8	8	8	8	8	8
Annual O&M cost (£m/year)	£28	£41	£106	£149	£27	£6	£323	£317
Annual energy output (GWh)	903	1,528	6,112	6,555	1,921	312	16,116	25,692
Load Factor (%)	32%	35%	35%	30%	31%	22%	32%	37%
Project Life (years)	80	80	80	80	80	80	80	80

A.2.2 No Pumping with Co-Located Storage

Table A-8 Tidal Range No Pumping Co-Located Storage Schemes: Design Specification & Costs (2010 prices, undiscounted)

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Total Installed Capacity (MW)	320	500	2,000	2,500	700	160	5,700	8,000
Number of Units	36	60	240	300	84	18	684	960
Unit Installed Capacity (MW)	8.89	8.33	8.33	8.33	8.33	8.89		8.33
Area of basin (km2)	11.5	20.0	80.0	265.0	60.0	7.4	425.0	504.0
Length of Barrage (km)	9.5	11.2	19.5	34.9	1.7	0.4	67.30	18.5
Number of 40m Power Caissons	12	20	80	100	28	6	228	320
Length of Power Caissons (km)	0.48	0.80	3.20	4.00	1.12	0.24	9.12	12.80
Mean Power Caisson Height (m)	25.0	28.4	29.3	26.0	24.0	25.0		26.0
Power Caisson cost per km (£m/km)	£269	£306	£316	£280	£258	£269		£280
Power Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Power Caisson cost (£m)	£174	£330	£1,363	£1,512	£391	£87	£3,596	£4,838
Length of Plain Caissons (km)	9.02	10.40	16.30	30.90	0.58	0.16	58	5.70
Mean Plain Caisson Height (m)	20.0	25.8	24.2	24.0	12.0	20.0		16.0
Plain Caisson cost per km (£m/km)	£61.1	£78.8	£73.9	£73.3	£36.6	£61.1		£49
Plain Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Plain Caisson cost (£m)	£744	£1,106	£1,626	£3,057	£29	£13	£5,819	£376
Navigation Lock (£m)	£100	£100	£200	£200	£200	£50	£700	£2,400
Buildings & site costs (17%)	£170	£256	£531	£795	£103	£25	£1,685	£1,269

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Civils Sub Total (£m)	£1,188	£1,792	£3,721	£5,564	£723	£175	£11,800	£8,883
Battery storage capacity (MW)	226	436	1,380	1,172	293	93	3,281	4,506
Battery storage requirement (MWh)	904	1,744	5,520	4,688	1,172	372	13,124	18,024
Hydrogen storage capacity (MW)	104	174	709	828	240	40	1,951	2,886
Hydrogen storage requirement (MWh)	9,984	16,704	68,064	79,488	23,040	3,840	187,296	277,056
Total Energy Storage costs (£m)	£388	£717	£2,460	£2,362	£630	£156	£6,169	£8,721
M&E plant unit cost (£m/MW)	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20		£1.20
Estimated M&E cost (£m)	£384	£600	£2,400	£3,000	£840	£192	£6,840	£9,600
Preconstruction cost (£m)	£24	£36	£92	£128	£23	£6	£280	£277
Engineering & Contingency	£472	£718	£1,836	£2,569	£469	£110	£5,592	£5,545
Environmental cost (£m)	£136.6	£206.1	£427.9	£639.9	£83.1	£20.2	£1,357.0	£1,021.5
Total Installed Cost (£m)	£2,592	£4,069	£10,936	£14,263	£2,768	£660	£32,037	£34,048
Installed Cost per MW (£m/MW)	£8.10	£8.14	£5.47	£5.71	£3.95	£4.12	£5.62	£4.26
Construction Period (years)	8	8	8	8	8	8	8	8
Annual O&M cost (£m/year)	£32	£51	£137	£178	£35	£8	£400	£426
Annual energy output (GWh)	735	1,203	4,987	5,364	1,586	253	13,140	20,927
Load Factor (%)	26%	27%	28%	24%	26%	18%	26%	30%
Project Life (years)	80	80	80	80	80	80	80	80

A.2.3 No Pumping with Grid Balancing Storage

Table A-9 Tidal Range No Pumping Grid Balancing Storage Schemes: Design Specification & Costs (2010 prices, undiscounted)

