OPTIMISATION OF TIDAL RANGE ELECTRICITY GENERATION AND ECONOMICS

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PhD Thesis

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DECLARATION

I declare that my thesis has not been previously submitted for award of a higher degree to this or any university, and that the contents, except where otherwise stated, are the author's own work. Artificial intelligence has not been used in this work.

Signed

Date   22-Jul-25

ABSTRACT

The purpose of this study is to improve knowledge and understanding of tidal range power by investigating the potential for generation and its economics. The approach used an existing model of electricity generation (Lancaster 0-D tidal model) to investigate optimal generation and financial return. The thesis examines the question of the feasibility of tidal range power and the issues that are commonly presented as barriers preventing deployment. Those barriers include economics (finance, scale, rate of construction and power generation), environment (climate change, habitat loss, pollution) and engineering (mechanical, civil and electrical).

Two case study sites were selected for investigation using scenarios with multiple configurations of:

- numbers and size of turbines
- sluice ratios
- generator ratings.

The economic issues were partly addressed by developing a simple financial model for the capital cost of schemes (CAPEX). It was used to indicate how specific components within a scheme best contribute to the financial return of investment. It can also be used to compare schemes in different locations and rank them in order of profitability.

A major environmental consideration is climate change; it is especially important as tidal range schemes are designed to have a functional life of at least 120-years. The climate change driven challenge of sea level rise (SLR) over the proposed operation life must be considered in both planning and operation. This study models tidal range power schemes so that they protect coastal habitats and communities by maintaining the existing tidal range. For the two sites studied, as sea level begins to rise, the annual electricity production (AEP) increases due to the greater water head in flood tides. As SLR continues, the AEP falls due to increased pumping required to achieve low tide levels. Initially, pumping can be performed by the turbines used as pumps (TaP). The TaPs are not sufficient for higher levels of SLR, so after about 40-years it may be necessary to install submersible pumps to effectively match the desired low tide limits.

The disciplines within engineering run as a constant thread through this thesis, essential in design, deployment, operation, maintenance and decommissioning. The time taken to deploy a barrage is

constrained by the civil engineering options. A preliminary analysis of precast concrete barrage designs was made, with both existing vertical units and my proposed horizontal units. The latter can be cast on shore and floated out in shallower water, the sloping sides reduce both ground bearing pressures and the volume of concrete needed.

The times of high and low tide are predictable for any site even though the tidal range varies for each cycle. A simplified 0-D program has been proposed based on varying the start of generation relative to the time of the previous high or low tide. The aim is to analyse a whole year of individual tides and include an efficiency reduction for reverse flow generation. During the development a simple spreadsheet was produced for a period of 22-days from the start of 2024 to be used to check the program. This identified that the simple time base program was effective but that it was not sufficient for operational use; there were several periods of generating at negative price which need not happen during operation. Consequently, a modified model was proposed that weighted the flow according to price and so better reflect demand. The adjustment created a significant increase in financial return whilst the total generation reduced. The algorithm will be complex and there was not sufficient time to write a program during this study. It is hoped to continue this work in future.

Finally, the methods of comparing costs of different energy generating technologies have been examined and a new metric developed. It overcomes some of the problems with the commonly used levelised cost of energy by comparing continuous generation over the longest lifespan of the technologies considered (120-years). For example, a tidal barrage is equivalent to two nuclear sites of 60-years operational life or four gas turbine stations with 30-year operational lives. The analysis shows how tidal range power is economically viable and would fit into the national power generation system. If the annual benefits of flood protection are included in the analysis, tidal range power becomes the cheapest of all grid scale renewable technologies.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Prof George Aggidis, and mentors Dr David Howard, and Simon Baker. All have given enormous support, and guidance as well as endless patience. Dr Howard has provided most of the environmental advice and editorial support for technical papers jointly produced. Simon Baker provided the initial 0-D computer code and helped me through the learning curve to understand MatLab and other software. He also provided many of the maps and LIDAR data for published papers.

In addition, I would like to thank the following people who have assisted me with information and advice: -

- David Kerr, former chair of ICE Energy committee and former Chief Design Engineer for Sir Robert McAlpine, for construction advice and cost information relating to pre-cast caisson construction.
- Prof Chris Binnie, a consulting engineer in water demand, water supply, water treatment, water resources development, hydro and tidal power, and flood risk assessment. A director and chair of Tidal Engineering and Environmental Services Ltd (TEES). Binnie is a director of the West Somerset Lagoon which proposes a 2.5-GW tidal range which would produce about 6.5-TWh/year with a capital cost of about £8.5bn. Binnie is a Past President of the Chartered Institution of Water & Environmental Management.
- Prof James DiLellio, Professor of Decision Sciences, Irvine, USA, has helped and guided work on economics which has been included in some of the published papers.

I would also like to thank my wife for her endless patience whilst I have been working on this research and over our 47-years of marriage.

DEDICATION

This work is dedicated to my children and grandchildren in the hope that they can repair some of the environmental damage done to our world by previous generations.

LIST OF JOURNAL PUBLICATIONS

Six papers have been published with help from my supervisor and mentors. All were conceived and drafted by myself. The papers are:-

1. *Tidal range electricity generation: A comparison between estuarine barrages and coastal lagoons*. (Vandercruyssen et al., 2022b)
2. *A Model of the Costs for Tidal Range Power Generation Schemes*.(Vandercruyssen et al., 2022a).
3. *Tidal range generation: combining the Lancaster zero-dimension generation and cost models,* (Vandercruyssen et al., 2023a).
4. *Tidal Range Electricity Generation into the 22nd Century (Vandercruyssen et al., 2023b)*..
5. Tidal range barrage design and construction (Vandercruyssen et al., 2024).
6. Economic Methods for the Selection of Renewable Energy Sources (DiLellio et al., 2025).

PRESENTATIONS GIVEN

- Vandercruyssen, D. Jun-21. *Optimization of tidal range generation and energy storage.* Lancaster university post graduate conference.

- Vandercruyssen, D. 29-Jan-25. *Tidal range costs and main structures.* to Morecambe Business Improvement District (BID) on the Morecambe Bay Scheme.

- A presentation to local politicians at UKCEH, Lancaster University on 1-Apr-25.

- A presentation to the IMechE Hydropower conference on 5-Jun-25 in Glasgow.

CONTRIBUTION TO KNOWLEDGE

This research has contributed to the development of knowledge of tidal range power generation as follows:-

- Explaining and demonstrating how 0-D modelling can be used to quickly analyse different combinations of the components of tidal range schemes. Using case study sites of a coastal lagoon and an estuarine barrage I showed how the annual electricity production changed with various numbers of turbines, sluice ratios and generator ratings.

- a cost model for tidal range schemes has been developed based on five elements:-
    - Turbo generator and equipment
    - Turbine halls
    - Sluices
    - Bunds
    - Cofferdams

    The model is for initial feasibility costs and can be used for both optimising schemes and comparing different projects.

- The implications of sea level rise over the 120-year operational life of tidal range schemes has been investigated to understand what would be required to protect existing low-level ecosystems and provide flood protection to coastal communities. Results showed that the full tidal range can be maintained within an impoundment and can also be maintained as average sea levels rise although additional submersible pumps would be required at higher increases.

- IA simplified 0-D tidal range power generation model was proposed by varying the time lag between high or low tide and the start of generation. This worked well for estimate maximising generation but was poor for income. This led to the development of a demand/price-based model which increased income and helped to stabilise the grid at the same time.

- A new design for horizontal precast concrete caisson units has been proposed for the barrage which can be built on shore and floated out in shallow water and ballasted with dredged sand and gravel. The horizontal caissons would use less reinforced concrete than vertical caissons, have lower ground bearing pressures and be easier to float into position. Precast concrete is less susceptible to storm damage during construction and minimises the risk to persons working offshore.

- Financial methods used to compare costs for various renewable energy schemes have been investigated. The levelised cost of energy method was poor when comparing technologies with different operational lives. A sustainable cost of energy method to compare different technologies over a continuous 120 years of generation was devised. The results showed that

tidal range produced electricity at similar costs to solar, wind and nuclear. Including the annual benefit of flood protection shows that tidal range is the cheapest of all current renewable technologies.

NOTATION

Item	Description	Units
ABS	Absolute value function.	
A_l	Surface area of lagoon.	m^2
A_s	Area of sluice opening.	m^2
At	Total area swept by all turbine blades.	m^2
At1	Area swept by single turbine blades.	m^2
C_d	Coefficient of discharge.	
g	Acceleration due to gravity, 9.81.	m/s^2
H	Head of water across the turbine.	m
MIN	Minimum value function.	
n_{11}	Rotational speed of model turbine.	rpm
n_s	The specific speed of a turbine.	rpm
N_t	Total number of turbines.	
Q_{11}	Model turbine discharge.	m^3/s
Qp	Pumped flow through a single turbine.	m^3/s
Qs	Sluice flow.	m^3/s
Qt	Total flow through turbines.	m^3/s
Qt1	Flow through a single full size turbine.	m^3/s
Sp	Synchronisation speed.	rpm
Sr	Sluice ratio, total area of sluices/total area of turbine diameters.	
TLC	Target level change.	m
WLC	Weighted level change in current timestep.	m
δh	Head difference for a time step.	m
δt	Time step.	s
η	Efficiency.	
ηa	Turbine availability.	
ηg	Gear box/drive train efficiency.	
ηp	Generator efficiency.	
ηt	Turbine efficiency.	
ηw	Efficiency loss due to water friction.	
ρ or γ	density of sea water, typically 1025.	kg/m^3
φ or D	Diameter of turbine blades.	m

LIST OF ACRONYMS

Item	Description
AC	Alternating current.
AEP	Annual Energy Production.
AONB	Area of Outstanding Natural Beauty.
CCGT	Combined Cycle Gas Turbines.
CfD	Contract for Difference, UK funding mechanism for renewable energy.
DC	Direct current.
DECC	UK Government Department of Energy and Climate Change.
DESNZ	Uk gov department for energy security and net zero.
DOE	Department of Energy.
EES	Electrical Energy Storage.
EMEC	European Marine Energy Centre.
FCEVs	Fuel cell electric vehicles.
FES	Flywheel energy storage.
Gp	Number of poles in the generator winding.
GW	Giga watt, 10^9 W.
ITP	ITP Energised Ltd advisors to Charles Hendy's review of tidal lagoons.
LCOE	Levelized Cost Of Energy.
MHWN	Mean high water neaps.
MHWS	Mean high water springs.
MJ	Maga Joules.
MLWN	Mean low water neaps.
MLWS	Mean low water springs.
MW	Mega watt, 10^6 W.
NNR	National Nature Reserves.
NPSH	Nett positive suction head.
NTPG	Northern Tidal Power Gateways, developer for Morecambe Bay & The Duddon.
NWTE	North Wales Tidal Energy & Coastal Protection Ltd, developer.
OCGT	Open Cycle Gas Turbines.
OD	Ordnance Datum.

Item	Description
P	Power, normally as MW.
PaT	Pumps as turbines.
Pe	Potential energy, normally as GWh or TWh.
PHS	Pumped Hydro Storage.
PPA	Power purchase agreement.
RAB	Regulated Asset Base, method of funding.
Ramsar	Ramsar Convention on Wetlands of International Importance especially as Waterfowl Habitat .
RSPB	Royal Society for the Protection of Birds.
SAC	Special Areas of Conservation. Protected areas in the UK designated under the Conservation of Habitats and Species Regulations 2017.
SLR	Sea level rise.
Sp	Synchronous speed, e.g. 3,000 rpm.
SPA	Special Protection Areas, are protected for birds in the UK, classified under the Wildlife & Countryside Act 1981.
SSSI	Site of Special Scientific Interest.
TaP	Turbines as Pumps.
TLC	Total level change for timeslots, m.
TLP	Tidal Lagoon Power Ltd, developers.
TR	Tidal range.
TW	Tera watt, 10^{12} W.
UK	United Kingdom of Great Britain and Northern Ireland.
UPS	Uninterruptable power supply.
WLC	Weighted level change for timeslots, m.

CONVERSIONS

Energy   1 MW h = 3.6 GJ

Pressure   1 bar = 0.1 MPa

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1   INTRODUCTION

The purpose of this research is to develop the knowledge and potential of tidal range generation in the UK. It is essential to raise awareness of the benefits of tidal range. It will be shown that tidal range can and should be included in the UK renewable energy mix to help meet zero emissions by 2050 and reduce reliance on imported fuels. To this end, six peer reviewed technical papers have been published and presentations given to local groups, politicians and the Inst of Mech Engs (IMechE).

Tidal range electricity generation is proven to work by plants operating since 1966 in La Rance, France (Andre, 1978) and 2010 at Lake Sihwa, South Korea (Young Ho Bae et al., 2010). Tidal range generation requires a barrage to separate a body of water from the sea, thus will be sited across estuaries or along suitable coastlines. The water in the impoundment is *held back* from high or low tide to create a difference in level, called the *head* of water. The head is then used to drive hydro-turbines linked to electricity generators. The efficiency of the system increases with the range between high and low tides. The Severn estuary has the 2nd highest tidal range in the world, and the coast of Great Britain has huge potential for tidal range generation. Tidal range energy is not constant but is predictable, very clean and long lived.

There are no tidal range schemes in the UK but several sites have been proposed, a barrage across the River Severn has been advocated since 1849 (Ford, 2013; Hendry, 2016). There is now a growing interest in tidal range generation due to the drive for more renewable energy. However, implementation in the UK is hampered by the lack of technical understanding, concerns over the large capital costs and environmental changes. This research is intended to provide current information on the technical aspects, environment benefits and cost evaluations.

1.1   Objectives and scope of this study

There are several tidal range schemes proposed in the UK for electrical generation. Currently there is no funding for development or feasibility studies into these schemes. The developer for the Swansea Bay Tidal Lagoon (Tidal Lagoon Power (TLP), 2025) is reported to have spent £30m on development (Binnie and Kerr, 2020) but TLP was not able to gain the subsidy necessary for the project to progress (BBC News, 2018). The contract for difference (CfD) subsidy for EDF's nuclear power station at Hinkley Point was £92.5/MWh (2012 prices) (UK Gov Department for Energy Security & Net Zero (DESNZ), 2018). The developers for Swansea Bay and the North Wales lagoon (North Wales Tidal Energy (NWTE), 2025) estimated it would need a similar minimum price subsidy for their tidal range

proposals. It is considered the major reasons for the lack of funding at this time are the lack of political will and the apparent economics which arise from the high initial capital expenditure.

The objectives of this study are to develop and disseminate the knowledge of tidal range generation and its economics, in particular: -

- Use the existing Lancaster 0-D model to investigate the difference generation modes, ebb, flood and 2-way, to see what flexibility is possible to generate more electricity when demand and price is high. The normal operating mode will be 2-way. In times of critically low generation the mode can be switched to ebb or flood to help balance the supply and demand situation.
- Examine the effects of sea level rise during the life of a tidal range scheme.
- Construct simplified and demand led models as an alternative to the existing Lancaster 0-D program.
- Develop a cost model that can be used to compare different schemes and optimise components within any scheme.
- Explore the various cost comparison mechanisms used by government and energy policy decision makers.

1.2   Optimising energy generation using the existing Lancaster 0-D model

Until recently tidal range generation schemes were proposed across estuaries and were considered most efficient in "*ebb only flow*" mode. For such schemes the surface area of the impounded water at high tide is usually many times the surface area at low tides. More recently coastal lagoons are being considered as they are perceived to be less prone to environmental challenges (Hendry, 2016). Coastal lagoons have a much lower ratio of surface areas between high and low tides, thus "*dual flow"* or "*2-way flow*" can be considered. Dual flow with pumping is of interest because it most closely matches the natural tidal cycle and generates electricity four times a day instead of two but does not take account of demand and pricing. We need to investigate any flexibility in the generation profile to optimise sales. We cannot control the tides but there is a little flexibility in the heads at start and end of generation, also in the speed of the water flow. It is possible to run the turbines at lower efficiency if doing so generates more electricity when demand and price are high.

The zero dimension (0-D) model assumes that the impounded water level is a flat surface. It is ideal for the initial development and assessment of schemes as it requires little input and gives rapid results. There are two site specific inputs required: -

- The surface area of impounded water between high and low tides. This can be estimated from LIDAR data (DEFRA.) in the absence of site-specific information.
- The tide levels at the chosen barrage location at specific times. These can be provided by tide constituent equations based on the latitude and longitude for the site to estimate the tide level at a particular time and date. Alternatively past or predicted tide tables can be used.

More accurate forms of tidal range analysis are possible using two- or three-dimensional models and are better at fine tuning the design than the broad-brush stroke of 0-D. They are not necessarily better than 0-D but have a greater precision and do allow more detailed examination of the operation of a scheme and its environment.

The latest version of the Lancaster 0-D model is a Matlab R2020b computer program (version Energy_Gen_53sm.mlapp) written by Simon Baker (Baker, 2021) who has mentored this research throughout. Version Gen_53 has been set to use the data for Morecambe Bay curved barrage and the North Wales coastal lagoon. There is an excellent graphical interface that lets the user select the number and size of turbines and sluices, the maximum generator rating and the date range to estimate the annual electricity production (AEP). The interface also shows graphical representation of the output with flows, power, head etc. The program is described in detail in Chapter 4, but it suffices to say here that the main benefit of the 0-D method is to give a first estimate of AEP for any location and proposed installation.

1.3   Outline of this thesis

Chapter 2 is a wide-ranging literature review that provides background and identifies the gaps that research can fill. It covers historical electricity demand, the history of tidal range generation, potential sites in the UK, types of hydro turbines and subsidies for renewable energy.

Chapter 3 describes the form and mathematics of the zero-dimensional (0-D) model in general.

Chapter 4 describes the operation and features of the Lancaster 0-D model. It focusses on the scenarios, how they are compiled and the potential outputs and significant results.

Chapter 5 describes a proposed simplified 0-D model that is demonstrated by a spreadsheet which highlighted the need for a demand led model which is also described.

Chapter 6 examines the economics of tidal range generation; it includes the capital expenditure and the major items for upgrade or replacement during the life of a scheme. It includes the Sustained Cost Of Energy metric which has been developed and the impact of including the financial benefit of flood protection.

Chapter 7 gives conclusions and recommendations for future work.

Appendix A.1 gives the outputs from this thesis.

Appendix A.2 gives the spreadsheets developed for the simplified and demand led models.

Appendix A.3 gives the spreadsheets developed for the economic comparisons.

2 LITERATURE REVIEW

Average global air temperatures have been increasing since the industrial revolution c1800. National governments and world organisations (Intergovernmental panel on Climate Change (IPCC), 2014) have declared a climate emergency. The climate is changing rapidly and there are major losses of fauna and flora. The major cause is considered to be the carbon dioxide levels in the atmosphere which have been rising exponentially. Figure 2-1 is copied from ref (2 degrees institute, 2024) and shows the average temperature rise closely follows CO_2 levels. Many countries have agreed to reduce, and eventually eliminate, the burning of fossil fuels for electricity generation, transport and heating. The last remaining coal fired power station in the UK at Ratcliff on Soar closed on 1-Oct-24. The UK is rapidly increasing its renewable energy capacity and hopes to reduce its reliance on the burning of petroleum gas.
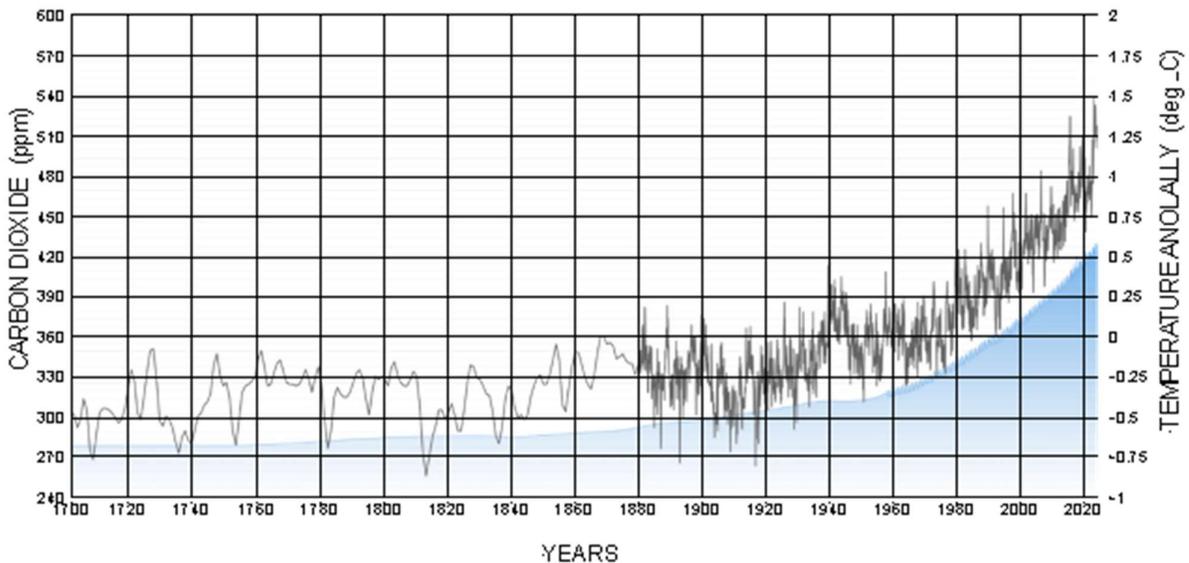
Figure 2-1 CO_2 levels and temperatures from 1700 to 2020 ref (2 degrees institute, 2024).

2.1 Electricity Demand

The demand for electricity is increasing on an annual basis in just about every country in the world. The main uses are for lighting, telecommunications, household appliances, computers and some transport (mainly trains in 2020). Some heating is provided by electricity, especially in high rise buildings where the use of gas is banned. This is due to change dramatically in the UK over the next 10- to 20-years, to reduce CO_2 emissions, to slow global warming and improve air quality. The UK government has stated their intention to ban the sale of new petrol and diesel cars by 2035 (UK

Department of Transport (DoT), 2020). Also, to dramatically reduce or stop the use of petroleum gas for heating.

Currently, around 45% of UK electricity generation is from renewable sources ref (UK Gov Digest of UK Energy Statistics (DUKES), 2024a), i.e. not carbon base fuels. Generation from coal has been phased out and oil generation is very limited, generally as backup supplies. Petroleum gas is now the main fossil fuel used in UK generation. To replace gas there needs to be a step change in the production of renewable electricity. Alternatively,, carbon capture and storage technology need to be developed.

Figure 2-2 has been produced from UK Government statistics (UK Gov Digest of UK Energy Statistics (DUKES), 2024b). The annual electricity generation has risen from just under 4.0-TWh in 1920 to 317.5-TWh in 2018; nearly an 80x increase in 98-years. The peak demand was 379-TWh in 2007, just before a worldwide economic slump. These figures exclude imported electricity, which was 14.7-TWh in 2018. Until 1950 the main fuel was coal, with a small amount of hydro generation. Wind and other renewable sources are reported from 1951. Nuclear power generation was first recorded in 1957. Pumped storage schemes are recorded from 1962. The UK has been importing electricity since 1986, from Ireland and France. Gas was first used for Combined Cycle Gas Turbines (CCGT) following privatisation of the generating industry in 1990. Over the 98-year period the efficiency against fuel used rose from 9.3% to 45.5%. Currently the nuclear AGRs are coming to the end of their lives. There is a strong growth of wind and other renewables.
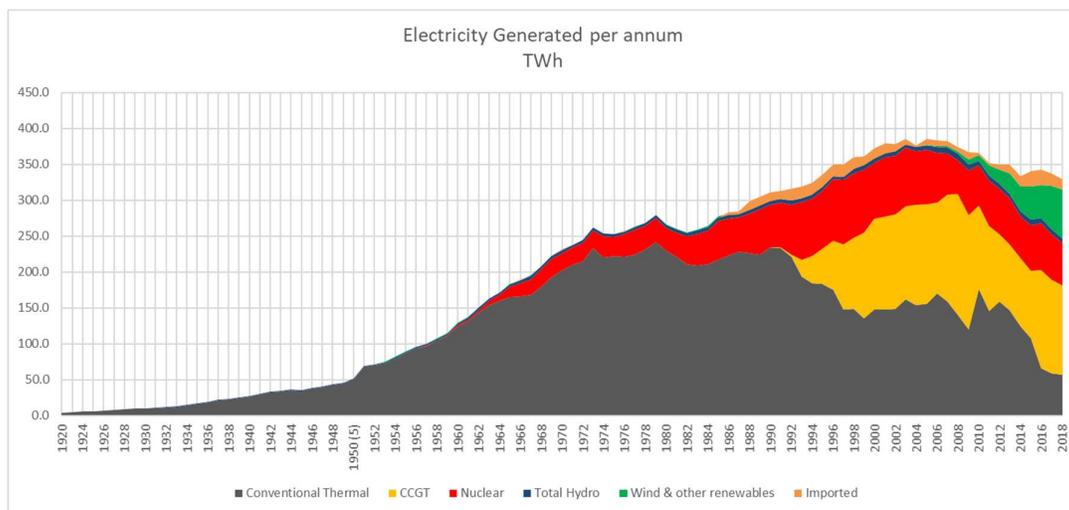
Figure 2-2 UK electricity generated & imported 1920 to 2018 by fuel (UK Gov Digest of UK Energy Statistics (DUKES), 2024b).

Figure 2-3, from Our World in Data (Our World in Data, 2025), shows more detail of UK electricity production since 1985 without imports. Note that production has declined since 2005. Some of the deficit is made up by imports from the current seven international connection cables.

Data source: Ember (2024); Energy Institute - Statistical Review of World Energy (2024)   OurWorldinData.org/energy | CC BY
Note: "Other renewables" include waste, geothermal, wave, and tidal.
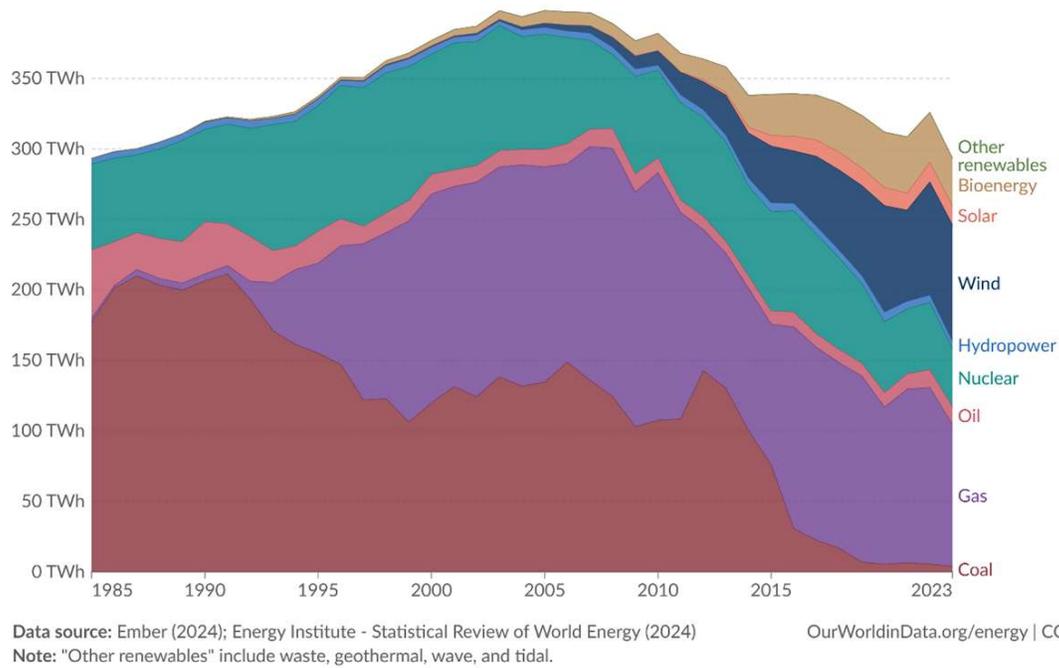
Figure 2-3 UK electricity generated from 1985 to 2023 by fuel (Our World in Data, 2025).

The electricity production for the world shows significant increases since 1985, Figure 2-4. The only years where there was a small decline were in the 2008 financial crisis and the 2020 covid-19 outbreak. Whilst the use of coal for generation has stopped in the UK the worldwide use is increasing, as it is for natural gas.
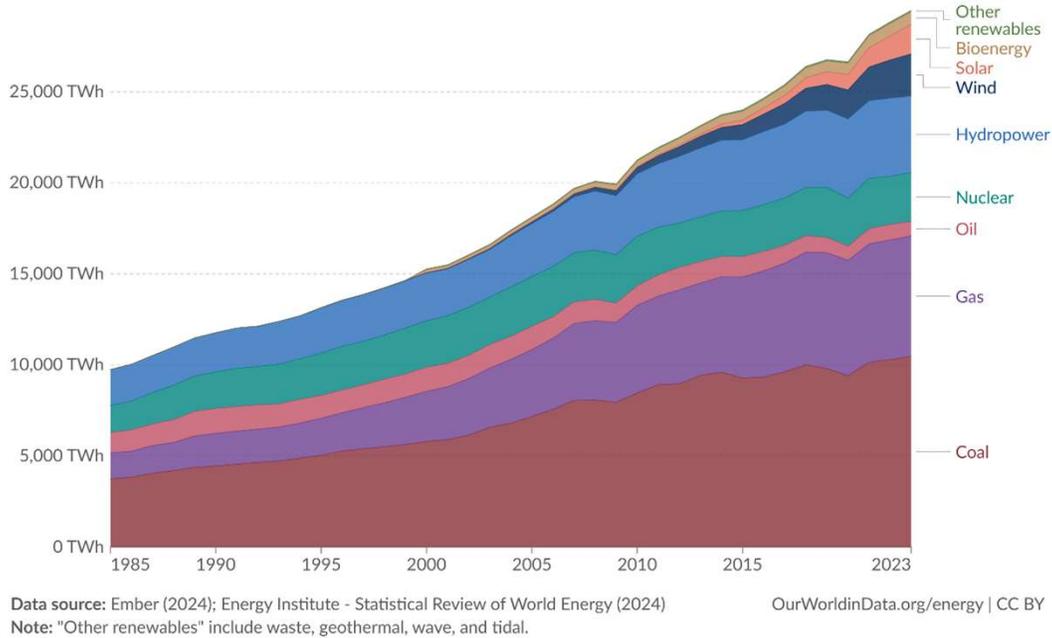
Figure 2-4 World electricity generation by fuel type (Our World in Data, 2025).

Table 2-1 shows world electricity generation ranked by country based on data from (Ember energy, 2025). The top three countries, China, USA and India, produce 53% of world generation. All three of these countries use a high proportion of coal fuel. The UK is in 16th place with 1% of world generation, coal is no longer used. The UK's reliance on petroleum gas may reduce but it will be needed for the foreseeable future to fill gaps in renewable generation as wind and solar are intermittent.

Table 2-1 Worlds top 16 electricity producers by percent in 2023 (Ember energy, 2025).

Order	Location	% of world	Percent of country								
			Coal	Gas	Hydro	Nuclear	Wind	Solar	Oil	Bio	Geo
	World	100	35	23	14	9	8	6	3	2	0
1	China	32	61	3	13	5	9	6	1	2	0
2	United States	14	16	42	6	18	10	6	1	1	0
3	India	7	75	3	8	2	4	6	0	2	0
4	Russia	4	18	45	17	18	0	0	1	0	0
5	Japan	3	32	34	7	8	1	10	4	4	0
6	Brazil	2	2	5	60	2	13	7	2	8	0
7	Canada	2	4	15	58	14	6	1	1	2	0
8	South Korea	2	33	27	1	29	1	5	1	3	0
9	France	2	0	6	11	65	9	4	2	2	0
10	Germany	2	25	16	4	1	28	12	4	9	0
11	Saudi Arabia	1	0	63	0	0	0	1	36	0	0
12	Iran	1	0	85	6	2	0	0	7	0	0
13	Mexico	1	8	58	6	3	6	8	9	2	0
14	Indonesia	1	62	18	7	0	0	0	2	6	5
15	Turkey	1	37	21	20	0	11	6	0	3	3
16	United Kingdom	1	1	34	2	14	29	5	3	12	0

2.2   History of tidal range generation

Waterpower has been used since ancient times for irrigation and motive power for mills. Its use to generate electricity, on a small scale, was recorded in 1928 (UK Gov Digest of UK Energy Statistics (DUKES), 2024b). There are two operational large scale tidal range plants in the world and one that has closed. The Severn Estuary in the UK has the second largest tidal range in the world (after Canada), the total potential around the UK coast is probably the highest. "It is hard to find an energy source where people are more instinctively supportive than tidal power" (Hendry, 2016).

La Rance Tidal Barrage (Andre, 1978; Libaux A, 2019)

This was the world's first tidal barrage built across the river Rance near Saint Marlo, Brittany, France. The estuarine barrage is 330m long, impounding a 22 km^2 basin. Some basic technical data is shown in Table 2-2.

Annapolis, Tidal Plant (Clark, 1997)

This plant is located on Hogg Island at the mouth of the Annapolis River as a federal and provincial government pilot project. It was the third largest tidal barrage in the world. Due to equipment failure, the plant was shut down in January 2019 and the project was subsequently cancelled (Tythys, 2020).

Lake Sihwa Tidal Plant (Andre, 1978; Bae et al., 2010; Schmid, 2005)

This plant was built into an existing barrage between a lake and the sea to improve the water quality in the 43 km^2 lake.

Table 2-2 Summary of existing tidal range schemes.

Name	Year commissioned	spring tidal range (m)	Turbine	unit rating (MW)	total capacity (MW)	Operating mode	Annual electricty produced GWh
La Rance, France	1967	8.0	5.4 dia. Alstom bulb with 4 blades	10	240	two way with pumping	507
Annapolis, Canada.	1984	16.0	7.6m dia. horizontal axis Straflow.	20	20	one way	30
Lake Sihwa, Douth Korea.	2005	7.8	7.5m dia. VaTech bulb with 3 blades.	26	260	one way	553

18-Jan-26

2.3 Tidal range schemes proposed for Great Britain

Historically tidal barrage schemes were proposed across river estuaries to take advantage of higher tidal ranges and reduced lengths of bunds. As the ratio of flooded areas between high and low tide were high, these schemes were mostly ebb only. Consequently, the water range inside the barrage was severely restricted and thus the schemes were opposed due to concerns over damage to the environment. An early study considered the effects of sea level rise (SLR) on flooding and intertidal mudflats for the Severn Barrage project (Ahmadian et al., 2014b). With the development of triple regulated turbines it has been shown that not only can the full tidal range be maintained (Vandercruyssen et al., 2023a) but that tidal barrages can protect the ecosystems from SLR (Vandercruyssen et al., 2023b).

Figure 2-6, a) shows the tide range taken from (Crown Estates, 2012) , b) is from (Waters and Aggidis, 2016). Unfortunately, the Humber Estuary is unlikely to happen as it is home to the 3rd largest port in the UK. Other schemes impounding major estuaries may cause concern over environment issues, but my research shows there are also positive benefits from estuarine barrages (Vandercruyssen et al., 2023b).

| a)   UK tidal range (Crown Estates) | b)   Tidal range potential |
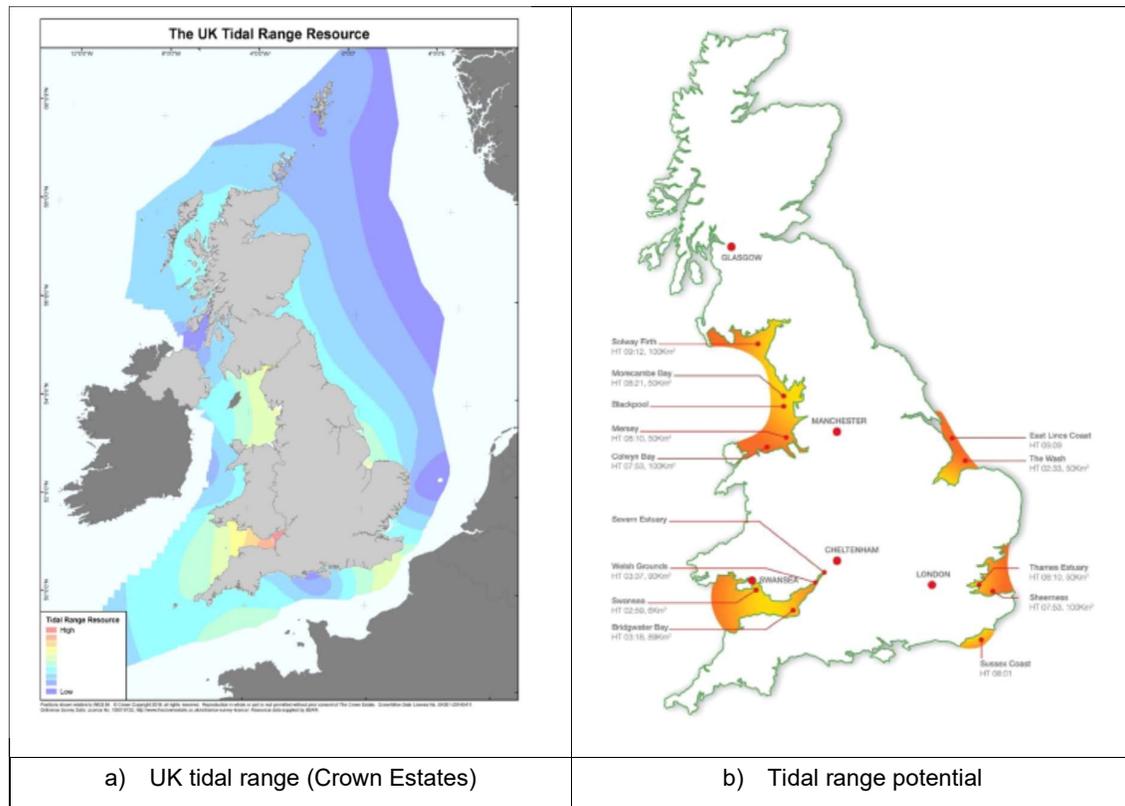
Figure 2-5 UK Tidal Range Resource.

To date, there are no tidal lagoons in operation anywhere but there are two major tidal barrage schemes in operation.

2.3.1 Tidal barrages

Guidelines for the assessment and planning of estuarine barrages have been published by the UK Institution of Civil Engineers (Burt and Rees, 2001).

2.3.1.1 Mersey Bay

The Mersey Bay barrage (Aggidis and Benzon, 2013) described and presented the results of a 0-D model. Several locations were considered as shown in Figure 2-6. The most recent proposal is for 28 bulb turbines of 8m diameter and a total installed capacity of 700-MW.
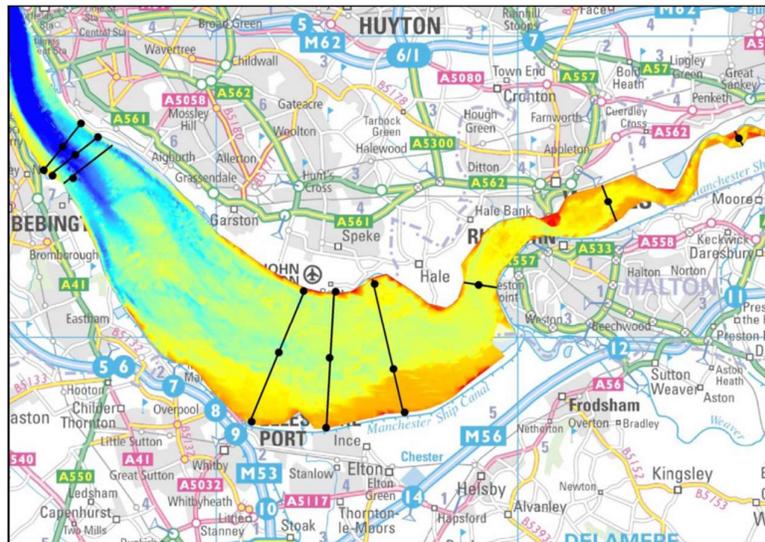
Figure 2-6 Nine locations for barrage considered by SeaZone in 2005, from (Aggidis and Benzon, 2013).

The mayor of Liverpool held a public consultation in 2024, and the majority of the public were in favour of a tidal barrage across the Mersey (Liverpool City Region, 2024), see Figure 2-7.

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Figure 2-7 Section through turbine hall, Mersey (Liverpool City Region, 2024).

2.3.1.2 Morecambe Bay & The Duddon Estuary

These schemes were proposed by NTPG (Northern Tidal Power Gateway, 2020a; Northern Tidal Power Gateway, 2021). NTPG are no longer active but aimed to design and build barrages across both Morecambe Bay and the Duddon Estuaries. The initial proposal for Morecambe Bay contained 120 No. 8m diameter bulb turbines, with 30-MW generators, giving an installed capacity of 3,600-MW. There will be sixty 14 m x 13m sluice gates. The proposed Duddon scheme contains twelve 8m diameter bulb turbines, with 30-MW generators, giving an installed capacity of 360-MW. Also, six 14m x 13m sluice gates. Later work (Vandercruyssen et al., 2022b) suggested that 20-MW generators may give a better return on investment.

Figure 2-8 Duddon and Morecambe Bay estuary crossings (Northern Tidal Power Gateway, 2020b).

2.3.1.3   Solway Firth

A study of the Solway Firth barrage (Aggidis and Feather, 2012) described and presented the results of a 0-D model, see Figure 2-10 for location. The most recent proposal is for 180 turbines of 7m diameter, with 20-MW generators, giving a total installed capacity of 3,600-MW. The estimated annual electricity production is around 9.44-TWh.

Figure 2-9 Proposed location of Solway Firth barrage (Aggidis and Feather, 2012).

2.3.1.4   Wyre Barrage at Fleetwood.

Binnie & Partners produced a report (UK Paliament, 1991) suggesting that the River Wyre was one of the best river sites for a demonstration tidal range scheme see Figure 2-10. Binnie found four x 15-MW turbo-generators would generate about 0.12-MWh per year (Delfgauw, 1991; Young, 1995). Due to its unique location the opportunity exists for a Compressed Air Energy Storage Plant (CAES) by injecting compressed air into some of the redundant salt caverns. The system can eliminate the problems associated with an intermittent power source and add to the economic viability of the project.
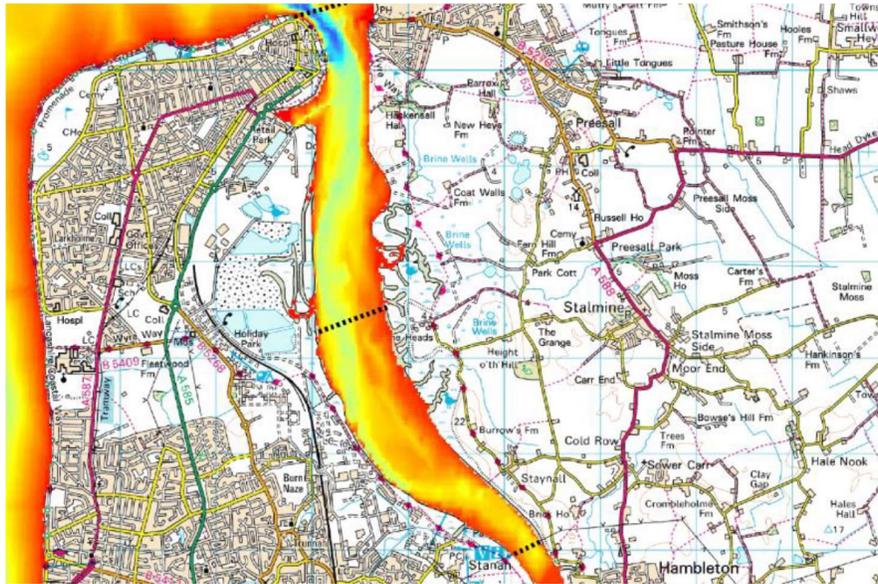
Figure 2-10 Three barrage locations initially studied (Inchley, 2014).

Due to the decline in the fishing and shipping industries the favoured barrage location is now close to the mouth of the estuary. Two locks will be included to always provide necessary access. The scheme is currently being promoted by (Natural Energy Wyre, 2025), see Figure 2-11.

Figure 2-11 The Wyre Gateway scheme in Fleetwood (Natural Energy Wyre, 2025).

The barrage will allow access across the river for service and emergency services vehicles only to preserve the rural community of Knott End. Press reports (Hunt, 2022) state there will be eight 8.2m diameter turbines with a total estimated cost of £380m.

2.3.2 Coastal lagoons

In Dec-16 Charles Hendry published his final report into "The Role of Tidal Lagoons" (Hendry, 2016). Charles Hendry was a former Energy Minister and chaired the review for the Secretary of State for Business, Energy and Industrial Strategy.

> *"There is a long history of proposals to harness marine energy at scale in the UK, with proposals for a Severn Barrage dating back to 1849. The tide mills at Eling and Woodbridge date back to the 17th/18th centuries with evidence of tidal power being used on site for centuries before that".*

The list of potential tidal lagoons in Table 2-2 is from (Hendry, 2016) but does not include all schemes proposed.

Notes for Table 2-2:

1) ITP estimate of the mean of spring and neap tidal ranges.
2) ITP's table includes Tidal Lagoons Power's (TLP) assumptions as at August 2016 for ten sites – Swansea Bay, Cardiff, Newport, Bridgewater, West Cumbria, Barrow, West Lancashire, Sefton, Wirral and Colwyn Bay. For the remainder, ITP has calculated installed capacities by applying a scaling factor (a ratio of installed capacity to maximum energy available from the tidal lagoon over one year) derived from TLP's more advanced tidal lagoons and calculated enclosed area and seawall lengths using other resources that consider site constraints.
3) Basin area at Highest Astronomical Tide.
4) Bridgwater Bay prohibits a tidal lagoon at Minehead.

Table 2-3 Potential Tidal Lagoon Sites in the UK from Hendry (Hendry, 2016)

Potential tidal lagoon sites in the UK					
Site	Tidal range (1)	Installed capacity (2)	Enclosed area (2) (3)	Seawall length (2)	Ratio of enclosed area to seawall length
	metres	MW	km²	km	km² per km
Severn Estuary					
Swansea Bay	6.2	320	11.5	9.5	1.2x
Stepping Stones	7.7	790	18.0	10.6	1.7x
Cardiff	8.6	3,240	71.8	21.0	3.4x
Newport	8.6	1,440	40.2	17.5	2.3x
Bridgwater Bay (4)	8.1	6,480	243.2	34.1	7.1x
North Wales and Liverpool Bay					
Conwy	5.2	740	40.0	16.5	2.4x
Colwyn Bay	5.5	3,200	119.8	22.8	5.3x
Sefton	6.1	2,600	101.9	27.7	3.7x
Wirral / Liverpool	6.3	1,600	67.1	21.9	3.1x
North West					
West Cumbria	5.6	2,200	92.1	22.4	4.1x
Blackpool	6.1	2,600	96.3	24.5	3.9x
Wyre	6.5	3,045	120.0	19.9	6.0x
Barrow in Furness	6.5	1,600	56.8	23.2	2.5x
East Coast					
The Wash	4.5	695	50.0	18.8	2.7x
East Lincs Coast	4.7	1,940	120.0	29.9	4.0x
South East					
Sheerness	4.2	1,310	100.0	28.6	3.5x
Thames Estuary	4.3	515	50.0	19.0	2.6x
Sussex Coast	4.6	2,415	160.0	34.8	4.6x

Source: ITP advisors to the Hendry report on tidal lagoons (ITP Energised, 2025).

2.3.2.1 Bridgewater Bay

The Bridgwater Bay tidal lagoon is located on the south side of the Severn Estuary; it would stretch from Brean Down to Hinkley Point, see Figure 2-12. It would generate an estimated 2.6-TWh of power per year and provide flood protection to the coastal community. The scheme has a projected construction cost of between £3.4 - £4.1bn.
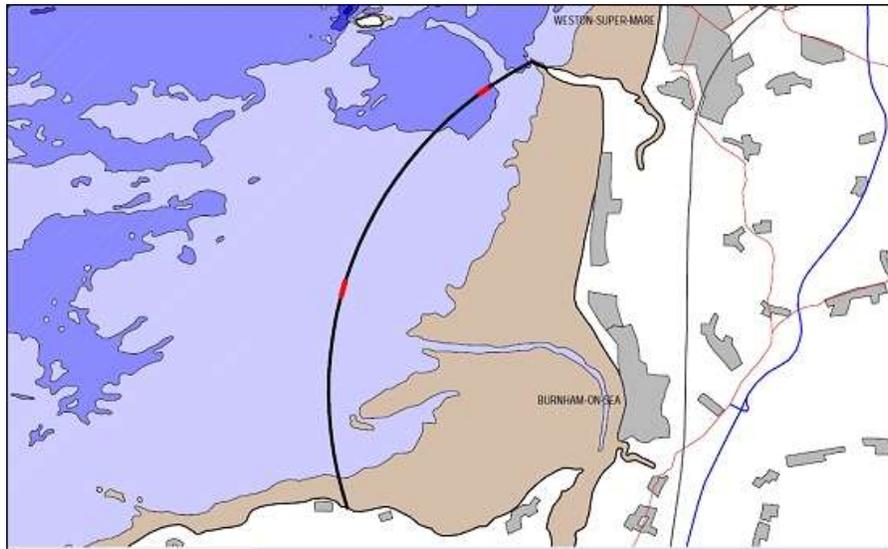
Figure 2-12 Bridgewater Bay Lagoon (Burnham on Sea News, 2009).