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Total Installed Capacity (MW)	320	500	2,000	2,500	700	160	5,700	8,000
Number of Units	36	60	240	300	84	18	684	960
Unit Installed Capacity (MW)	8.89	8.33	8.33	8.33	8.33	8.89		8.33
Area of basin (km2)	11.5	20.0	80.0	265.0	60.0	7.4	425.0	504.0
Length of Barrage (km)	9.5	11.2	19.5	34.9	1.7	0.4	67.30	18.5
Number of 40m Power Caissons	12	20	80	100	28	6	228	320
Length of Power Caissons (km)	0.48	0.80	3.20	4.00	1.12	0.24	9.12	12.80
Mean Power Caisson Height (m)	25.0	28.4	29.3	26.0	24.0	25.0		26.0
Power Caisson cost per km (£m/km)	£269	£306	£316	£280	£258	£269		£280
Power Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Power Caisson cost (£m)	£174	£330	£1,363	£1,512	£391	£87	3,596	£4,838
Length of Plain Caissons (km)	9.02	10.40	16.30	30.90	0.58	0.16	58	5.70
Mean Plain Caisson Height (m)	20.0	25.8	24.2	24.0	12.0	20.0		16.0
Plain Caisson cost per km (£m/km)	£61.1	£78.8	£73.9	£73.3	£36.6	£61.1		£49
Plain Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Plain Caisson cost (£m)	£744	£1,106	£1,626	£3,057	£29	£13	£5,819	£376
Navigation Lock (£m)	£100	£100	£200	£200	£200	£50	£700	£2,400
Buildings & site costs (17%)	£170	£256	£531	£795	£103	£25	£1,685	£1,269

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Civils Sub Total (£m)	£1,188	£1,792	£3,721	£5,564	£723	£175	£11,800	£8,883
Battery storage capacity (MW)	96	150	600	750	210	48	1,710	2,400
Battery storage requirement (MWh)	384	600	2,400	3,000	840	192	6,840	9,600
Hydrogen storage capacity (MW)	60	94	375	469	131	30	1,069	1,500
Hydrogen storage requirement (MWh)	5,760	9,000	36,000	45,000	12,600	2,880	102,600	144,000
Total Energy Storage costs (£m)	£184	£288	£1,150	£1,438	£403	£92	£3,278	£4,600
M&E plant unit cost (£m/MW)	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20		£1.20
Estimated M&E cost (£m)	£384	£600	£2,400	£3,000	£840	£192	£6,840	£9,600
Preconstruction cost (£m)	£24	£36	£92	£128	£23	£6	£280	£277
Engineering & Contingency	£472	£718	£1,836	£2,569	£469	£110	£5,592	£5,545
Environmental cost (£m)	£136.6	£206.1	£427.9	£639.9	£83.1	£20.2	£1,357.0	£1,021.5
Total Installed Cost (£m)	£2,388	£3,640	£9,627	£13,339	£2,541	£595	£29,146	£29,927
Installed Cost per MW (£m/MW)	£7.46	£7.28	£4.81	£5.34	£3.63	£3.72	£5.11	£3.74
Construction Period (years)	8	8	8	8	8	8	8	8
Annual O&M cost (£m/year)	£30	£45	£120	£167	£32	£7	£364	£374
Annual energy output (GWh)	903	1,528	6,112	6,555	1,921	312	16,116	25,692
Load Factor (%)	32%	35%	35%	30%	31%	22%	32%	37%
Project Life (years)	80	80	80	80	80	80	80	80

A.2.4 Pumping with No Energy Storage

Table A-10 Tidal Range Pumping No Energy Storage Schemes: Design Specification & Costs (2010 prices, undiscounted)

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Total Installed Capacity (MW)	320	500	2,000	2,500	700	160	5,700	8,000
Number of Units	36	60	240	300	84	18	684	960
Unit Installed Capacity (MW)	8.89	8.33	8.33	8.33	8.33	8.89		8.33
Area of basin (km2)	11.5	20.0	80.0	265.0	60.0	7.4	425.0	504.0
Length of Barrage (km)	9.5	10.9	19.5	34.9	1.7	0.4	67.0	18.5
Number of 40m Power Caissons	12	20	80	100	28	6	228	320
Length of Power Caissons (km)	0.48	0.80	3.20	4.00	1.12	0.24	9.12	12.80
Mean Power Caisson Height (m)	25.0	28.4	29.3	26.0	24.0	25.0		26.0
Power Caisson cost per km (£m/km)	£269	£306	£316	£280	£258	£269		£280
Power Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Power Caisson cost (£m)	£174	£330	£1,363	£1,512	£391	£87	3,596	£4,838
Length of Plain Caissons (km)	9.02	10.10	16.30	30.90	0.58	0.16	58	5.70
Mean Plain Caisson Height (m)	20.0	25.8	24.2	24.0	12.0	20.0		16.0
Plain Caisson cost per km (£m/km)	£61.1	£78.8	£73.9	£73.3	£36.6	£61.1		£49
Plain Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Plain Caisson cost (£m)	£744	£1,074	£1,626	£3,057	£29	£13	£5,787	£376
Navigation Lock (£m)	£100	£100	£200	£200	£200	£50	£700	£2,400
Buildings & site costs (17%)	£170	£251	£531	£795	£103	£25	£1,680	£1,269