2.3.2.2 North Wales Tidal Energy and Coastal Protection (NWTE)

NWTE (North Wales Tidal Energy (NWTE), 2025) is proposing a 32-km barrage along the coast of North Wales from Llandudno to Prestatyn, see Figure 2-13, enclosing an area of approximately 150 km^2 and protect the adjoining land from flooding. NWTE proposed to install between 100 and 125 turbines of 15- to 20-MW capacity with 8m blades, based on the Andritz/GE bulb turbine. The project also provides flood protection to several low-lying areas between The Great Orm and Prestatyn.
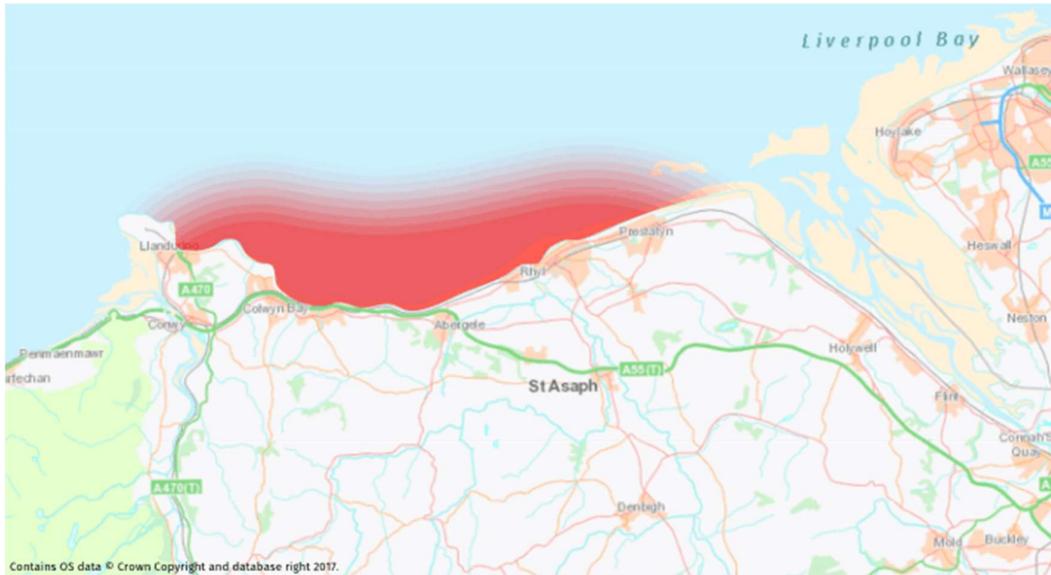
Figure 2-13 area of interest proposed by (North Wales Tidal Energy (NWTE), 2025).

2.3.2.3 Swansea Bay

The Swansea Bay lagoon was considered to be the "pilot" plant (Hendry, 2016), as it was the most developed and relatively small scale at the time of Hendry's review. A study (Petley and Aggidis, 2016) described the scheme and presented an estimate of the annual electricity generation, see Figure 2-14. The proposal is for 16 turbines, each of 20-MW maximum rating. Thus, installed capacity would be 320-MW. More detailed modelling was carried out by Cardiff University (Xue, 2021).
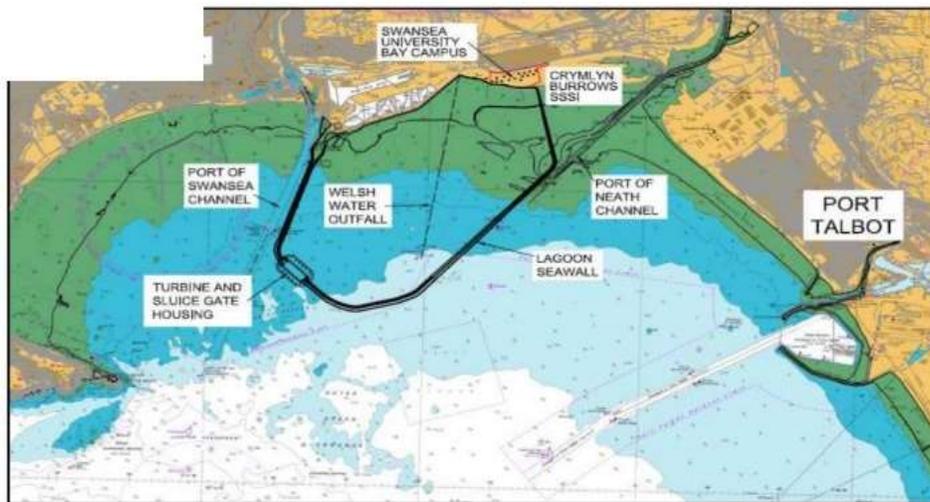
Figure 2-14 Swansea Bay Lagoon layout overlaid on the Admiralty Chart background (Xue, 2021).

2.3.2.4   West Somerset Lagoon

The West Somerset lagoon is in the Bristol Channel or Severn Estuary and one of many proposals for that area, see Figure 2-15. It is almost semi-circular between Minehead and Watchet on the south bank of the estuary. In the preliminary stage, the options for bulb turbines numbers were 75, 100 or 125, each of diameter 7.2m, and each rated at 20-MW (Xue, 2021). Units would be installed within a single concentrated block.

Figure 2-15 Map of the West Somerset Lagoon (Xue, 2021).

2.4   Hydro Turbines

Tidal range is classed as "low-head" in terms of turbine technology, i.e. a maximum 10m head as opposed to 300m "high-head" turbines. A study (Waters and Aggidis, 2016) gives an excellent "state of the art" review of turbine technologies. Some of the following figures in Figure 2-16 and Table 2-4 are taken from their paper.

Bulb turbine	Straflo turbine
Modified bulb turbine	Archimedes screw

Counter rotating turbine	Pentair Nijhuis Turbine
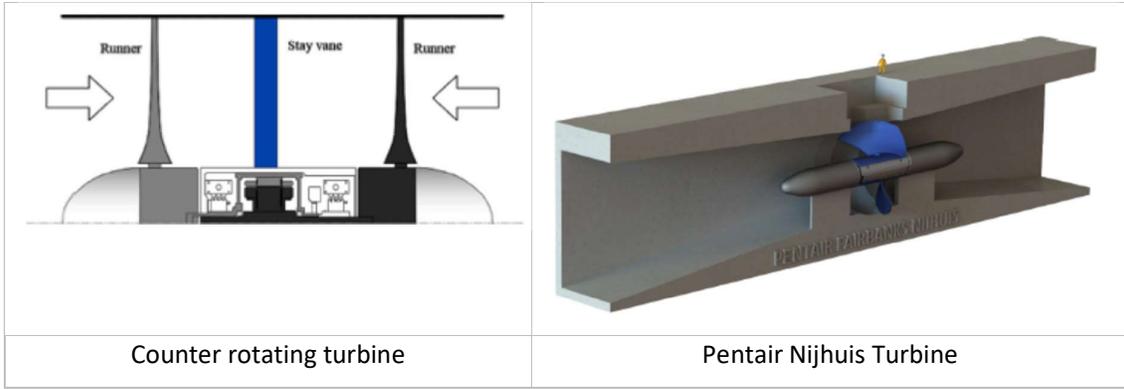
Figure 2-16 Low head turbines suitable for tidal range.

Table 2-4 Turbine comparison (Waters and Aggidis, 2016).

	Turbine Type	Environment	Efficiency	Cost	Maintenance
Operational	**Bulb** First created in 1913 by Victor Kaplan. It is now the most common turbine currently in low head tidal range situations and also planned for use in upcoming projects such as Swansea Bay. 20 MW.	Can damage marine life in a variety of forms, such as pressure changes, cavitation, strike, grinding, turbulence, and shear stress. Manufacturers are trying to make these more fish friendly.	Ebb 90% reverse 72% pumping %	Very complex design so costs are very high.	Low maintenance and long life. Trash screens required to prevent damage.
	Straflo Created in 1919, this is an axial turbine currently only deployed in a single location – Annapolis. 20 MW	Similar issues with marine life as Bulb Turbines.	Single direction 78–89%, can not pump.	Civil costs less than bulb turbines, but manufacture similar.	Access easier than bulb but sealing of water cooling and generator may be a problem. Trash screens needed.
Under Development	**Modified Bulb** utilises all of the positive aspects of the original bulb turbine. Has extra set of guide vanes to increase efficiency when operating in reverse.	Slightly worse than Bulb because the exta set of guide vanes increases chances of fish impact.	Ebb 80% reverse 80% pumping %	More complex than bulb turbine so costs even greater.	Greater than bulb due to extra maintenance of more guide vanes. Trash screens more important.
	Archimedes screw not yet been used in a tidal range situation, it has had success as an inclined axis stream turbine. It has also been suggested for use within an enclosed pipe system as it would for a tidal range.	Frequently used as fish ladders. The low RPM cause low values of shear stress and turbulence which fish are exposed to in normal open seas.	Generate 78-85%. Pump ? Good. Lower than bulb but can operate over a larger range.	The simple nature of the design and composite materials make it remarkably cheap. Avoids need for sub-marine turbine halls gives major savings in construction cost and time.	lack of adjustable parts means very low maintenance. Expect 30-year life. Gearboxes may need work.
	Counter rotating uses two tandem runners connected to a counter rotating permanent magnet AC generator.	The low solidity of the turbine blades and lack of guide vanes allow fish to pass through easily.	Not yet even theoretically tested in a tidal range scenario. Equal efficiency in either direction.	May not need gearbox. Less torque on support structure.	No high-risk objects such as gearboxes or guide vanes, mechanical maintenance is fairly simple, hassle free and low cost. However, debris screens will be needed which require regular maintenance.

The colour formatting in Table 2-4 shows the respective strengths of each turbine analysed.

Green = good, Yellow = Acceptable and Pink = Poor (subjective).

The bulb turbine has been proven at La Rance (Andre, 1978) and Lake Shewa (Bae et al., 2010). The Straflo turbine at Annapolis had mechanical problems and was shut down (Tythys, 2020).   A counter rotating turbine is being developed to the model stage (Jacobs, 2025). Figure 2-17 by (Waters and Aggidis, 2016) shows estimated efficiency of turbines against maximum design flows. The Archimedes Screw may be worth further investigation for low heads as it is regarded as fish friendly and requires less civil engineering construction.
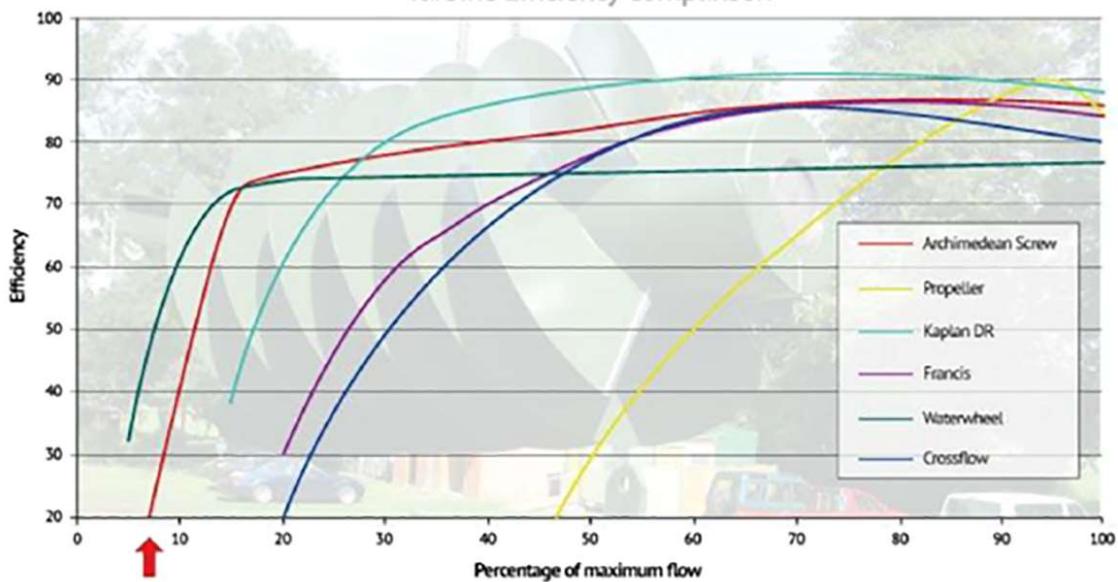
Figure 2-17 Turbine efficiencies with varying flow (Waters and Aggidis, 2016).

2.5   Energy storage options

The literature review for energy storage options has been removed from this work. It was originally intended to study energy storage but was omitted in favour of the economics of tidal range.

2.6   Summary

CO_2 levels and global average temperatures are still increasing exponentially. The UK is trying to reach net zero emissions by 2050. However, as the UK is only responsible for 1% of the world's emissions it requires all nations to reduce emissions. This is very unlikely to occur due to population growth and 3rd world development.

There are currently only two operational grid scale tidal range (TR) power plants, La Rance in France has been operating since 1966 and Lake Sihwa in South Korea since 2011; smaller trial plants have been built in several other countries. There are more than a dozen TR schemes proposed around the coast of Great Britian (GB), most are concentrated along the west coast which has enormous potential. None of the proposed GB schemes are currently actively progressing. The main impediments to investment are: -

- The economic viability
- Perceived damage to the environment

To a lesser extent, the intermittency of generation is a concern, although common to most renewable sources, but is at least predictable for TR. Thus, electrical storage is becoming an urgent need as the UK switches to renewable energy. The most efficient form of storage is pumped hydro storage (PHS) and there are proposals to develop more of these, mainly in Scotland as suitable sites are limited. Typical schemes can generate electricity for several hours as the water is released through turbines to a bottom lake. Converting potential energy to electricity. Although not efficient in terms of energy, it is the most efficient financially and the best way of balancing supply and demand.

3   THE 0-D MODEL

0-D models are a first approximation to the tidal range concept and assume that the change in levels of a body of water occur everywhere at the same time. I.e. pulling the plug out of a bath the water level drops at the same rate over the whole surface in the bath. Some have described this as 1-D which seems more logical as the two water bodies are at different surface levels. 2-D and 3-D models also exist and should be more accurate but require full knowledge of the bathymetry and involve much more complicated mathematics and computation power. The 0-D model is ideal for the initial assessment of schemes (Ahmadian et al., 2017; Angeloudis et al., 2015), but some researchers believe it can over-estimate the potential generation by up to 10% (Angeloudis et al., 2017).

The 0-D model should be linked to a simple cost model (Vandercruyssen et al., 2022a; Vandercruyssen et al., 2023a) to optimise the components of:-

- Number and sizes of turbines
- Number and sized of sluices
- Maximum generator ratings.

If an optimised 0-D scheme appear favourable in-depth site surveys and evaluations will be needed for the next stage. When the water quality, specific tide ranges and bathymetry are available, 2-D and 3-D investigations will be needed (Ahmadian et al., 2014a; Kadiri et al., 2012).

3.1   Basic Hydraulic Equations

The concept and basic equations for tidal range are remarkably simple. By forming a barrage between the sea and a large body of water it is possible to "hold-back" the tide. This produces a difference in level between the two bodies of water, termed *head*. Creating potential energy from gravitational pull of the sun and moon. Water can then be released through sluices or turbines to flow into the lower body of water, as Kinetic Energy, used to generate electricity.

3.1.1   Potential Energy

Potential energy (Pe) is the energy stored when a mass m is subject to an acceleration (gravity g) and can fall by a specific distance $h,$ see Equation 3-1.

$$Pe = mgh$$

Equation 3-1 Potential energy.

Where: -

      m =   the mass of water above the lower water level.

      g =   the acceleration due to gravity (9.81 m/s^2).

      h =   height of the centre of gravity of the upper water above the surface of the lower water level (head).

It is not possible to liberate all the potential energy in conversion to electrical/mechanical energy without an infinite number of machines. Turbines need minimum operational heads, and some water must flow freely at the ends of each cycle.

In the tidal range situation, consider two bodies of water with a head difference H. Assuming 10-minute timeslots, we consider the potential energy stored in the top layer of water at head H. The centre of mass of this element is at height H- δh but δh is small. Over the 10-minutes the water level will drop by δh. The potential energy released in 10-minutes is shown in Equation 3-2.

$$Pe = mgh = A \times \delta h \times \rho \times 9.81 \times H$$

Equation 3-2 potential energy.

Where: -

      Pe   is the potential energy

      A   is surface area of lagoon

      δh is the change in water level over 10-minute period

      H   is the head between the sea and impoundment water levels

      P   is the density of sea water, typically 1,025 kg/m^3.

Units are m^2 x m x kg/m^3 x m/s^2 x m = kg m^2 / s^2 = 1 Joule

Converting 1 MW h = 3.6 GJ.

3.1.2 Fluid Dynamics

In 1643, Torricelli showed that the velocity of efflux of an ideal fluid from a small orifice under a static head varies with the square route of the head, written as $V = \sqrt{2gh}$, see Figure 3-1.
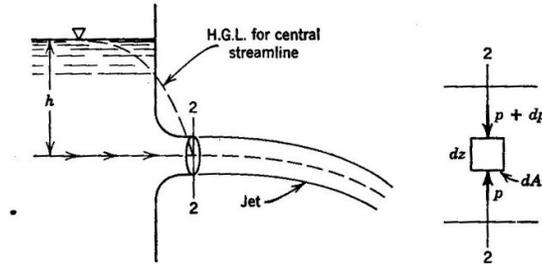
Figure 3-1 Torricelli's flow through orifice copied from (Vennard, 1961).

In practice, a drag coefficient C_d is included to represent losses in the system. C_d is dimensionless and generally taken as 0.95. However, for flow through a turbine where the intake area is greater than the area of the turbine blades C_d can be greater than 1.0 as the flow accelerates towards the turbine. The flow Q through the orifice is the velocity times the area of the orifice A_s, see Equation 3-3.

Equation 3-3
$$Q = A_s \times C_d \times \sqrt{2gh} \quad m^3/s$$

Where: -

Q	=	the water flow (m³/s).
As	=	the area of the opening or sluice (m²).
Cd	=	the drag coefficient.
g	=	the acceleration due to gravity (9.81 m/s²).
h	=	the water head above the centre of the opening.

Equation 3-3 is independent of the depth of the orifice below the lower water level, provided h is the difference in level (head) between the two bodies of water. Sluices and/or locks are provided to increase the flow of water when the water head is too low for generation. These are opened around low and high time times, and the turbines allowed to run free, so that water levels equalise as fast as possible. The total area As in Equation 3-3 is thus the combined area of turbine shaft diameters, sluices and any locks. Generally, all orifices are closed as soon as the water levels equalise.

These free-flow equations do not apply during generation, and pumping, as there is a breaking torque on the turbines which reduces the speed of the water discharge and turns part of the kinetic energy into mechanical/electrical energy.

3.2   Turbine Performance

The design of hydro turbines starts with small scale models to test the performance and predict the behaviour and efficiencies of the full-scale units. The standard model test is for a 1m diameter turbine with a 1m head of water (CEI/IEC, 1999), the angles of guide vanes and blades are altered to vary the flow and speed of the water, called *double regulation*. A 3-D surface model is produced which is usually represented as a contour map called a Hill Chart. They are unique for each type of turbine and are normally highly classified by the manufactures. Figure 3-2 has been published (Aggidis and Feather, 2012) for the Andritz 20-MW bulb turbine. The vertical axis is the model discharge, from 0 to 6 m3/s. The horizontal axis is the model speed as rpm from 150 to 400. The blue line represents the maximum output. α represents the wicket gate opening in gradians and β the runner blade opening.
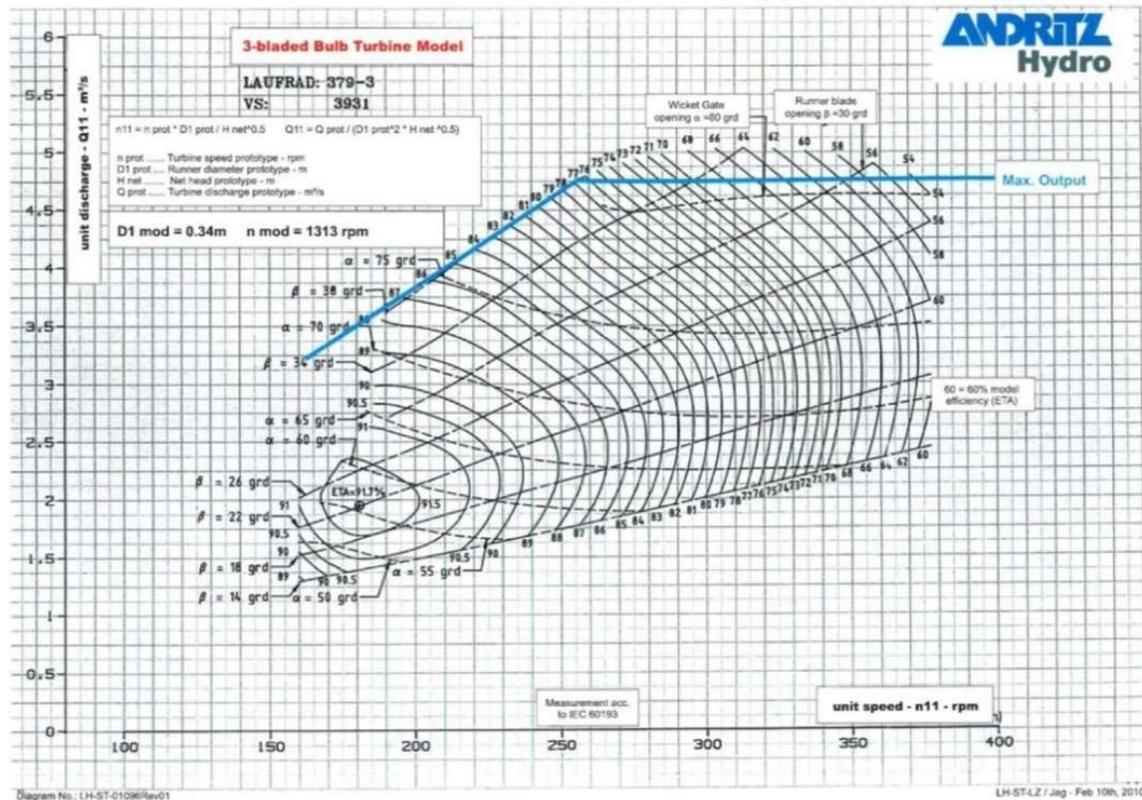
Figure 3-2 Andritz Hydro Three-Blade low head bulb turbine unit, ref (Aggidis and Feather, 2012).

The Affinity, or Similarity laws, define the relationship between the full-size turbine and the model used to develop the hill chart (Aggidis and Židonis, 2014), see Equation 3-4.

$$\frac{Turbine\ flow\ Q_t}{Model\ flow\ Q_m} = \left(\frac{Turbine\ head\ H_t}{Model\ head\ H_m}\right)^{0.5} \times \left(\frac{Turbine\ runner\ diameter\ D_t}{model\ runner\ diameter\ D_m}\right)^2$$

$$\frac{Turbine\ speed\ n_t}{Model\ speed\ n_m} = \left(\frac{Turbine\ head\ H_t}{Model\ head\ H_m}\right)^{0.5} \times \frac{model\ runner\ diameter\ D_m}{Turbine\ runner\ diameter\ D_t}$$

Equation 3-4 Affinity laws (Aggidis and Židonis, 2014)

Where *t* is the full-size turbine and *m* is the model. The hill chart is normalised to 1 m head and 1 m diameter runner. So, the equations full size turbine speed is given by Equation 3-5.

$$n_t = n_{11} \times D^2 \times \sqrt{H}$$

Equation 3-5 Speed (Aggidis and Židonis, 2014)

Where: -

n_t	=	the full-size turbine speed (rpm).
N_{11}	=	the model turbine speed (rpm).
D	=	the diameter of the full-size turbine (m).
H	=	the head (m).

Rearranging Equation 3-6 gives the model speed in as Equation 3-6.

$$n_{11} = \frac{Sp\ \times\ D_1}{\sqrt{H}}\ rpm$$

Equation 3-6 model speed

The flow through a full-size turbine is given by Equation 3-7.

$$Q_t = Q_{11} \times D^2 \times \sqrt{H}$$

Equation 3-7 Flow through full size turbine (m³/s).

Where: -

       Q_t is the full-size turbine flow (m³/s).

       Q_{11} is the model turbine flow (m³/s).

       D   is the diameter of the full-size turbine (m).

       H   is the head (m).

Rearranging Equation 3-7 gives the model flow as Equation 3-8.

$$Q_{11} = \frac{Q}{D^2 \times \sqrt{H}} \quad m^3/s$$

Equation 3-8 model flow

The power output can then be calculated as Equation 3-9.

$$P = \rho \times g \times H \times Q_t \times \eta$$

Equation 3-9 power

Where: -

       P   is the power output.

       ρ is the density of water (sea) (kg/m³)

       g   is the acceleration due to gravity (m/s²).

       H   is the head (m).

       Q_t is the full-size turbine flow (m³/s).

       η is the overall efficiency.

For dual regulation the speed of the turbine is governed by the grid frequency, number of poles in the winding and the chosen gear ratio will fix the turbine speed at a constant value. Triple regulation gives the freedom to vary the turbine speed and hence manipulate n_{11} as desired.

From the hill chart the minimum operating speed of the model is about 160 rpm. As the flow increases the efficiency reduces as the speed increases up to about 255 rpm. Above 255 rpm the flow is at its maximum of Q_{11} = 4.75 m³/s and the efficiency drops with increasing speed. At around 375 rpm the efficiency has reduced to 52% and is the maximum operable speed of the model.

Aggidis & Feather (Aggidis and Feather, 2012) scanned the Hill Chart and produced two dimensional plots to aid understanding. Figure 3-3 shows a linear increase in model flow Q11 between model speeds of 160 rpm to a maximum flow at about 255 rpm.
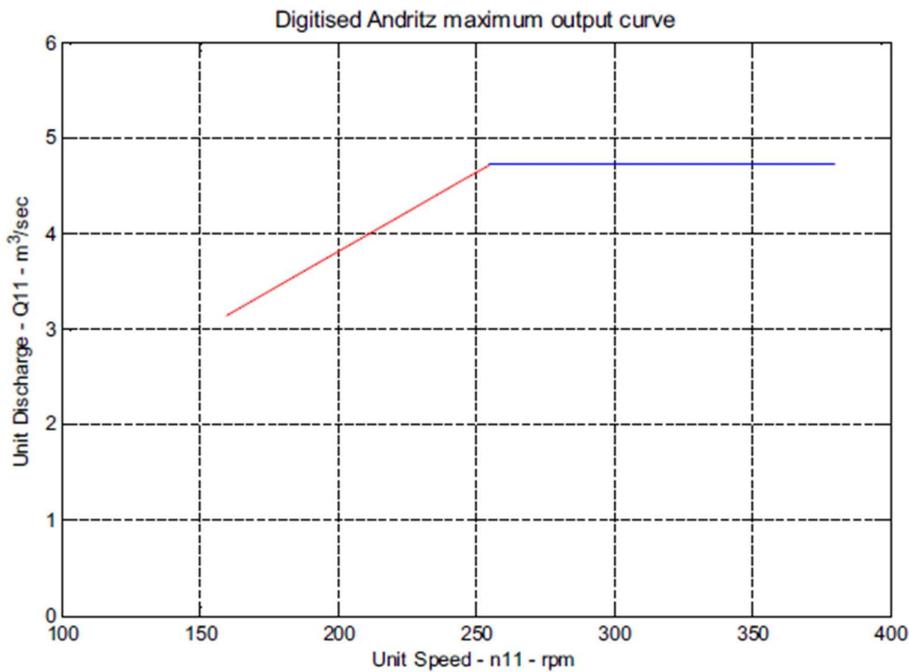
Figure 3-3 Model discharge v speed from (Aggidis and Feather, 2012).

The model flow between speeds of 160 and 255 rpm is given by Equation 3-10.

$$Q_{11} = (0.0166) \times n_{11} + 0.4861$$

Equation 3-10 Model flow between 160 and 255 RPM.

Where: -

Q_{11}	=	the model turbine flow (m³/s).
n_{11}	=	the model turbine speed (rpm).

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Above 255rpm the turbine is "running free" and the discharge is limited by the pressure head and diameter of the orifice. For this turbine Q_{11} is limited to 4.75 m³/s.

3.2.1 Efficiency

From the hill chart Aggidis plotted the turbine efficiency against unit speed which produced a straight line inverse function of the model speed, see Figure 3-4.
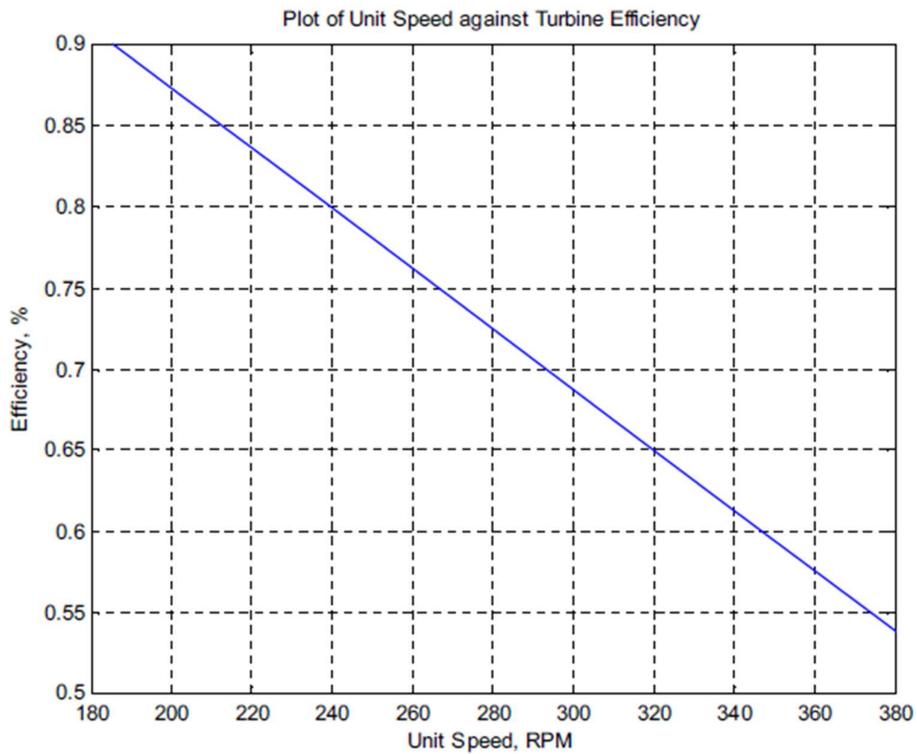
Figure 3-4 Efficiency v model speed for the Andritz 3-blade turbine (Aggidis and Feather, 2012).

Efficiency as a linear equation given in Equation 3-11.

$$\eta_t = (-0.0019) \times n_{11} + 1.2461$$

Equation 3-11 Efficency vs model speed (Aggidis and Feather, 2012).

Where: -

η_t	=	the turbine efficiency.
n_{11}	=	the model turbine speed (rpm).

3.2.1.1 Other losses

A study (Aggidis and Benzon, 2013) summarised other efficiency losses as follows:-

- Generator efficiency, η_p will vary from manufacturer to manufacturer, for 12-MW generators, it is typically in the region of 98% or 97% Andre, (Andre, 1976).

- Transformer efficiency, η_t, will vary depending on the size of the transformer, manufacturer, cost, etc. However, based on experience with power plants of a similar scale, a typical figure of 99.5% was used, (Libaux, 2011).

- Water friction, η_w is an estimate of the losses due to water friction. For a study looking at a Tidal Lagoon Swansea Bay, the efficiency was given as 95% (Baker and Leach, 2006).

- Gear box/drive train efficiency, η_g as with the previously mentioned losses, the gearbox losses will vary from turbine to turbine, depending on the type of gear, material, friction, temperature etc. A study done by 'NHT Engineering' looks at the various losses in a bulb turbine unit, giving an average gearbox efficiency of 97.2% (Taylor, 2008).

- Turbine availability, η_a refers to the losses based on the availability of all the turbines for power generation throughout the barrage lifecycle. Although varying depending on the potential problems with the turbines as well as maintenance requirements, a loss of 5% is usually used (Baker C and Leach P, 2006).

All the losses described above can be multiplied together to give the overall barrage system efficiency (excluding turbine), see Equation 3-12.

$$\eta = \eta_h \times n_p \times n_t \times n_w \times n_g \times n_a$$

Equation 3-12 Other efficiency losses, (Aggidis and Benzon, 2013).

Inserting typical figures into Equation 3-12 gives Equation 3-13.

$$\eta = \eta_h \times 0.97 \times 0.995 \times 0.95 \times 0.972 \times 0.95 = 0.85\,\eta_h$$

Equation 3-13 Typical other efficiency losses, (Aggidis and Benzon, 2013).

3.2.2 Discharge

Figure 3-5 is and extract from a graphical user interface (Mathworks, 2025) by (Aggidis and Feather, 2012). It is based on the full size 3-blade Andritz turbine and shows the discharge against head of water.
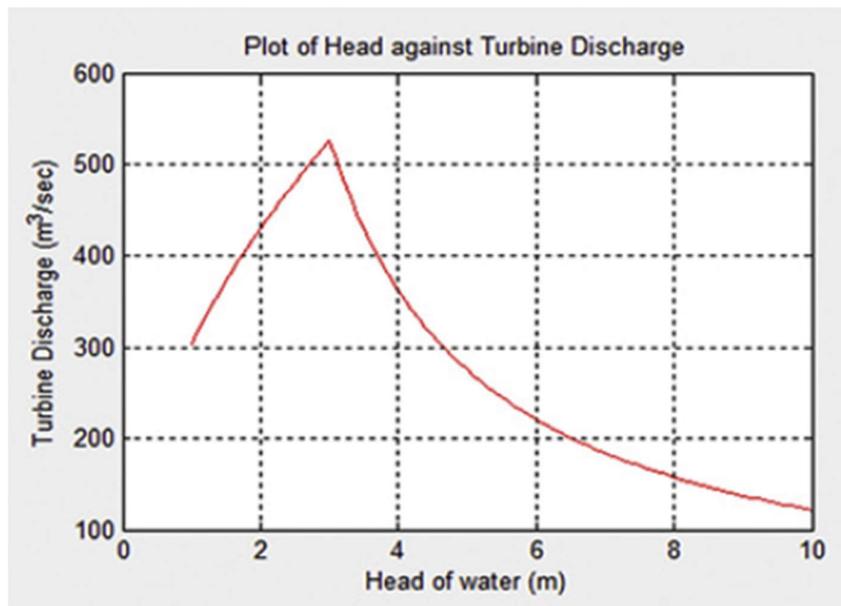
Figure 3-5 Discharge v Head copied from (Aggidis and Feather, 2012).

3.3 Scheme Optimisation

Once you have a potential scheme in mind you have, or can investigate the following: -

- Tidal range
- Length of barrage
- Depth of water along barrage
- Impoundment area

With this information it is then necessary to select the number and size of turbines to give optimum performance or return on investment.

3.3.1 Size of turbine

For bulb turbines there is a general rule of thumb (Pentair, 2017) to minimise cavitation on the blades which states that *the centreline of the turbine should be at least 1 blade diameter below the lowest water level (Pentair, 2017).*

- For a 20-MW turbine with 8m dia. blades, the centreline of the turbine would be 8m below lowest water level (chart datum). The invert would be at -12m chart datum. To avoid too much silt and sedimentation the invert should be above the natural seabed level, say at least 1m. Thus, minimum depth of water needed would be -13m below chart datum.
- For a 10-MW turbine with 6m dia. blades, the centreline of the turbine would be 6m below lowest water level (chart datum). The invert would be at -9m. To avoid too much silt and sedimentation the invest should be above the natural seabed level, say at least 1m. Thus, minimum depth of water needed would be -10m chart datum.

Normally the larger the turbine the slower the speed and the greater is the efficiency. However, where there is a limit on the water depth smaller output turbines may be more suitable.

An early version of the Lancaster 0-D model was used to investigate the Solway Firth scheme with 180 x 9m diameter turbines (Aggidis and Feather, 2012). See Figure 3-6 which shows there is no benefit for increasing the generator limit above 25-MW and it may be that 20-MW limit is more cost effective.
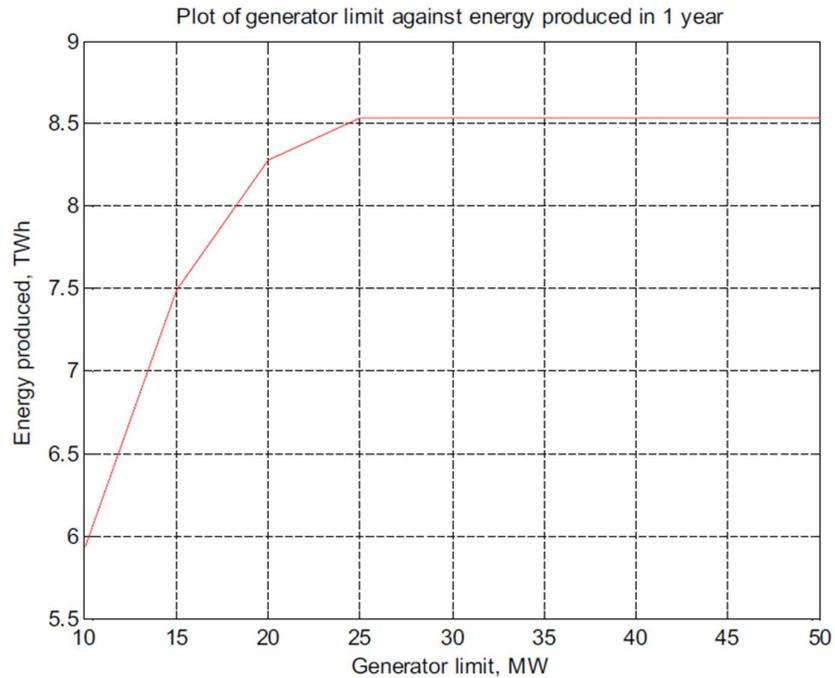
Figure 3-6 Energy generated v Generator limit copied from (Aggidis and Feather, 2012).

3.3.2 Diameter of the blades

Figure 3-4 shows that efficiency is inversely proportional to the rotational speed of the model. For the Andritz 20-MW turbine the optimum model speed is 190 rpm. This would lead one to think that the larger the blade diameter the better efficiency. However, other factors come into play. Figure 3-5 shows the turbine discharge v head of water. Remember also that the total volume of water available is also finite. Too large a discharge and you will run out of water.

A plot of annual energy production (AEP) v turbine diameter (Aggidis and Feather, 2012) for the Solway Firth is shown in Figure 3-7, there appears no benefit for turbines larger than 7m diameter.
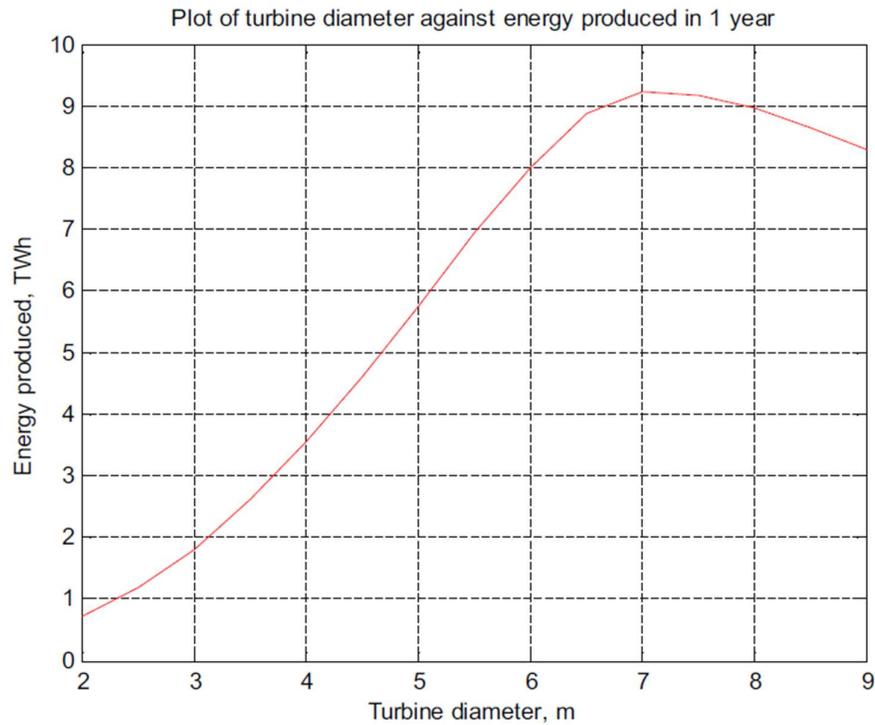
Figure 3-7 Energy generated v blade diameter for the Solway Firth copied from (Aggidis and Feather, 2012).

3.4   Scheme Operation

Once the turbines are selected and installed at a particular site the controls, or variables, available to the operator are: -

- Operating mode, Ebb, flood or 2-way.
- Head to start generation, may be different for ebb and flood.
- Head to end generation, may be different for ebb and flood.
- Turbine speed & discharge.
- Pumping, when and maximum head.

The operator seeks to maximise the financial return by generating as much electricity as possible at the highest available price. The operator will use historical price data and weather forecasts to predict the price for the coming hours. As there are 2 full tide cycles every day, the prediction need only be for the coming 12-hrs.

3.4.1 Head to start of generation.

The ideal head to start generation will depend on the tidal range and the scheme configuration. Thus, each scheme will have different optimum curves, even if the turbines are the same. The tidal range varies with each tide. Figure 3-8 shows the optimum starting head for the full range of ebb tides from the Lancaster Universities' 0-D model of the Mersey Estuary (Aggidis and Benzon, 2013). This was done by analysing a single tidal cycle of specific range and changing the start head and recording the energy generated. By running several starting heads, the optimum value can be obtained for that tidal range. The process is repeated for different ranges between the spring and neap tides.
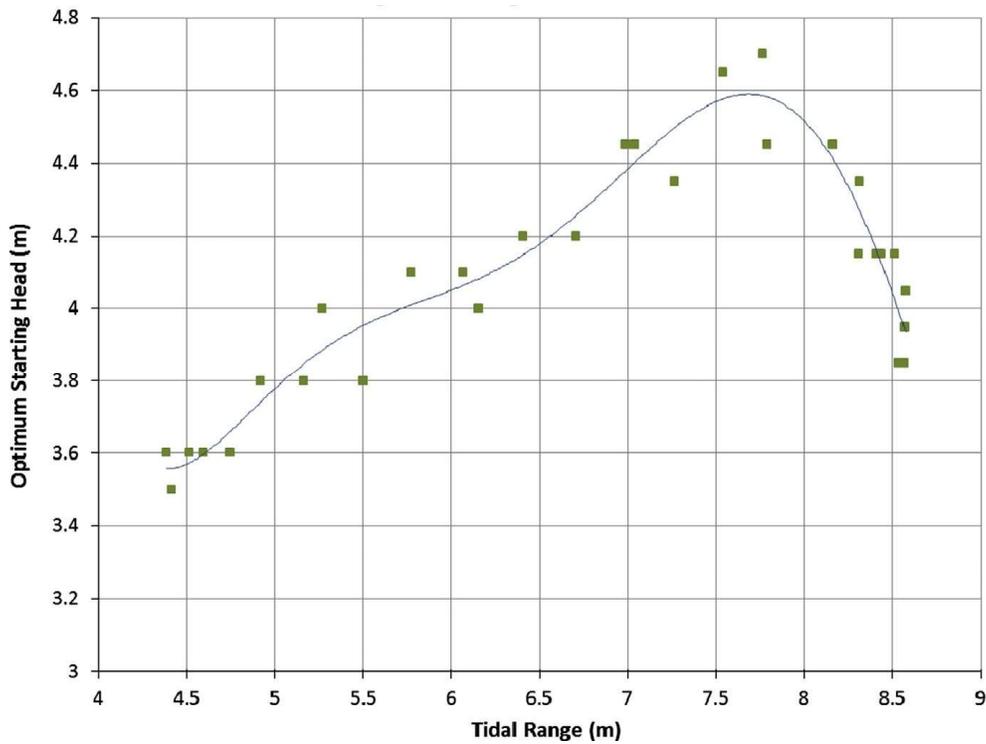
Figure 3-8 Optimum starting head copied from Mersey example (Aggidis and Benzon, 2013).

Thus, the O-D model can include a function for the optimum starting head for each tide range.

3.4.2 Operating modes

Figure 3-9 shows sea and impoundment water levels for ebb only generation (Waters and Aggidis, 2016). The orange area represents the generation phase. Note that the high level in the

impoundment approaches the high sea level but does not reach it. The lowest impoundment level is only just below mean sea level so much of the low intertidal area will remain flooded.
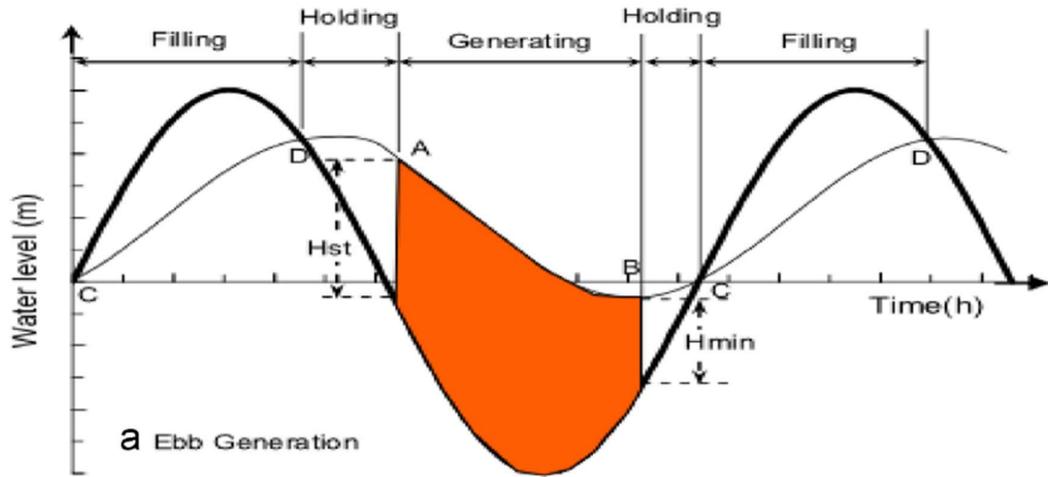
Figure 3-9 One way generation – ebb only (Waters and Aggidis, 2016).

Figure 3-10 shows typical two-way generation without pumping (Waters and Aggidis, 2016). Note that the minimum impoundment level is closer to the lowest sea level.
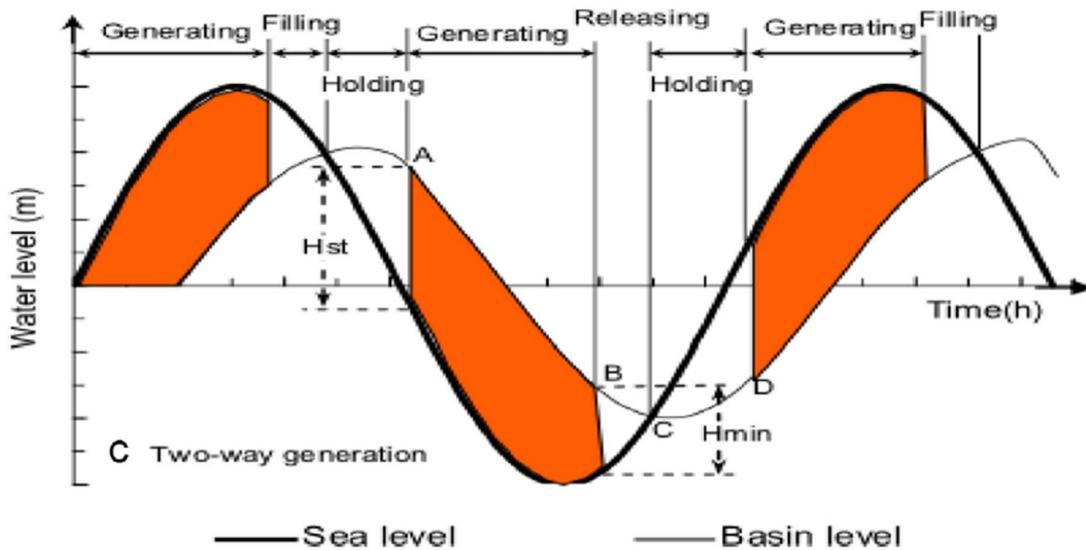
Figure 3-10 Typical cycle for two-way generation without pumping (Waters and Aggidis, 2016).

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Figure 3-11 shows two-way generation with pumping (Xue, 2021). Note that there is a short period of pumping after the water levels have equalised. In this case both the high and low impoundment levels exceed the sea levels. The pumping only lasts for a short period at low head.
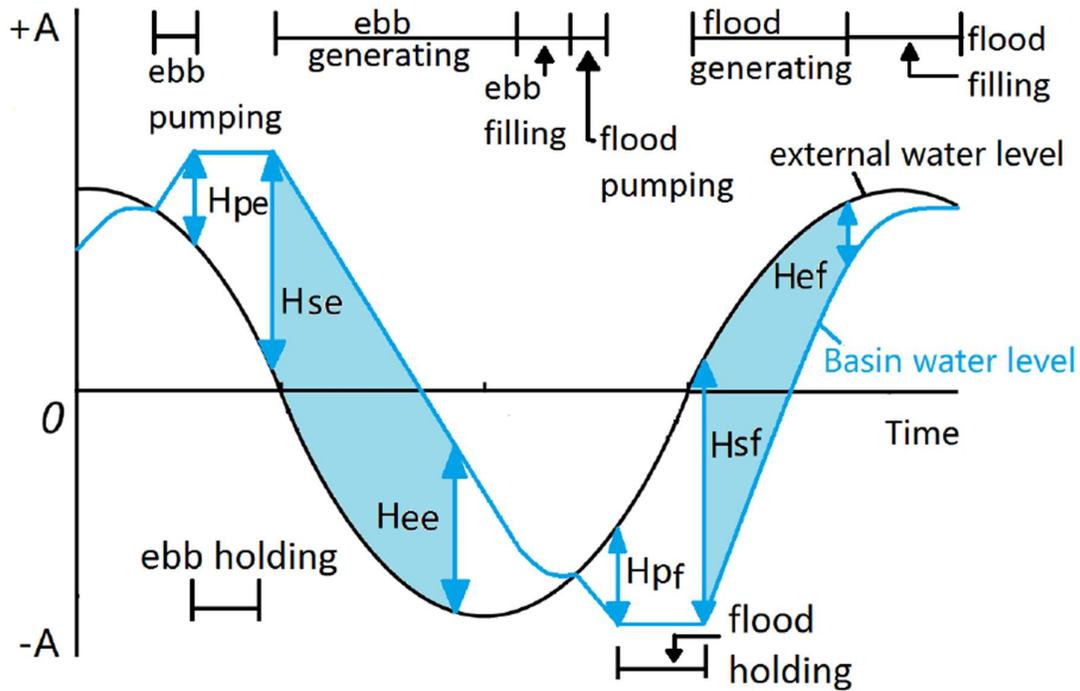
Figure 3-11 Typical cycle for two-way generation with pumping (Xue, 2021).