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Civils Sub Total (£m)	£1,188	£1,755	£3,721	£5,564	£723	£175	£11,763	£8,883
M&E plant unit cost (£m/MW)	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20
Estimated M&E cost (£m)	£384	£600	£2,400	£3,000	£840	£192	£6,840	£9,600
Preconstruction cost (£m)	£24	£35	£92	£128	£23	£6	£279	£277
Engineering & Contingency	£472	£707	£1,836	£2,569	£469	£110	£5,581	£5,545
Environmental cost (£m)	£136.6	£201.9	£427.9	£639.9	£83.1	£20.2	£1,352.7	£1,021.5
Total Installed Cost (£m)	£2,204	£3,299	£8,477	£11,901	£2,138	£503	£25,815	£25,327
Installed Cost per MW (£m/MW)	£6.89	£6.60	£4.24	£4.76	£3.05	£3.15	£4.53	£3.17
Construction Period (years)	8	8	8	8	8	8	8	8
Annual O&M cost (£m/year)	£28	£41	£106	£149	£27	£6	£323	£317
Annual energy output (GWh)	960	1,637	6,550	7,173	2,144	358	17,504	27,936
Load Factor (%)	34%	37%	37%	33%	35%	26%	35%	40%
Project Life (years)	80	80	80	80	80	80	80	80

A.2.5 Pumping with Co-Located Storage

Table A-11 Tidal Range Pumping Co-Located Storage Schemes: Design Specification & Costs (2010 prices, undiscounted)

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Total Installed Capacity (MW)	320	500	2,000	2,500	700	160	5,700	8,000
Number of Units	36	60	240	300	84	18	684	960
Unit Installed Capacity (MW)	8.89	8.33	8.33	8.33	8.33	8.89		8.33
Area of basin (km2)	11.5	20.0	80.0	265.0	60.0	7.4	425.0	504.0
Length of Barrage (km)	9.5	11.2	19.5	34.9	1.7	0.4	67.30	18.5
Number of 40m Power Caissons	12	20	80	100	28	6	228	320
Length of Power Caissons (km)	0.48	0.80	3.20	4.00	1.12	0.24	9.12	12.80
Mean Power Caisson Height (m)	25.0	28.4	29.3	26.0	24.0	25.0		26.0
Power Caisson cost per km (£m/km)	£269	£306	£316	£280	£258	£269		£280
Power Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Power Caisson cost (£m)	£174	£330	£1,363	£1,512	£391	£87	3,596	£4,838
Length of Plain Caissons (km)	9.02	10.40	16.30	30.90	0.58	0.16	58	5.70
Mean Plain Caisson Height (m)	20.0	25.8	24.2	24.0	12.0	20.0		16.0
Plain Caisson cost per km (£m/km)	£61.1	£78.8	£73.9	£73.3	£36.6	£61.1		£49
Plain Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Plain Caisson cost (£m)	£744	£1,106	£1,626	£3,057	£29	£13	£5,819	£376
Navigation Lock (£m)	£100	£100	£200	£200	£200	£50	£700	£2,400
Buildings & site costs (17%)	£170	£256	£531	£795	£103	£25	£1,685	£1,269

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Civils Sub Total (£m)	£1,188	£1,792	£3,721	£5,564	£723	£175	£11,800	£8,883
Battery storage capacity (MW)	235	409	1,421	1,301	335	100	3,466	4,650
Battery storage requirement (MWh)	940	1,636	5,684	5,204	1,340	400	13,864	18,600
Hydrogen storage capacity (MW)	107	145	651	794	238	40	1,828	2,512
Hydrogen storage requirement (MWh)	10,272	13,920	62,496	76,224	22,848	3,840	175,488	241,152
Total Energy Storage costs (£m)	£402	£650	£2,438	£2,471	£677	£165	£6,235	£8,437
M&E plant unit cost (£m/MW)	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20
Estimated M&E cost (£m)	£384	£600	£2,400	£3,000	£840	£192	£6,840	£9,600
Preconstruction cost (£m)	£24	£36	£92	£128	£23	£6	£280	£277
Engineering & Contingency	£472	£718	£1,836	£2,569	£469	£110	£5,592	£5,545
Environmental cost (£m)	£136.6	£206.1	£427.9	£640	£83	£20	£1,357	£1,022
Total Installed Cost (£m)	£2,606	£4,003	£10,914	£14,372	£2,815	£668	£32,104	£33,764
Installed Cost per MW (£m/MW)	£8.14	£8.01	£5.46	£5.75	£4.02	£4.17	£5.63	£4.22
Construction Period (years)	8	8	8	8	8	8	8	8
Annual O&M cost (£m/year)	£33	£50	£136	£180	£35	£8	£401	£422
Annual energy output (GWh)	777	1,342	5,362	5,933	1,788	290	14,425	23,063
Load Factor (%)	28%	31%	31%	27%	29%	21%	29%	33%
Project Life (years)	80	80	80	80	80	80	80	80

A.2.6 Pumping with Grid Balancing Storage

Table A-12 Tidal Range Pumping with Grid Balancing Storage Schemes: Design Specification & Costs (2010 prices, undiscounted)

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Total Installed Capacity (MW)	320	500	2,000	2,500	700	160	5,700	8,000
Number of Units	36	60	240	300	84	18	684	960
Unit Installed Capacity (MW)	8.89	8.33	8.33	8.33	8.33	8.89		8.33
Area of basin (km2)	11.5	20.0	80.0	265.0	60.0	7.4	425.0	504.0
Length of Barrage (km)	9.5	11.2	19.5	34.9	1.7	0.4	67.30	18.5
Number of 40m Power Caissons	12	20	80	100	28	6	228	320
Length of Power Caissons (km)	0.48	0.80	3.20	4.00	1.12	0.24	9.12	12.80
Mean Power Caisson Height (m)	25.0	28.4	29.3	26.0	24.0	25.0		26.0
Power Caisson cost per km (£m/km)	£269	£306	£316	£280	£258	£269		£280
Power Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Power Caisson cost (£m)	£174	£330	£1,363	£1,512	£391	£87	3,596	£4,838
Length of Plain Caissons (km)	9.02	10.40	16.30	30.90	0.58	0.16	58	5.70
Mean Plain Caisson Height (m)	20.0	25.8	24.2	24.0	12.0	20.0		16.0
Plain Caisson cost per km (£m/km)	£61.1	£78.8	£73.9	£73.3	£36.6	£61.1		£49
Plain Caisson Installation (%)	35%	35%	35%	35%	35%	35%		35%
Total Plain Caisson cost (£m)	£744	£1,106	£1,626	£3,057	£29	£13	£5,819	£376
Navigation Lock (£m)	£100	£100	£200	£200	£200	£50	£700	£2,400
Buildings & site costs (17%)	£170	£256	£531	£795	£103	£25	£1,685	£1,269

Tidal Range Option Cost Comparison	Swansea Bay 320 MW	Severn Lagoon 500 MW	Severn Lagoon 2,000 MW	North Wales Lagoon 2,500 MW	Mersey Estuary 700 MW	Wyre Estuary 160 MW	Combined Tidal Range 5700 MW	Severn Tidal Bar 8,000 MW
Civils Sub Total (£m)	£1,188	£1,792	£3,721	£5,564	£723	£175	£11,800	£8,883
Battery storage capacity (MW)	100	141	618	833	240	52	1,831	2,477
Battery storage requirement (MWh)	399	563	2,471	3,330	960	206	7,325	9,907
Hydrogen storage capacity (MW)	62	78	344	450	130	30	1,002	1,306
Hydrogen storage requirement (MWh)	5,926	7,500	33,055	43,152	12,495	2,880	96,202	125,339
Total Energy Storage costs (£m)	£191	£258	£1,134	£1,510	£436	£96	£3,338	£4,455
M&E plant unit cost (£m/MW)	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20	£1.20
Estimated M&E cost (£m)	£384	£600	£2,400	£3,000	£840	£192	£6,840	£9,600
Preconstruction cost (£m)	£24	£36	£92	£128	£23	£6	£280	£277
Engineering & Contingency	£472	£718	£1,836	£2,569	£469	£110	£5,592	£5,545
Environmental cost (£m)	£137	£206	£428	£640	£83	£20	£1,357	£1,022
Total Installed Cost (£m)	£2,394	£3,610	£9,610	£13,412	£2,574	£600	£29,207	£29,781
Installed Cost per MW (£m/MW)	£7.48	£7.22	£4.81	£5.36	£3.68	£3.75	£5.12	£3.72
Construction Period (years)	8	8	8	8	8	8	8	8
Annual O&M cost (£m/year)	£30	£45	£120	£168	£32	£7	£365	£372
Annual energy output (GWh)	960	1,637	6,550	7,173	2,144	358	17,504	27,936
Load Factor (%)	34%	37%	37%	33%	35%	26%	35%	40%
Project Life (years)	80	80	80	80	80	80	80	80