Normally you would seek to maximise the shaded area of the graphs. However, if you multiply the functions by the price, you would then be maximising the price by generating more when the demand is high.

3.4.3 Discharge Volume

The total discharge in each cycle is a function of tide range and impoundment areas. Where there is a linear relationship between sea level and surface area the total discharge is the range times the surface area at mean sea level. If the area/level is non-linear the volume can be calculated by summing the areas in horizontal slices.

3.4.4 Flow Rate.

The average flow rate is the total volume divided by the discharge time. The operator can adjust the flow to suit the head and operating regime by varying the wicker gate and bland angles. The speed of the turbine affects its efficiency, but it is also important to finish the cycle at an appropriate level for the next cycle. With modern developments of inverters and distribution, the unit does not need to be synchronised with the grid. Together with the operation of the blade and wicker gate angles it is called triple regulation. Also, the rate of discharge at the end of the cycle, with lower head and open sluices, will be different from the generating discharge.

In Figure 3-9 to Figure 3-11 the gradient of the flow rate varies with the operating mode. For 2-way generation the gradient is approximately equal to the maximum gradient of the sea level curve. For the ebb only modes it is a flatter gradient. The desired gradient will also change if pumping is involved. The 2-way generation mode is more popular with developers because it most closely follows the natural tide cycle and provides four generating periods a day rather than the two from ebb or flood. However, if it is required to match generation to demand it is possible to vary the mode to suit each individual tide cycle and time of day. The effects on the environment would need to be considered but may be acceptable if the energy was required as a matter of urgency. As the reliance on wind power expands the likelihood of a shortage of supply would occur during a period of high air pressure and little wind. Flexible operation of tidal range would be highly desirable.

Given the optimum starting head, it is simple to calculate the time at which this occurs. The flow rate can be set to bring the impoundment level towards the sea level at the optimum time for the operating regime or demand curve. For 2-way generation you could set the rate to the maximum drop of sea level in 10-minute time slices. Alternatively, you could determine the time when you require the sea and impoundment levels to equalise and divide the total volume by the time remaining. It is likely that an iterative procedure would be required to vary the optimum head and discharge rate to gain the maximum benefit from the energy produced. If the price of electricity is included in the calculations the operation will change from optimum total energy to optimum sales or financial return.

3.5   Summary

The 0-D model is suitable for the initial assessment of the annual electricity production (AEP) of any scheme as it is quick to change options and requires minimum data. Options like the number and size of turbines, sluice ratios and generator rating. Minimum data required is the tidal sequence and the surface area of the impoundment over the maximum tidal range.

The basic equations for tidal range generation are relatively simple but there is only a small amount of data publicly available for the turbine performance. Mainly the hill chart for the Andritz three blade turbine.   However, this lacks information on pumping and reverse flow performance.

4 OPERATION OF THE LANCASTER 0-D MODEL

The aim of this chapter is to describe the Lancaster 0-D model in detail and explain the options available to the user. The latest version of the Lancaster 0-D model is titled *Gen_53* (Baker, 2025). Baker made some modifications to allow the investigations necessary for this thesis and the published papers. Having used the software for 4-years it was found to be an excellent research tool and teaching aid for anyone interested in tidal range. The user interface is easy to use and provides full output information in graphical and tabular forms.

4.1 Primary site input

For 0-D analysis there are only two required input streams for any site: -

- Tide levels. These can be provided as a numerical function or read from tide tables. These are based on the closest tide monitoring site until site specific data is available.
- The bathymetry of a site is provided in tabular form containing the impounded surface area at various levels throughout the tidal range.

4.1.1 Tide levels

The tide model for Morecambe Bay was derived from the tide records from the Heysham recording station available from the National Tidal and Sea Level Facility (The National Oceanography Centre (NOC), 2023). The site's published measured data were at a 15-minute sample rate, together with a residual value. The residual was calculated as the difference between the measured value and the model data, the residual being due to wind and storm surge.

This tide data was analysed by a MATLAB routine called UTide (MathWorks, 2017). The complete dataset for 2018 was analysed and the 10 tidal constituents with the highest amplitude (greater than 0.1m) were used in the tide series code. The UTide long term trend parameter value was not included in the model and although tides can be generated with any start date, the further it is removed from the start of 2018 the less accurate it will be.

Tidal predictions were made based on the superposition of these 10 main harmonic constituents using the following formula shown in Equation 4-1.

$$h = \sum M_2 \cos\left(\omega_{M_2} t + \phi_{M_2}\right) + S_2 \cos\left(\omega_{S_2} t + \phi_{S_2}\right) + \cdots$$

Equation 4-1 Tide level from harmonics (Baker, 2021).

where ω is the angular velocity (rad/hour), *t* is time (hours) from the start of the series, and ϕ is the phase at *t*=0. The 10 constituents are as follows (where ϕ_{t0} is the phase at 1 Jan 2018 00:00):

Constituent:	M2	S2	N2	K2	M4	NU2	L2	K1	MS4	O1	
Amplitude:	3.1638	1.0271	0.6042	0.2988	0.1999	0.1361	0.1279	0.1227	0.1164	0.1114	m
ω:	0.5059	0.5236	0.4964	0.5250	1.0117	0.4976	0.5154	0.2625	1.0295	0.2434	rads/hr
ϕ_{t0}:	1.0612	6.1366	1.6528	3.1241	2.9217	1.7977	3.7682	2.9775	1.5813	6.0057	radians

The tide model is assumed to act uniformly over the entire impoundment. This will not be the case for large impoundments but the error inherent in the 0-D approach, together with the assumption that the barrage has no impact on the behaviour of the tide. A more accurate representation of the tide warrants a more sophisticated modelling method.

Figure 4-1 shows a screen shot of the tide input model with Figure 4-2 showing an enlarged view of the tide constituent's box. To make the program more general a file option was created with the format shown in Table 4-1, file name *tide_table_input.xlsx*. *Tide Plotter* software (Belfield Software Ltd, 2025) can export tide levels to an excel spreadsheet at 5 or 10-minute intervals. The levels are based on chart datum. The conversion to ordnance datum is added in the tide input box shown in Figure 4-2.
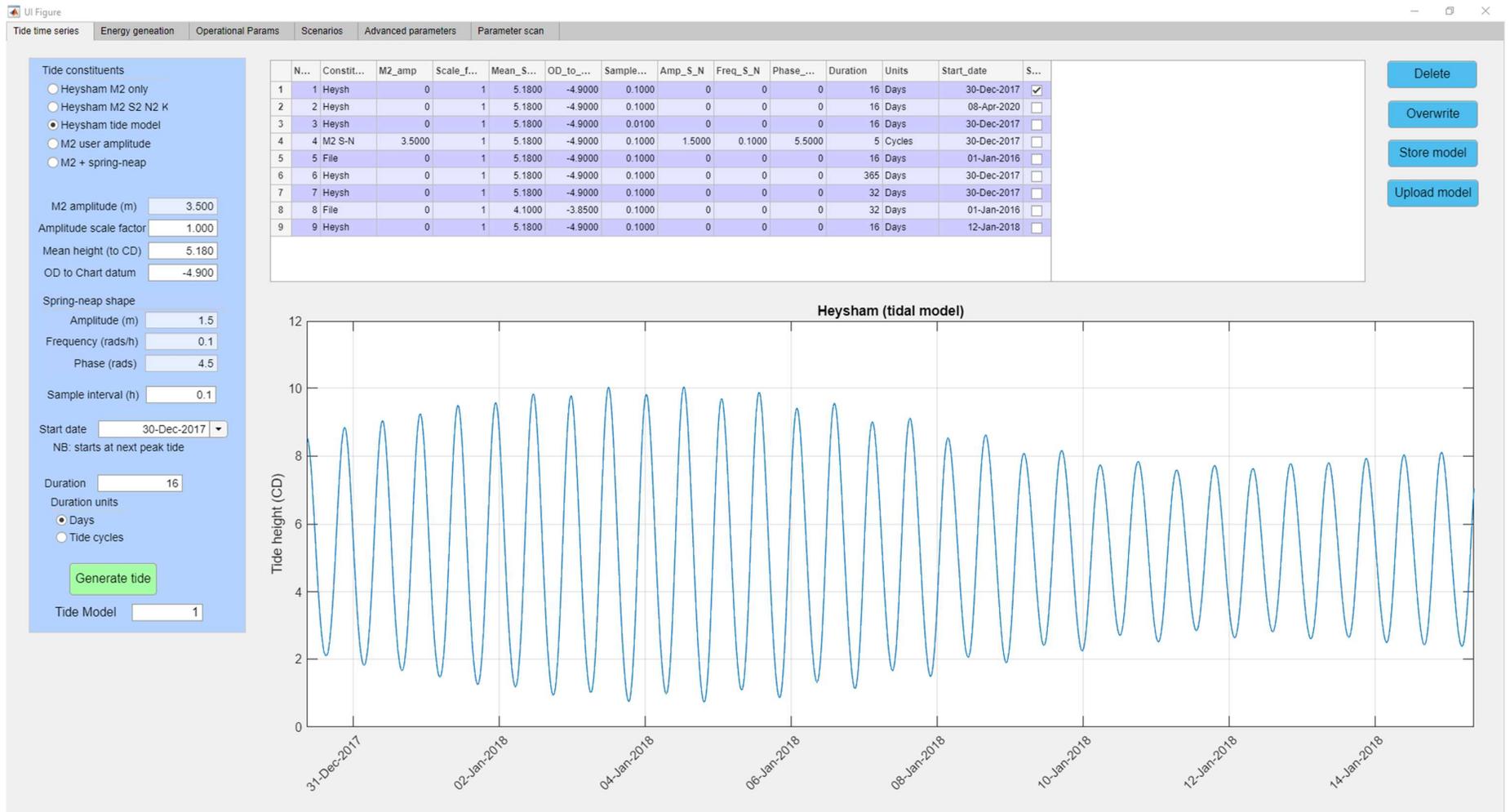
Figure 4-1 screen shot of the tide input (Baker, 2025).

Table 4-1 Extract from tide table input spreadsheet exported from (Belfield Software Ltd, 2025).

	A	B
1	Date	Height
2	01/01/2016 00:00	2.73
3	01/01/2016 00:10	2.91
4	01/01/2016 00:20	3.09
5	01/01/2016 00:30	3.28
6	01/01/2016 00:40	3.47
7	01/01/2016 00:50	3.67
8	01/01/2016 01:00	3.87
9	01/01/2016 01:10	4.07
10	01/01/2016 01:20	4.26
11	01/01/2016 01:30	4.46
12	01/01/2016 01:40	4.65
13	01/01/2016 01:50	4.83
14	01/01/2016 02:00	5.01
15	01/01/2016 02:10	5.17
16	01/01/2016 02:20	5.33

Figure 4-2 shows an enlarged tide selection box from the tide input tab.

The start date for the analysis and duration are set in days or the number of tide cycles.

The user can select the full Heysham profile or use only the main constituents. In theory any start date can be selected.

The amplitude can be modified if required.
The difference between chart and ordinance datums is required.

The sample interval is set in hours, i.e. 0.1 equals 6 minutes.

The start date is entered, and the program finds the first peak tide after the start.

The duration for the assessment can be set as days or tides but should not be less than 16-days to ensure capturing at least one spring and one neap tide. Increasing the duration increases the processing time.

Figure 4-2 Tide selection box.

4.1.2 Bathymetry

The bathymetry function is an important element of the model; defined as a function of the surface or wetted area of the impoundment with elevation. The elevation is not restricted by the level of the highest and lowest astronomical tide. Increasing the water level above highest astronomical tide would generally result in a larger volume, unless the area was restricted by sea walls or cliffs. The Morecambe Bay function was created by Simon Baker from LIDAR data and admiralty charts (Baker, 2025). The North Wales Lagoon function was similarly created by Xue (Xue, 2021). Xue's plot has been transposed and added to the Morecambe Bay data. See Figure 4-3 which shows the difference between an estuary and coastal lagoon, at mean high water springs (MHWS) the wet area of Morecambe Bay (blue lines) is about double that for North Wales (red lines). At mean low water springs (MLWS) the reverse is true, North Wales area being about double that of Morecambe Bay, explaining why estuaries were mainly considered for ebb only generation. The flood generation for a coastal lagoon would still be less than the ebb generation, but it would be more significant than for a typical estuary.
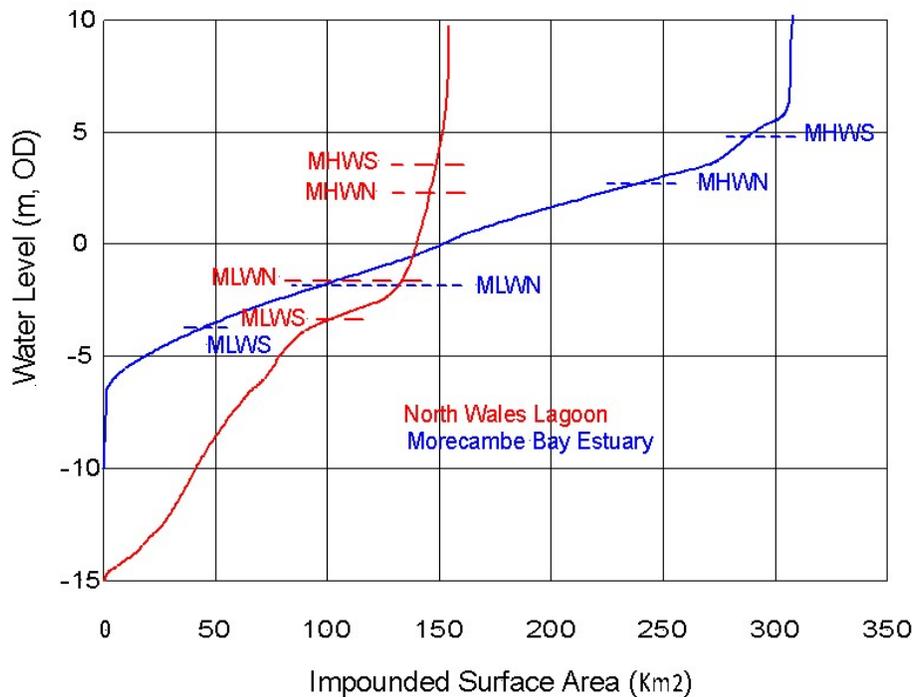
Figure 4-3 Surface areas by water levels for North Wales lagoon and Morecambe Bay barrage.

The bathymetry function is stored in '*bathy_hght_funcs.mat*' for both sites and is the level relative to Ordnance Datum for each area. The site is selected from the generation tab shown in Figure 4-4. Other sites could be considered by substituting in the *.mat file. Note that the *lagoon* option is for a constant area with water level.

Figure 4-4 Selection of site bathymetry (Baker, 2025).

4.2   Advanced parameters

The following parameters are included in the advanced parameters tab and can be changed by the user if required. Most parameters are self-explanatory.

4.2.1 Turbine parameters

The discharge coefficient Cd is greater than 1.0 because the intake and outfall areas are much larger than the area swept by the blades so that water flow accelerates towards the turbine. The pumping power is fixed and based on La Rance working at 25% of rated power for good efficiency, see Figure 4-5

Figure 4-5 Setting the turbine parameters in Gen-53 (Baker, 2025).

There are no published figures for the performance of the Andritz bulb turbine in reverse flow or pumping mode.

- Tidetec manufacture a reversible Straflo hydro-turbine and claim that bulb turbines can have up to 30% lower efficiency in reverse flow (Tidetec, 2025). Jacobs are also designing a very low head contra-rotating turbine which should have the same efficiency in both directions (Jacobs, 2025). There is little technical information publicly available, but it is understood that Jacobs have built a model and are currently testing it. The current version of the Lancaster 0-D model does not include an efficiency reduction for reverse flow so will overestimate the possible generation. However, the hill chart used is more than 13-years old and some efficiency improvements may be expected.
- In the absence of information on pumping performance the Lancaster 0-D model uses published pumping data from the La Rance scheme in France; details of which are given in 4.6.1.

4.2.2 Sluice gates

For sluices the discharge coefficient Cd is less than 1.0, with a default of 0.85 see Figure 4-6. An average value of 0.88 has been estimated (Prof Jong-Song Jo and Prof Kwang-Su Kim, 2024). The theory requires the height must be fully submerged at low water level.

Sluice gates	
Width	15
Height	15
Discharge coefficient	0.85

Figure 4-6 Setting the sluice gate parameters (Baker, 2025).

4.2.3 Other

Setting other data for minimum turbine starting head (m) and combined mechanical/transformer efficiency, see Figure 4-7.

Figure 4-7 Setting other parameters (Baker, 2025).

4.2.4 General

Figure 4-8 shows the general setting for sea water density, scale for cumulative flow and the amount of kg of CO_2 saved compared to petroleum gas generation.

Figure 4-8 Setting other parameters (Baker, 2025).

4.3   Electricity generation

After the tide data and advanced parameters have been selected or modified, the main operation is in the energy generation tab shown in Figure 4-9 which is expanded in subsequent figures.

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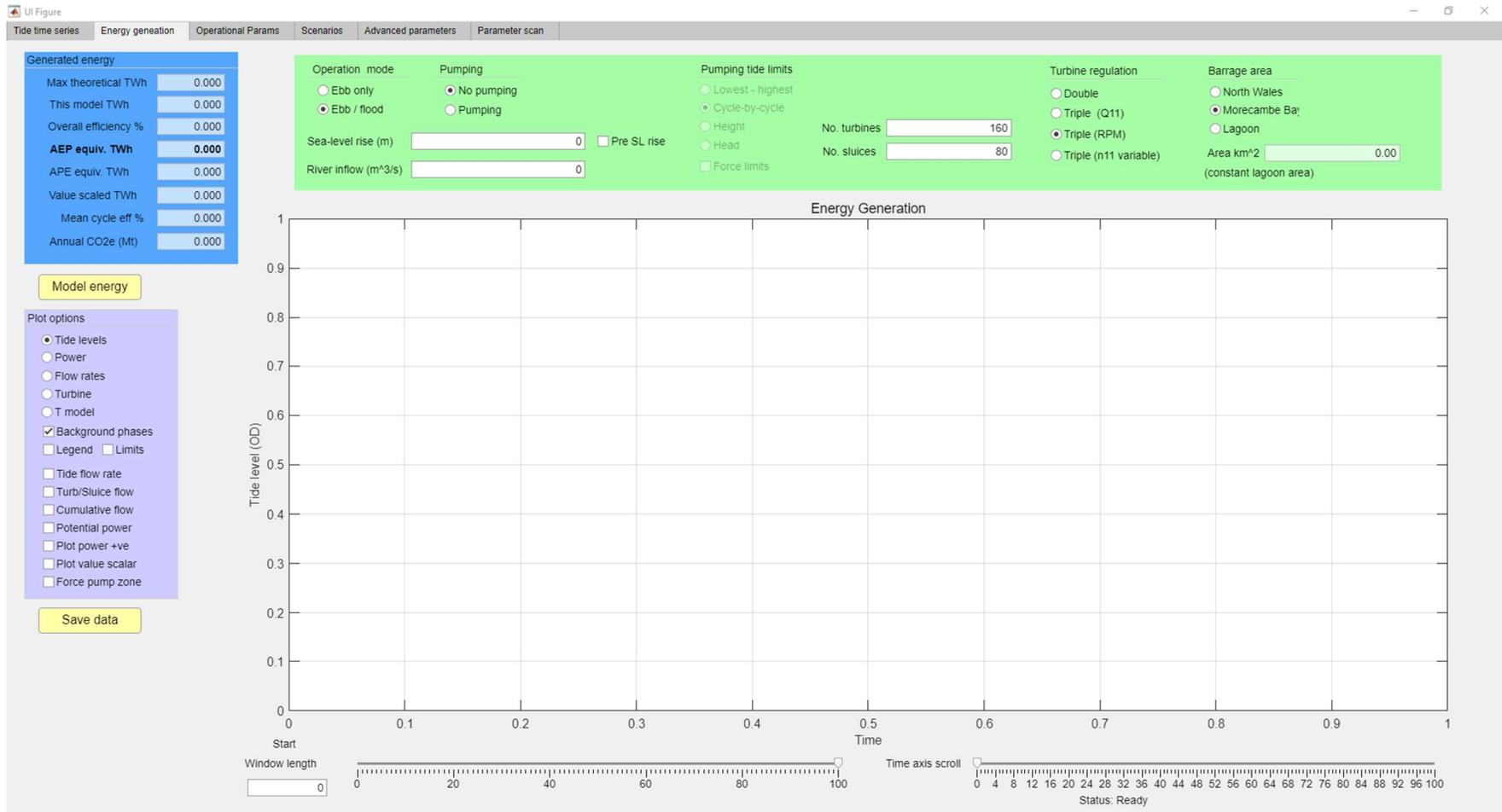
Figure 4-9 Electricity generation tab.

4.3.1 Operation mode

The operation mode can be set to *ebb only* or *ebb and flood*, with or without pumping, see Figure 4-10. If river inflows are known these can be added and will increase the ebb generation but reduces during flood. Sea level rise, if set, raises the whole tide sequence without altering the amplitude. If the *pre-SL rise* box is ticked the optimisation tries to match the existing sea levels.

Figure 4-10 Extract from the electrical generation tab, pumping (Baker, 2025).

4.3.2 Tide limits and plant installation

The tide limits is normally set to cycle-by-cycle which tries to match each individual tide as Figure 4-11. The force limits tick box will stop generation early to ensure the tide limits are met. The other limits are :-

- Lowest to highest
- Height
- Head

Figure 4-11 Extract from the electrical generation tab, pumping limits & number of turbines and sluices (Baker, 2025).

The number of turbines and sluices must be set based on the sizes given in the advanced parameters tab.

4.3.3 Turbine regulation

Double regulation is where the guide vanes and blade angles are altered to control the flow, and the turbine is synchronized with the grid; these are α and β on the hill chart. Triple regulation is commonly applied to wind turbines which are not synchronized with the grid and the power is inverted to direct current. This means the turbogenerator can operate at any flow or speed. The options are constant flow, constant or variable speed. The triple regulation options in Figure 4-12 can be based on controlling model flow or speed or the speed for the full-size turbine.
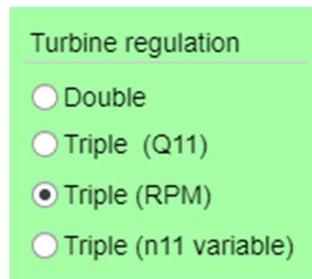
Figure 4-12 Turbine regulation mode.

Before running the program by pressing the *model energy* button it is necessary to set the operational parameters as detailed.

4.4 Operational parameters

Figure 4-13 shows the operational parameters tab which has several areas as expanded below.
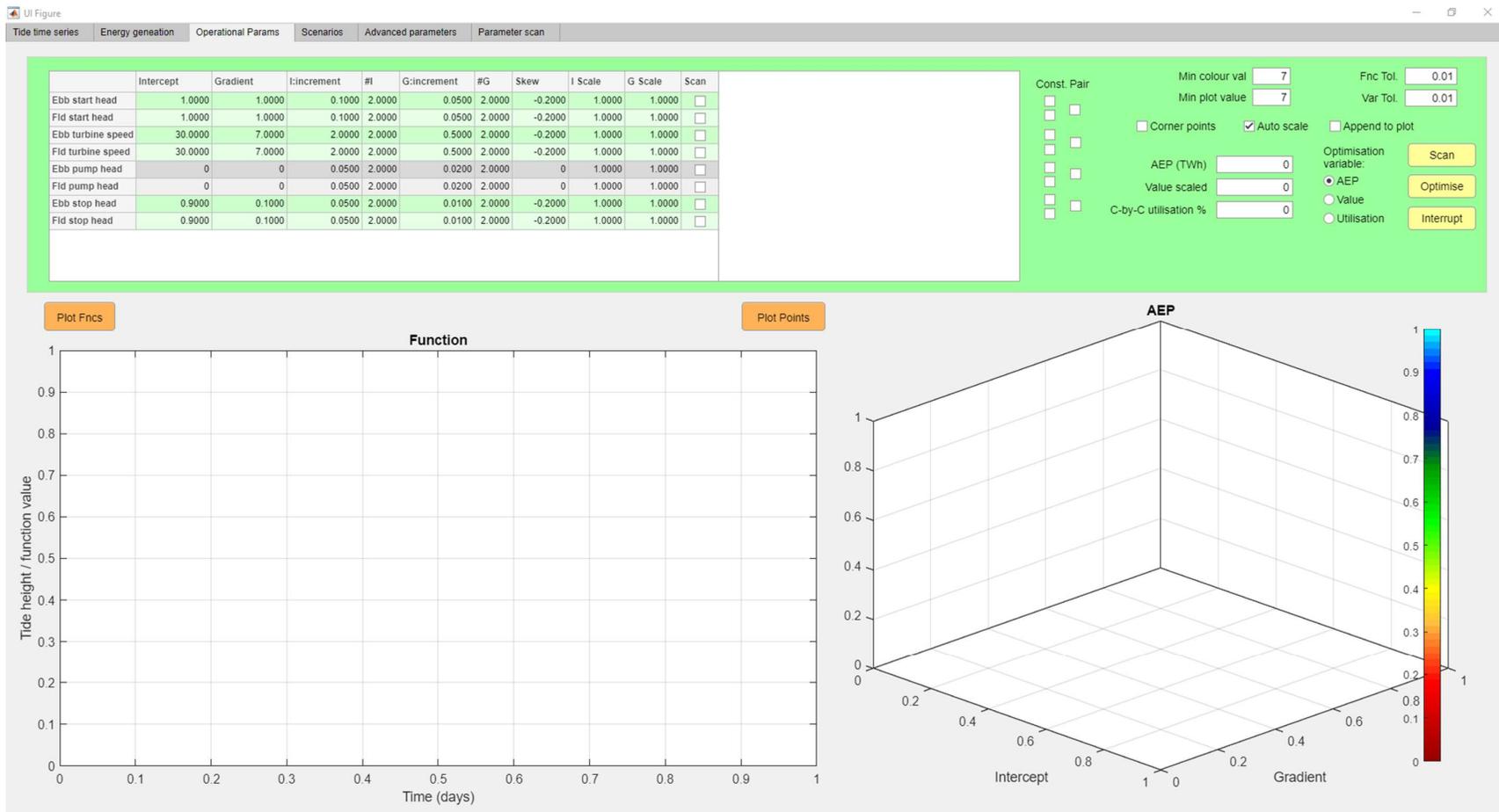
Figure 4-13 Operational parameters tab.

4.4.1 Optimising

The Gen_53 program (Baker, 2025) allows the user to choose four of eight variables to be optimised, shown in the top left corner of the tab, see Figure 4-14; typically, the ebb and flood start heads and turbine speed or flow rates.

	Intercept	Gradient	I:increment	#I	G:increment	#G	Skew	I Scale	G Scale	Scan
Ebb start head	0.2186	1.0300	0.1000	2.0000	0.0500	2.0000	-0.2000	0.2100	1.0000	☑
Fld start head	1.5796	0.7056	0.1000	2.0000	0.0500	2.0000	-0.2000	1.6000	0.7000	☑
Ebb turbine speed	17.6601	9.1980	2.0000	2.0000	0.5000	2.0000	-0.2000	18.0000	9.3000	☑
Fld turbine speed	27.6576	6.5174	2.0000	2.0000	0.5000	2.0000	-0.2000	28.0000	6.5000	☑
Ebb pump head	0	0	0.0500	2.0000	0.0200	2.0000	0	1.0000	1.0000	☐
Fld pump head	0	0	0.0500	2.0000	0.0200	2.0000	0	1.0000	1.0000	☐
Ebb stop head	0.8000	0	0.0500	2.0000	0.0100	2.0000	-0.2000	1.0000	1.0000	☐
Fld stop head	0.8000	0	0.0500	2.0000	0.0100	2.0000	-0.2000	1.0000	1.0000	☐

Figure 4-14 Selected parameters with optimised intercept and gradient.

The program analyses the tide levels over a representative period of 16 or 32-days typically. The analysis can work over much longer periods but at increased processing time. The program produces linear functions for the four chosen parameters over the tidal period selected. The optimisation is carried out using a standard MatLab subroutine *fminsearch* which gives the maximum energy production using the derivative-free method. The result is in the form of an intercept and gradient for each parameter shown in Figure 4-14 are shown in Table 4-2 below. These are applied to the amplitude of each tide cycle. The annual electricity produced (AEP) is then approximated by factoring the AEP over the selected time series. For a more detailed description of the program please refer to (Baker, 2021).

Table 4-2 Optimised operating parameters vs tidal amplitude

			Tidal amplitude (m)			
Operating paramiter	Intercept	Gradient	0	2	4	6
Ebb start head (m)	0.2186	1.0300	0.22	2.28	4.34	6.40
Fld start head (m)	1.5796	0.7056	1.58	2.99	4.40	5.81
Ebb turbine speed (rpm)	17.6601	9.1980	17.66	36.06	54.45	72.85
Fld turbine speed (rpm)	27.6576	6.5174	27.66	40.69	53.73	66.76

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From Table 4-2 for a high spring tide of 4.0m OD the optimum ebb starting head is 4.34m; for a neap tide of 2.0m OD the optimum ebb starting head is 2.28m. These parameters only relate to the specific configuration or bathymetry and number of turbines and slices used for the optimisation.

4.5   Running the Lancaster 0-D model

The MatLab application used for this research is Energy_Gen_53sm.mlapp written by S Baker (Baker, 2021). Figure 4-15 shows the flow chart for operation.
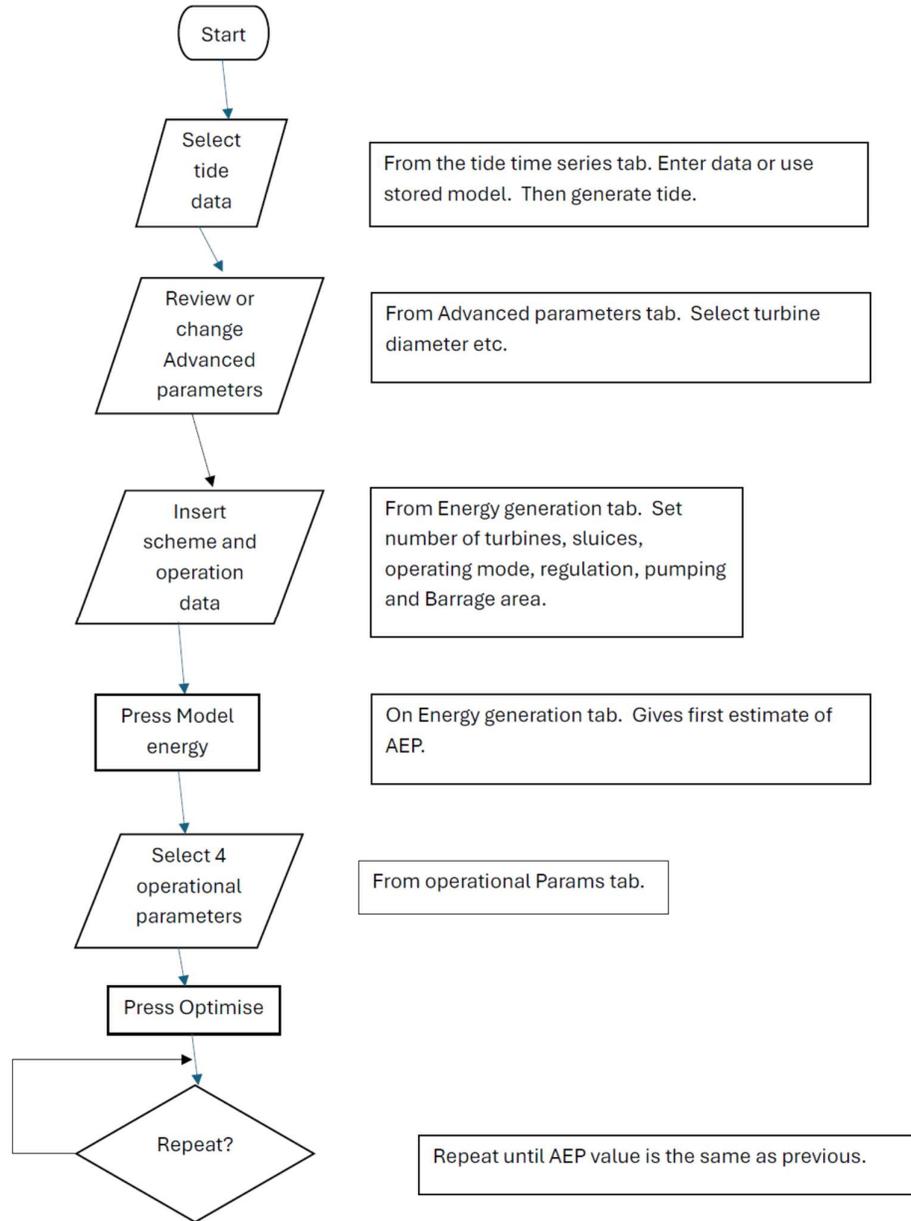
Figure 4-15 Flow chart for Lancaster 0-D model Energy_Gen_53sm.mlapp

To run the program the first step is to select the tide model and press the *Generate tide* button, see green button in Figure 4-16 Tide model generated.
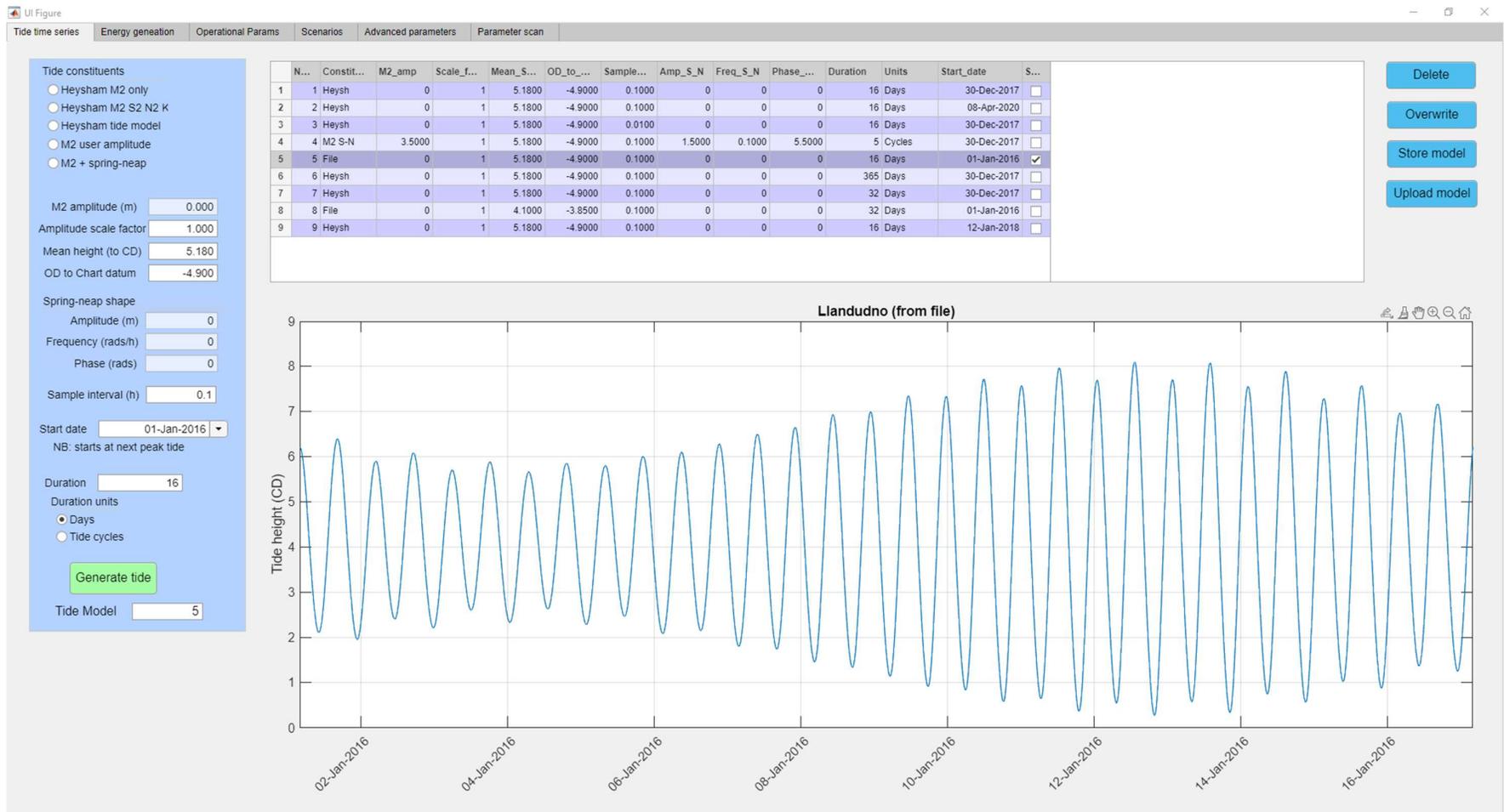
Figure 4-16 Tide model generated.

Secondly enter the number of turbines and sluices and the barrage model on the generation tab and press model energy as Figure 4-17.
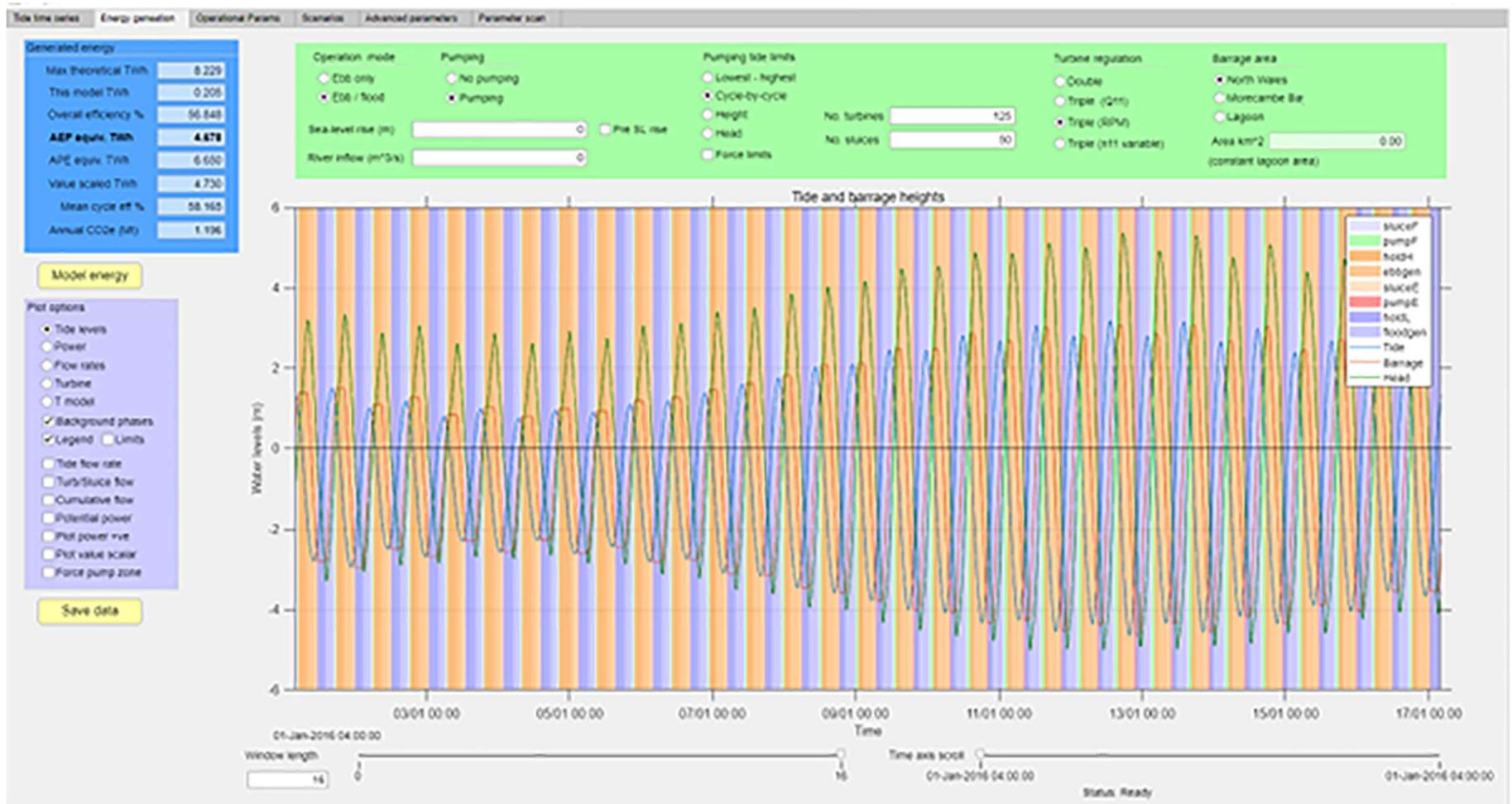
Figure 4-17 Modelled energy.

In Figure 4-17 the estimated AEP is 4.678-TWh as a first estimate only. Next move to the operational parameters tab and tick four of the eight parameters to optimise. The intercept and gradients of the chosen parameters are optimised to give the maximum AEP, value or utilisation depending on the radar button selected. This can take five minutes for a 16-day tide series, see Figure 4-18 where the AEP increases to 4.717 TWh. It may not be the maximum possible and it is necessary to optimise repeat the optimisation until the AEP matches the previous reading.
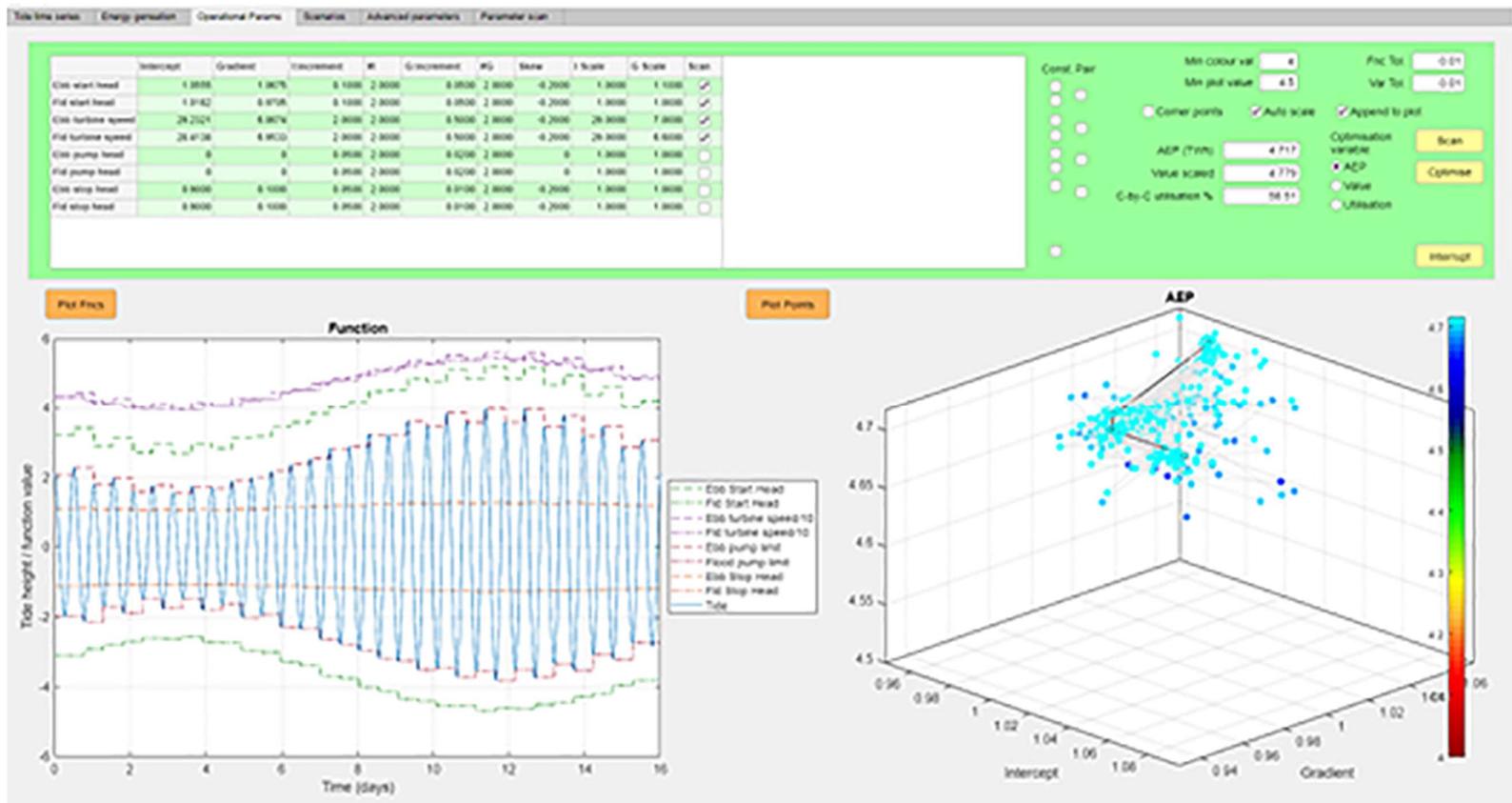
Figure 4-18 Operational parameters

4.5.1 Parameter scan

The final tab shown in Figure 4-19 was developed to automatically analyse AEP for various numbers of turbines, sluices or sea level rise (SLR). The AEP initially increases with SLR, but this is not always the case. This routine takes 30 minutes for 11 iterations using a laptop computer with an AMD Ryzan 5 2.1GHz chip and 8Gb of RAM, but the program can be left to run without user input.
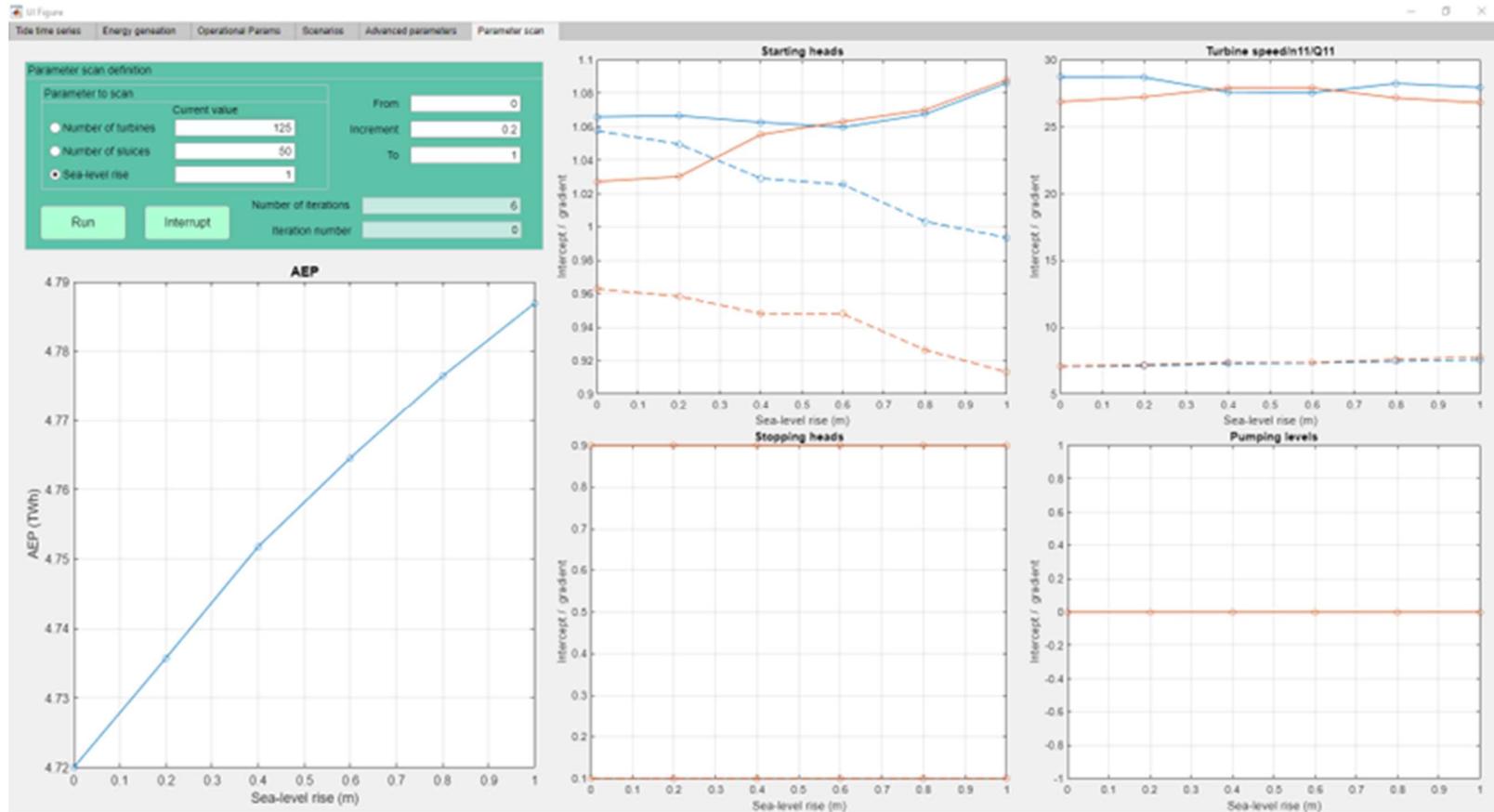
Figure 4-19 Parameter scan for 1m of sea level rise.

4.6 Pumping

In (Vandercruyssen et al., 2023b) the effects of sea level rise (SLR) on generation and the ability of tidal range to maintain pre-SLR limits. The paper showed that limiting high tides to pre-SLR levels can be simply and easily achieved by shutting the turbines off when sea levels reach the target levels inside the impoundment. Achieving the target levels at low tide requires more pumping as mean sea levels rise. In the initial stages of SLR the AEP increases slightly but later starts to fall as more power is needed to pump out the impoundment to reach low levels. The level of SLR that produces a fall in AEP depends on the scheme bathymetry and the initial number and size of turbines installed. The paper proposed several options for upgrading the system during refits that would allow pre-SLR to be maintained and possibly increase AEP. This section deals with the option for installing auxiliary pumps (probably submersible) that can be provided at any future date and operate independently of the turbo-generators.

The advantages are: -

- pumps are more efficient that turbines as pumps,
- pumps can be installed in shallower water and do not require vast structures used as turbine halls.
- The auxiliary pumps are only used to assist the turbines to reach target low water levels.

4.6.1 Turbines as Pumps

Hydro turbines can be run in reverse as pumps against a low head to increase the head available during the next generation phase. There is very little information published on the performance of turbines as pumps (TaP) due to commercial reasons. The Lancaster 0-D model uses information from La Rance tidal range scheme as described by (Baker, 2021). Figure 4-20 shows pump curves of head against flow (a) and power used (b).
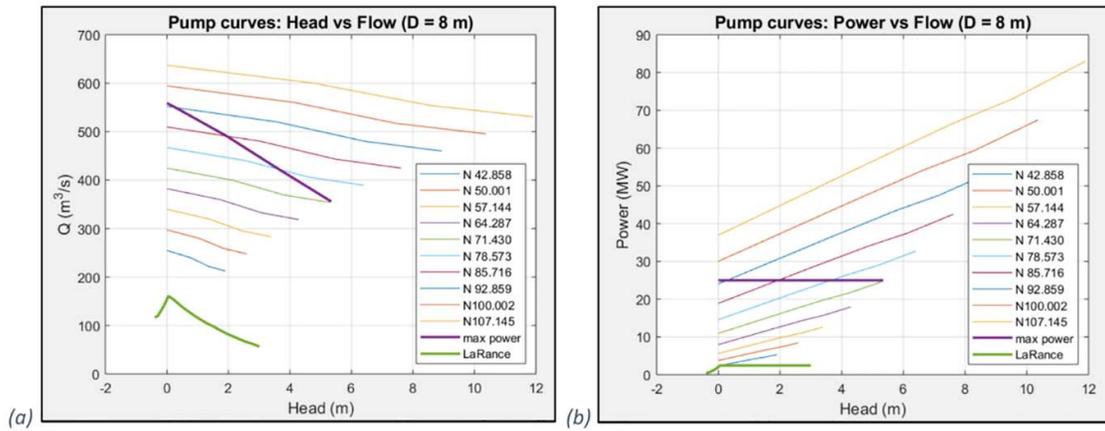
Figure 4-20 Turbines as pumps performance curves from S Baker (Baker, 2021).

Figure 4-21 shows pump flow rates against head for 25-MW power (a) and 7.5-MW power (b). The green lines represent the performance of the pumps at La Rance.
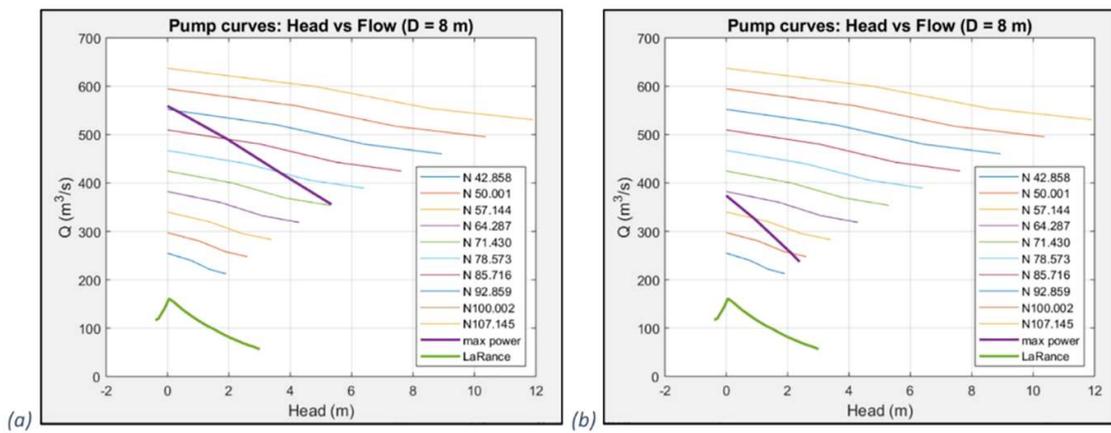
Figure 4-21 Turbines as pumps flow rates: (a) 25 MW, b) 7.5 MW (Baker, 2021).

For a constant pump power of 7.5-MW the flow at zero head is 380 m³/s reducing to zero flow at the maximum head of 2.2m. There is a linear relationship between flow and head. In practice the maximum pumping head is limited to 1.5m for better efficiency. Thus, the equation for flow is given Equation 4-2.

$$Q = 380 \times \frac{(2.2 - H)}{2.2} \ m^3/s$$

Equation 4-2   Linear equation for pump flow using 7.5-MW power (Baker, 2021).

Where :-

Q   =   the pump flow

H   =   head of water.

Table 4-3 is based on Equation 4-2.

Table 4-3 La Rance turbine as pump flow v head at 7.5 MW power (Baker, 2021).

Vol.Flow [m³/s]	Head [m]	Power [MW]
0.0	2.2	7.5
34.5	2.0	7.5
69.1	1.8	7.5
103.6	1.6	7.5
138.2	1.4	7.5
172.7	1.2	7.5
207.3	1.0	7.5
241.8	0.8	7.5
276.4	0.6	7.5
310.9	0.4	7.5
345.5	0.2	7.5
380.0	0.0	7.5

4.6.2 Information from TideTec.

(Tidetec, 2025) are developing a turbine in a turret that can be rotated to provide maximum efficiency in both directions, see Figure 4-22. Diameters are claimed to be between 2.0 and 8.0m. A model has been built and tested to provide classified performance data.

Figure 4-22 Images from (Tidetec, 2025).

TideTec claim their: -

> *"… technology improves efficiency by more than 20% of the most cost-effective tidal turbine technology by obtaining optimal efficiency both ways. This is achieved by integrating the turbine into a rotating turret. The turning mechanism is patented and has received international recognition. The technology enables optimal turbine function (generation and pumping) with bi-directional flow. Tidetec's technology consists of three main technology components: The turret with a turning mechanism, the turbine, and caisson."*

On 1-Sep-23 TideTec provided the following information: -

> *"We cannot share our pumping curves directly, but we can give you some numbers related to the topic. For our technology we have a maximum pumping efficiency of approximately 70%. We can also give an example for a 5.0m diameter turbine with a maximum head of 1.2m, we can expect the pump to discharge approx. 60-90 m^3/s."*

4.6.3 Auxiliary pumps

Also, from (Vandercruyssen et al., 2023b), it becomes apparent that there may be advantages from installing standalone pumps to help maintain existing low water levels when faced with SLR greater than 0.5m or thereabouts.

Following an internet search, the following organisations were contacted to try to obtain the latest information on large, low-head pumps. Pump curves of flow rate vs head were requested for the largest available very low-head pumps.

- VANHECK (Tenkate, 2025) replied and advised to contact designers at Pentair.
- Bedford Pumps, (Bedford Pumps, 2023) no response.
- Sultzer. A video meeting was held and Sultzer later provided information on their current maximum submersible pump.
- Andritz Pumps, (Andritz, 2025), not response.
- KSB, sven.baumgarten@ksb.com; (Behrends, 2024), no response
- Pentair, (Pentair, 2017) no response.

4.6.3.1   Example of cooling water pumps from Pembroke Power Station

The power station is direct cooled Combined Cycle Gas turbines (CCGT) by 10 x 1-MW pumps , see Figure 4-23. These pumps provide a total flow of 40 m^3/s. Unfortunately, this is less than 1/10th of the capacity of an 8m diameter bulb turbine as pump.

Figure 4-23 Photographs from Pembroke CCGT cooling water pumps.

4.6.3.2   Information from Sulzer.

The most useful information was provided by (Sulzer, 2025) who advised that low head submersible pumps in the 10 to 15-MW range are readily available, higher power pumps would be possible and would need to be designed to meet specific needs.

For initial consideration Sulzer suggested a large unit, impeller diameter 1.88m running at 224 rpm, see Figure 4-24. An axial flow pump, specific speed of 350 rpm, driven via a gearbox with a higher speed motor, to save on motor mass, speed between 1,480 to 990 rpm.

Figure 4-24 Section through Sulzer vertical submersible pump (Sulzer, 2025).

Design flow of 12.5 m³/s @ 3m head. Unfortunately, the 25m³/s is out of the range. Several units will be needed to achieve the combined flow required. Based on the first iteration, Sulzer could look at pumping more but would need the total flow to find the ideal number of pumps that are practical to build and achieve the best efficiency they can offer.

Figure 4-25 shows the pump performance curve and Table 4-4 some extracted points which can be used for inputting into the 0-D model.

Table 4-4 Sulzer extracted points from their pump curve.

Vol. Flow [m³/s]	Head [m]	Eta [%]	Power [kW]	NPSH 3% [m]	NPSH Rec [m]
9.00	5.90	69.14	751.80	16.22	23.78
9.50	5.74	72.14	740.00	14.79	20.89
10.00	5.50	75.03	717.90	13.87	18.90
10.50	5.20	77.72	687.70	13.12	17.27
11.00	4.85	80.09	651.60	12.43	15.79
11.50	4.46	82.04	611.60	11.83	14.49
12.00	4.04	83.45	569.40	11.32	13.37
12.50	3.62	84.21	526.50	10.93	12.45
13.00	3.19	84.19	482.70	10.67	11.95
13.50	2.74	83.30	434.80	10.57	11.83
14.00	2.25	81.35	378.70	10.63	11.90
14.64	1.53	73.78	296.60	11.00	12.32

Note: NPSH is Nett positive suction head. 3% head flow

The pump discharge nozzle will be around 2.4m and required submergence of 4m above the inlet of the bell-mouth to. This is to ensure there is ample NPSH available to prevent cavitation and in addition to prevent vortex's developing in the sump. The bell-mouth diameter will be 3.2m in diameter. The sump floor to the bell mouth entry will be 1.6m. The pump centre lines will need to be 6.4m apart.
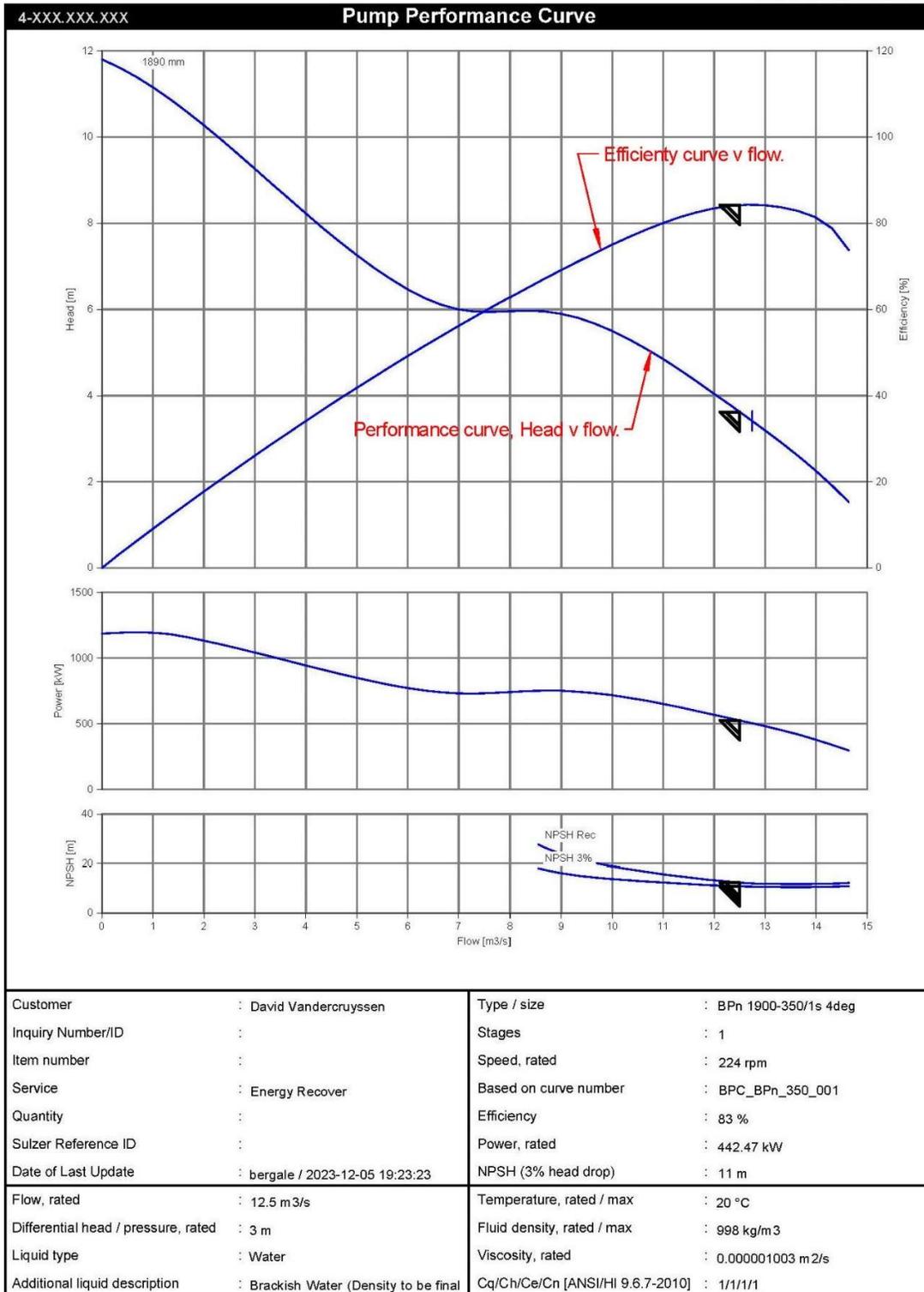
Figure 4-25 Sulser 12.5 m³/s pump performance curves.

Figure 4-26 shows a part 3-D section of the pump and intake. For tidal range banks of pumps will be needed. These can be added at a future date should it becomes necessary to expose existing low intertidal areas.
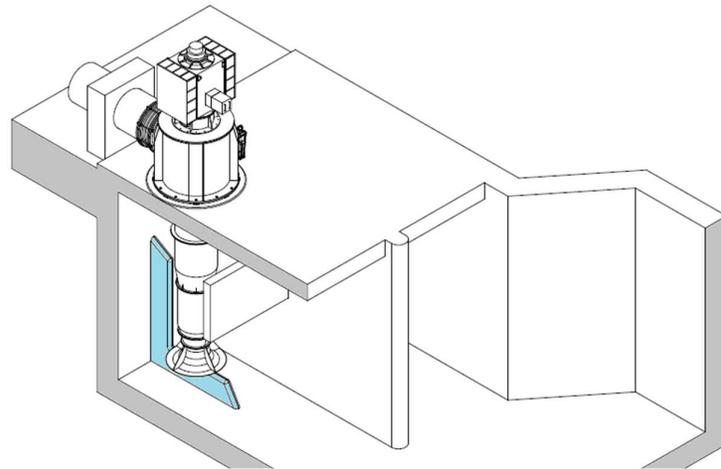
Figure 4-26 Sulzer's typical Intake design (Sulzer, 2025).

4.6.4 Case study using both Turbines as Pumps and auxiliary submersible pumps.

The Andritz TaP has a much larger flowrate which is mostly due to its blade diameter of 8.0m; the blue line in Figure 4-27 is for the Andritz turbine operating in pump mode at constant power of 7.5-MW. The proposed Sulzer pump has a much smaller impeller diameter of 1.8m, but the power is variable, and the unit can be installed in shallower water than the turbine. The maximum flow rate is 380 m³/s at zero head, decreasing linearly to 0 m³/s at a head of 2.2m.
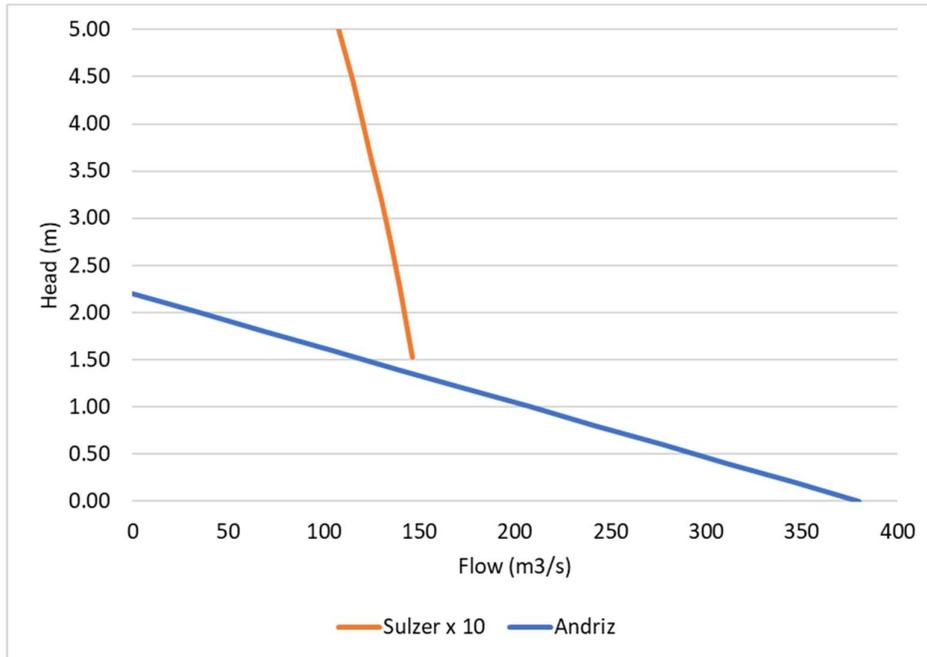
Figure 4-27 Pump flow curves for ten Sulser pumps and 1 Andritz TaP for low heads.

The orange line in Figure 4-27 represents 10 Sulzer pumps which have a combined power demand similar to the Andritz TaP. Interestingly the lines almost meet at 1.5 m head which is about the maximum efficient head for the TaP and the minimum head for the submersible stand-alone pumps. So, the pumps are unsuitable to run in parallel, but the submersibles can take over from the TaP if more pumping is required to meet minimum sea levels in the face of sea level rise (SLR).

An example from Morecambe Bay.

The following example is based on the Morecambe Bay site with a mean spring tide plus 1.4m of SLR taken from (Vandercruyssen et al., 2023b). Figure 4-28 shows the difference between the red cycle by cycle (C-by-C) mode which produces maximum electrical generation but may not reach the tide limits and the dotted green line representing the forced limit mode (FL) which stops generation early to match the pre-SLR low tide limits. The pumping capacity of the TaP has been limited to a 1.5m head. The FL mode starts generating earlier than the C-by-C mode with a slightly steeper gradient, faster flow, and reduced head. The end of the C-by-C mode is above the desired minimum impoundment level, but independent pumps could further reduce the impoundment level. Thus, independent pumps could bring the FL mode closer to the higher generation C-by-C mode. The cost/benefit between additional pumping and more generation needs to be investigated. If the pumping head is less than the generating head, there should be a benefit. Further investigation will require a modification to the 0-D program.
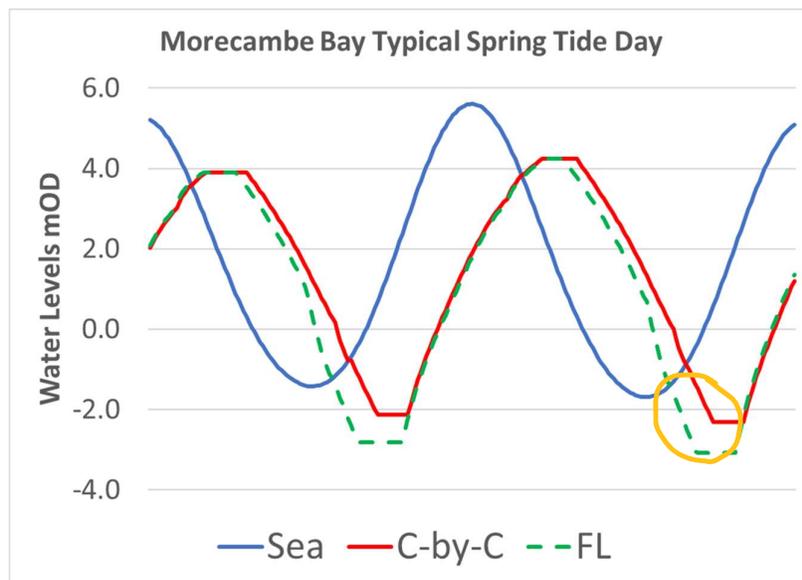
Figure 4-28 Morecambe Bay with a spring tide and 1.4m of SLR using 140 x 8m x 20-MW turbogenerators.

4.7 Analysis of data output from Gen53

Output data from the base cases of the North Wales Coastal Lagoon (NW) and Morecambe Bay Barrage (MB) have been copied to Microsoft Excel spreadsheets and analysed to determine the time of generation and pumping from the previous high or low tide, also the flow rate against tidal range. The time interval in the following analysis has been set to 1 minute, which is 0.0167 hours. The sluice ratio (SR) is 2.0 for both sites, using 15m x 15 m sluices and 8.0m diameter turbines. For NW with 125 turbines there are 56 sluices, and for MB with 140 turbines there are 63 sluices. Sea level rise (SLR) has not been included. Pumping is set to C-by-C mode. Generation is two-way (i.e. ebb and flood), with triple regulation based on rotational speed. The duration for each site has been set to 32-days to include some of the variation between spring and neap tides.

The tabular data was exported as MatLab matrices by pressing the "*save date*" button on the "Energy generation" tab. The relevant date lines are cut and pasted into a spreadsheet for analysis.

4.7.1 North Wales Coastal Lagoon

The selected scenario is 125 x 8.0m diameter turbines with 15-MW generators and zero SLR. Table 4-5 shows a summary of the first 12-days of tides. Table 4-6 shows some analysis of data for times to start and stop pumping and generation.

Table 4-5 Example of summary data from NW.

Day	Peak	Levels		Head @ peak tide (m)	time (minutes)	stop pumping		Start generating		stop generating Open sluice		Time to close sluice & start pumping	Tide Range (m)
		Sea	Impounded			Impounded level	time	Head	time	Head	time		
	max	3.18	0.29			2.77	maximum	4.05				ave	5.500
	Min	-4.63	-1.92			-4.36	Minimum	1.70				Std Div	1.370
												max	7.810
												min	3.020
1	High	1.29	0.29	1.00	1	1.27	52	-2.23	196	-0.80	411	440	4.090
	Low	-2.80	-1.36	-1.44	379	-2.80	454	2.94	602	0.78	781	811	-4.280
	High	1.48	-0.05	1.53	744	1.50	833	-2.39	938	-0.79	1,151	1,181	4.430
	Low	-2.95	-1.74	-1.21	1,128	-2.95	1,190	2.83	1,361	0.79	88	120	-3.940
2	High	0.99	-0.48	1.47	52	1.00	137	-1.92	245	-0.80	450	482	3.490
	Low	-2.50	-1.20	-1.30	422	-2.50	492	2.74	667	0.79	827	859	-3.670
	High	1.17	-0.31	1.48	791	1.17	876	-2.11	992	-0.79	1,192	1,226	3.860
	Low	-2.69	-1.70	-0.99	1,181	-2.69	1,232	2.67	1,430	0.78	142	175	-3.480
3	High	0.79	-0.62	1.41	108	0.79	189	-1.73	305	-0.80	484	522	3.090
	Low	-2.30	-1.41	-0.89	478	-2.30	527	2.60	739	0.80	884	918	-3.270
	High	0.97	-0.50	1.47	848	0.97	933	-1.95	1,053	-0.79	1,242	1,278	3.540
	Low	-2.57	-1.71	-0.86	1,237	-2.57	1,282	2.63	58	0.79	204	238	-3.320
4	High	0.75	-0.63	1.38	172	0.76	252	-1.70	369	-0.80	548	585	3.020
	Low	-2.27	-1.27	-1.00	535	-2.27	589	2.58	804	0.79	947	980	-3.210
	High	0.94	-0.50	1.44	912	0.96	996	-1.97	1,115	-0.79	1,315	1,349	3.560
	Low	-2.62	-1.56	-1.06	1,299	-2.62	1,356	2.69	111	0.79	265	298	-3.510
5	High	0.89	-0.48	1.37	233	0.90	313	-1.85	429	-0.79	627	660	3.330
	Low	-2.44	-1.20	-1.24	601	-2.44	669	2.70	854	0.80	1,009	1,041	-3.530
	High	1.09	-0.43	1.52	971	1.10	1,059	-2.14	1,172	-0.79	1,378	1,409	3.910
	Low	-2.82	-1.63	-1.19	1,356	-2.82	1,418	2.86	153	0.79	323	354	-4.010

Table 4 5 continued

Day	Peak	Levels		Head @ peak tide (m)	time (minutes)	stop pumping		Start generating		stop generating Open sluice		Time to close sluice & start pumping	Tide Range (m)
		Sea	Impounded			Impounded level	time	Head	time	Head	time		
6	High	1.19	-0.32	1.51	286	1.20	373	-2.14	481	-0.79	689	719	3.940
	Low	-2.75	-1.41	-1.34	659	-2.75	729	2.90	893	0.79	1,066	1,096	-4.120
	High	1.37	-0.28	1.65	1,024	1.37	1,118	-2.41	1,222	-0.80	1,434	22	4.470
	Low	-3.10	-1.80	-1.30	1,408	-3.10	32	3.07	187	0.82	374	403	-4.680
7	High	1.58	-0.31	1.89	323	1.58	427	-2.55	527	-0.78	745	772	4.740
	Low	-3.16	-1.49	-1.67	702	-3.16	785	3.14	924	0.84	1,115	1,144	-4.900
	High	1.74	-0.07	1.81	1,071	1.74	1,172	-2.77	1,264	-0.79	48	73	5.200
8	Low	-3.46	-1.81	-1.65	10	-3.46	88	3.36	218	0.92	419	448	-5.480
	High	2.02	-0.05	2.07	370	2.03	482	-2.96	564	-0.84	795	819	5.600
	Low	-3.58	-1.64	-1.94	749	-3.58	836	3.41	956	0.94	1,159	1,188	-5.660
	High	2.08	-0.07	2.15	1,109	2.09	1,225	-3.10	1,302	-0.89	94	118	5.850
9	Low	-3.77	-1.71	-2.06	48	-3.77	137	3.58	249	1.01	462	491	-6.200
	High	2.43	0.02	2.41	407	2.44	535	-3.37	603	-1.01	844	868	6.430
	Low	-4.00	-1.63	-2.37	796	-4.00	892	3.65	988	1.06	1,203	1,232	-6.420
	High	2.42	-0.13	2.55	1,146	2.43	1,280	-3.41	1,340	-1.03	139	163	6.490
10	Low	-4.07	-1.51	-2.56	85	-4.06	186	3.80	281	1.13	510	538	-6.870
	High	2.80	-0.26	3.06	444	2.77	604	-3.72	640	-1.15	906	929	7.120
	Low	-4.32	-0.72	-3.60	833	-4.32	978	3.83	1,021	1.13	1,250	1,278	-6.980
	High	2.66	-0.23	2.89	1,192	2.61	1,343	-3.61	1,377	-1.11	191	214	6.920
11	Low	-4.26	-1.09	-3.17	127	-4.26	252	3.97	316	1.18	560	586	-7.310
	High	3.05	-0.60	3.65	485	2.64	648	-3.93	690	-1.23	956	979	7.580
	Low	-4.53	-0.38	-4.15	874	-4.20	1,031	3.96	1,069	1.21	1,297	1,325	-7.310
	High	2.78	-0.62	3.40	1,229	2.50	1,388	-3.71	1,424	-1.17	235	258	7.140
12	Low	-4.36	-0.95	-3.41	169	-4.36	305	4.05	353	1.22	604	630	-7.540
	High	3.18	-0.70	3.88	528	2.56	690	-4.05	735	-1.30	998	1,022	7.810
	Low	-4.63	-0.33	-4.30	917	-4.12	1,072	4.00	1,112	1.22	1,337	1,365	-7.420
	High	2.79	-0.76	3.55	1,266	2.46	1,428	-3.70	23	-1.16	271	295	7.120

Table 4-6 Example of analysis of data from NW, zero SLR.

Day	Time between peaks (minutes)			lag to start generation (minutes)	lag to open sluice (minutes)	Pumping duration (minutes)		Generating duration (minutes)	
	All	Ebb	Flood			Ebb	Flood	Ebb	Flood
	372	382	362	203	418	22	38	230	200
	12	7	7	18	18	14	18	22	27
1	378	378		195	410	14		215	
	365		365	223	402		22		179
	384	384		194	407	9		213	
	364		364	233	400		17		167
2	370	370		193	398	10		205	
	369		369	245	405		17		160
	390	390		201	401	6		200	
	367		367	249	401		14		152
3	370	370		197	376	5		179	
	370		370	261	406		15		145
	389	389		205	394	4		189	
	375		375	261	407		14		146
4	363	363		197	376	4		179	
	377		377	269	412		16		143
	387	387		203	403	7		200	
	374		374	252	406		15		154
5	368	368		196	394	9		198	
	370		370	253	408		18		155
	385	385		201	407	9		206	
	370		370	237	407		19		170
6	373	373		195	403	10		208	
	365		365	234	407		22		173
	384	384		198	410	10		212	
	355		355	219	406		24		187
7	379	379		204	422	13		218	
	369		369	222	413		28		191
	379	379		193	417	15		224	
8	360		360	208	409		34		201
	379	379		194	425	17		231	
	360		360	207	410		37		203
	379	379		193	425	19		232	
9	359		359	201	414		44		213
	389	389		196	437	24		241	
	350		350	192	407		48		215
	379	379		194	433	23		239	
10	359		359	196	425		66		229
	389	389		196	462	49		266	
	359		359	188	417		65		229
	375	375		185	439	38		254	
11	358		358	189	433		62		244
	389	389		205	471	52		266	
	355		355	195	423		63		228
	380	380		195	446	47		251	
12	359		359	184	435		60		251
	389	389		207	470	50		263	
	349		349	195	420		63		225
	380	380		197	445	43		248	

The highest starting head of 4.05m occurs on day 12, see Figure 4-28. The highest generating head of - 4.98m also occurs on day 12 on the ebb tide; the value is seen as negative in Table 4-4 and Figure 4-29 as the sea level is below the impoundment. The head increases during generation because the volume of water flowing through the turbines is less than optimum to match the natural tide flows, i.e., the gradient of the red line (impoundment level) is shallower than the blue line (sea level). At the time of the highest operating head the sea level is -3.951m OD, and the impoundment level is 1.032m OD.
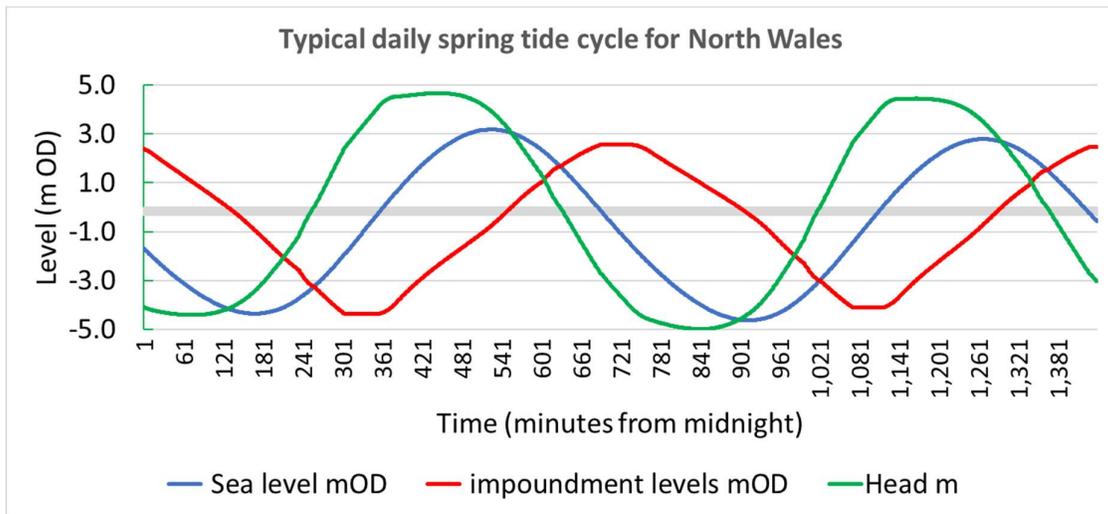
Figure 4-29 Example of highest tidal range of 7.81m and highest starting head of 4.05 m on day 12.

Note that the gradient of the red, impoundment level, line is shallower than the blue sea level line for the high spring tide. For lower tides the red line is steeper than the blue, the pumping period is shorter, and the barrage level matches the full tidal range, see Figure 4-30.
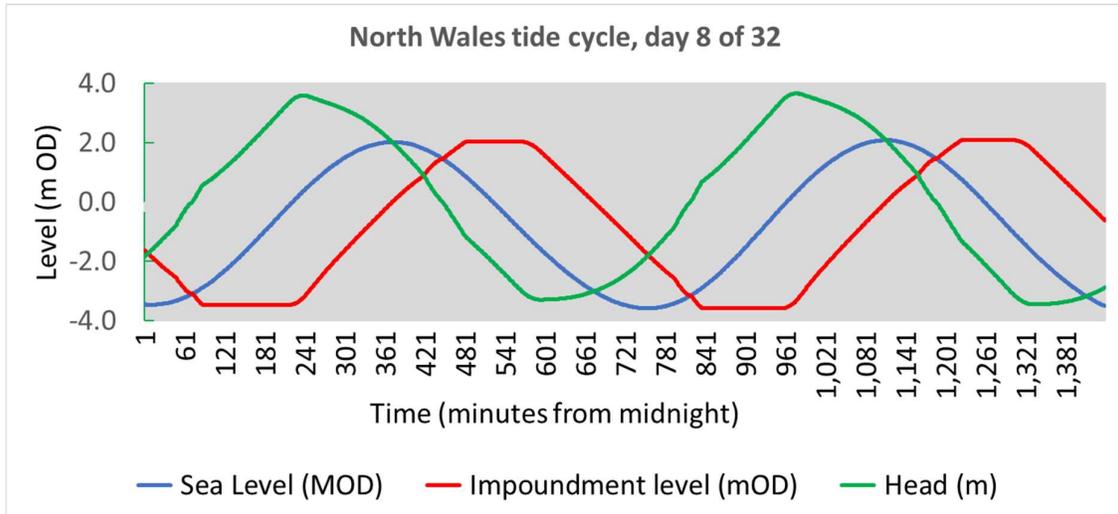
Figure 4-30 Example of a low tidal range of 5.85m on day 8.

For efficient operation of the turbine the operator needs to know when to start generation and what speed or flow to set for best effect. The duration of the tide cycle is fairly consistent at around 12-hours 20-minutes, although varying with location. So, it is interesting to plot the data for tidal range and start of generation from the previous peak from Table 4-5. In Figure 4-31 the start times after a high tide (ebb generation) are clumped within a fairly narrow start time of 180 to 210 minutes after high tide. This does not vary significantly with the height of the tide. The start of generation after a low tide (flood generation) appears almost as a linear function of earlier start time for the spring tide of 180 minutes to 270 minutes for the neap flood tide.
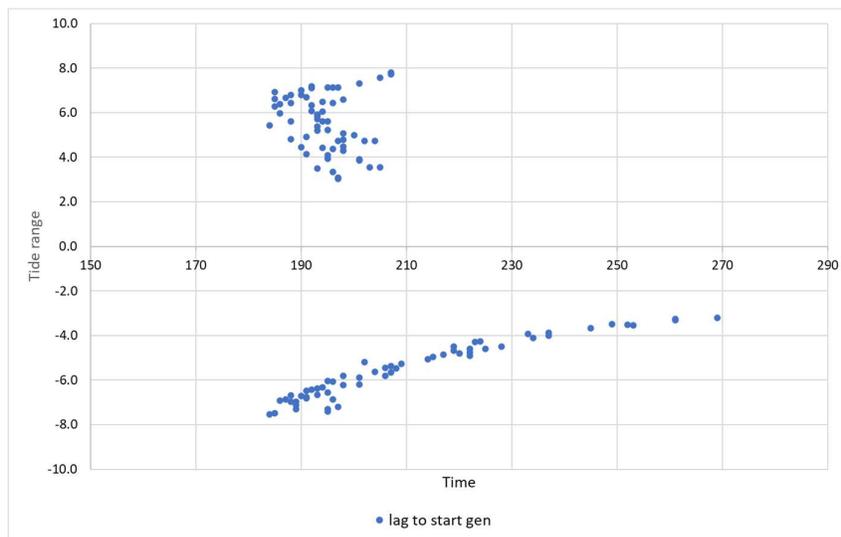
Figure 4-31 Scatter diagram for time lag to start generation after high and low tide for NW.

The scatter diagram for the end of generation Figure 4-32 is almost a mirror image of Figure 4-30. The time to stop generation on a falling tide (ebb) is almost a linear function from 390 minutes to 475 minutes after high tide; excluding one early finish at 375 minutes. The end of generation for the rising tide (flood) is clubbed together between 395 minutes and 475 minutes.
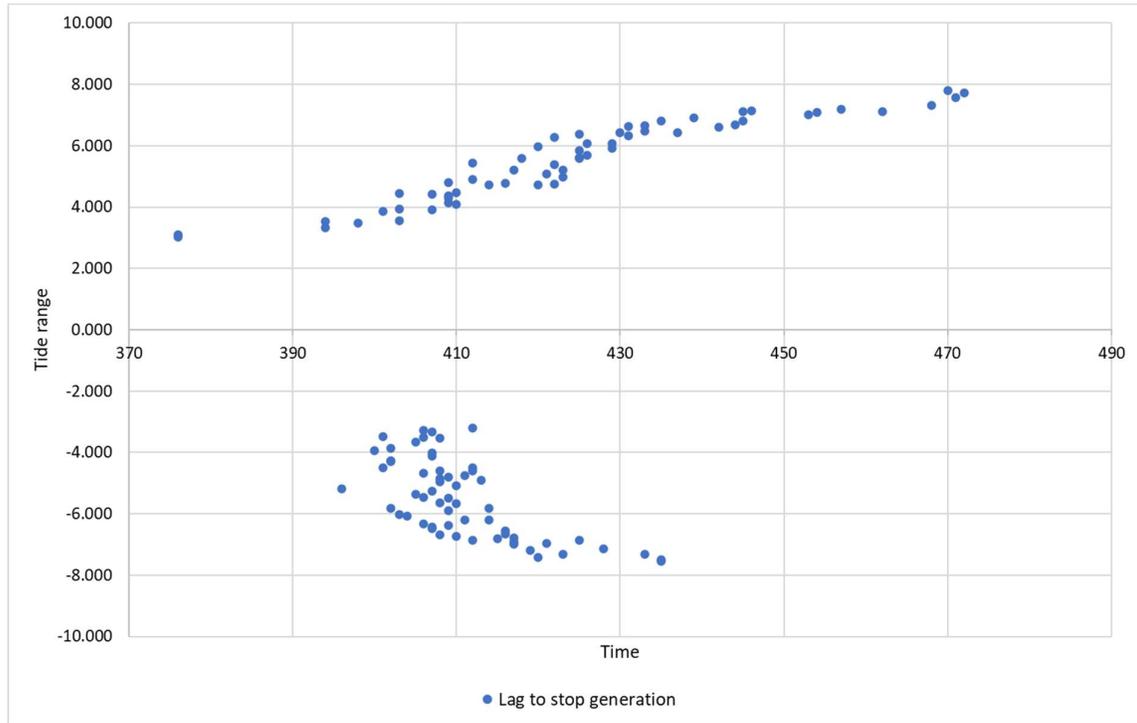
Figure 4-32 Scatter diagram for time lag to the end of generation after high and low tide for NW.

Table 4-7 shows a summary of the neap and spring tide data from the analysis for the North Wales lagoon. The maximum tidal range during this period is 7.81m, compared with Morecambe Bay in section 4.7.3.

Table 4-7 Range of parameters from NW.

North Wales, no SLR			Neap Tide		Spring Tide	
			Day 4	Range 3.02 m	Day 12	Range 7.81 m
			Max	Min non zero	Max	Min non zero
Tide height		td	0.940	-2.620	3.180	-4.630
Barrage height		BZ	0.956	-2.620	2.561	-4.360
Tide-barrage head diffeerence		dH	2.709	-2.198	4.667	-4.983
Power single turbine	4 Ebb gen	Pw1	5.89E+06	1.51E+06	1.50E+07	2.20E+06
	8 Flood gen		8.39E+06	1.34E+06	1.50E+07	2.30E+06
	Pumping		-7.50E+06	-7.50E+06	-7.50E+06	-7.50E+06
Power all turbines		PwA	9.37E+08	-9.47E+08	1.68E+09	-9.47E+08
turbine model speed (rpm)		n11	339.9	182.2	372.4	193.1
Nett energy		Enet	5.63E+10	-5.70E+10	1.01E+11	-5.70E+10
turbine model efficiency	4 Ebb gen	eta	0.914	0.685	0.915	0.537
	8 Flood gen		0.906	0.611	0.911	0.532
	Pumping		0.194	0.002	0.781	0.004
turbine model flow (m^3/s)		Q11	4.8	2.4	4.8	2.3
flow if no barrage		Qb	3.26E+04	-3.27E+04	7.78E+04	-7.32E+04
Total flow through all sluices		Qs	4.21E+04	-4.23E+04	5.25E+04	-5.42E+04
turbine flow (all) (m^3/s)		Qt	4.44E+04	-4.44E+04	5.98E+04	-6.15E+04
turbine flow (m^3/s)	4 Ebb gen	Qt1	-207.5	-330.9	-328.9	-517.7
	8 Flood gen		372.3	272.7	503.9	341.3
	Pumping		373.6	352.2	373.4	220.9
turbine speed (rpm)		Tspd	62.8	31.3	62.8	46.0

4.7.2 Morecambe Bay Barrage

The base case for MB is 140 x 8.0m diameter turbines with 20-MW generators and zero SLR. Table 4-8 shows a summary of the first 12-days of tides. Table 4-8 shows some analysis of data for times to start and stop pumping and generation.

Table 4-8 Example of summary data from MB.

Day	Peak	Levels		Head @ peak tide (m)	time after peak (minutes)	stop pumping		Start generating		stop generating Open sluice		Time to close sluice & start pumping	Tide Range (m)
		Sea	Impounded			Impounded level		Head	time	Head	time (mins)		
	maximum	5.137	2.640			3.990	maximum	4.470				Average	6.614
	Minimum	-4.169	-0.067			-3.433	Minimum	3.063				Std Div	1.256
												Max	9.306
												Min	4.723
1	High	3.640	2.640	1.000	1	3.648	81	-3.577	189	-1.124	449	472	6.452
	Low	-2.812	0.532	-3.343	379	-2.794	494	3.926	594	1.310	793	831	-6.749
	High	3.937	1.507	2.430	745	3.610	904	-3.758	942	-1.246	1,194	1,217	7.028
	Low	-3.091	0.377	-3.467	1,128	-3.091	1,237	4.049	1,336	1.385	99	137	-7.228
2	High	4.137	1.605	2.532	51	3.709	208	-3.861	248	-1.245	510	532	7.381
	Low	-3.244	0.616	-3.860	436	-3.244	558	4.122	637	1.459	843	882	-7.589
	High	4.344	1.706	2.639	795	3.801	951	-4.000	993	-1.317	1,263	1,286	7.778
	Low	-3.433	1.706	-5.139	1,181	-3.433	1,320	4.227	1,377	1.575	146	187	-8.022
3	High	4.588	1.803	2.785	98	3.912	253	-4.141	298	-1.404	583	605	8.239
	Low	-3.651	1.387	-5.037	487	-3.285	645	4.301	688	1.652	891	932	-8.324
	High	4.674	1.697	2.977	841	3.894	997	-4.196	1,043	-1.446	1,327	1,349	8.389
	Low	-3.715	1.451	-5.166	1,230	-3.156	1,389	4.392	1,432	1.729	198	238	-8.646
4	High	4.931	1.593	3.338	142	3.926	301	-4.332	349	-1.555	641	664	8.896
	Low	-3.966	1.665	-5.630	536	-2.892	703	4.432	746	1.758	944	984	-8.840
	High	4.874	1.326	3.548	885	3.801	1,047	-4.284	1,094	-1.518	1,374	1,396	8.762
	Low	-3.888	1.475	-5.363	1,276	-3.114	1,435	4.459	37	1.795	247	287	-9.009
5	High	5.121	1.391	3.730	185	3.894	348	-4.441	398	-1.651	690	713	9.267
	Low	-4.145	1.753	-5.898	582	-2.771	752	4.469	794	1.825	989	1,030	-9.061
	High	4.915	1.175	3.740	928	3.767	1,092	-4.307	1,141	-1.549	1,418	1,440	8.839
	Low	-3.924	1.467	-5.392	1,321	-3.065	38	4.470	81	1.802	291	331	-9.061

Day	Peak	Levels		Head @ peak tide (m)	time after peak (minutes)	stop pumping		Start generating		stop generating Open sluice		Time to close sluice & start pumping	Tide Range (m)
		Sea	Impounded			Impounded level		Head	time	Head	time (mins)		
6	High	5.137	1.318	3.819	227	3.894	393	-4.466	444	-1.642	736	759	9.306
	Low	-4.169	1.779	-5.948	627	-2.706	798	4.447	840	1.778	1,031	1,072	-8.957
	High	4.788	1.211	3.578	972	3.764	1,137	-4.236	1,185	-1.489	19	41	8.605
	Low	-3.817	1.366	-5.183	1,366	-3.152	80	4.403	121	1.739	329	370	-8.792
7	High	4.975	1.528	3.447	270	3.961	435	-4.382	486	-1.568	780	803	9.011
	Low	-4.036	1.751	-5.788	673	-2.712	843	4.340	884	1.703	1,069	1,112	-8.542
	High	4.506	1.334	3.172	1,016	3.765	1,181	-4.090	1,228	-1.403	55	77	8.085
	Low	-3.579	1.101	-4.680	1,411	-3.369	116	4.288	158	1.603	366	408	-8.232
8	High	4.653	1.754	2.900	315	3.990	478	-4.204	528	-1.460	818	840	8.423
	Low	-3.769	1.540	-5.309	719	-2.995	881	4.207	922	1.538	1,109	1,152	-7.871
	High	4.101	1.407	2.695	1,062	3.719	1,228	-3.863	1,272	-1.233	90	111	7.343
9	Low	-3.241	0.624	-3.865	18	-3.241	142	4.098	204	1.425	410	452	-7.454
	High	4.213	1.671	2.542	362	3.863	529	-3.949	575	-1.292	846	867	7.621
	Low	-3.408	0.842	-4.250	767	-3.408	902	4.021	956	1.351	1,151	1,195	-7.039
	High	3.631	1.449	2.182	1,112	3.634	1,279	-3.601	1,319	-1.117	133	155	6.484
10	Low	-2.853	0.428	-3.281	68	-2.281	181	3.894	262	1.233	461	501	-6.572
	High	3.719	1.442	2.276	413	2.908	586	-3.667	627	-1.134	884	905	6.728
	Low	-3.010	0.334	-3.344	819	-2.281	928	3.819	1,018	1.170	1,206	1,248	-6.184
	High	3.175	1.226	1.949	1,167	2.908	1,305	-3.340	1,387	-0.948	182	203	5.358
11	Low	-2.183	0.406	-2.590	180	-2.281	225	3.716	329	1.070	519	558	-5.123
	High	2.940	1.039	1.900	537	2.908	623	-3.420	694	-0.996	935	957	5.314
	Low	-2.374	0.169	-2.544	935	-2.281	977	3.645	1,088	1.013	1,270	1,310	-5.058
	High	2.684	0.925	1.759	1,297	2.908	1,354	-3.154	19	-0.878	242	264	4.867
12	Low	-2.183	0.406	-2.590	180	-2.281	286	3.564	403	0.951	585	622	-5.123
	High	2.940	1.039	1.900	537	2.908	674	-3.247	765	-0.904	993	1,015	5.314
	Low	-2.374	0.169	-2.544	935	-2.281	1,033	3.561	1,163	0.934	1,340	1,377	-5.058
	High	2.684	0.925	1.759	1,297	2.908	1,419	-3.063	87	-0.829	307	329	4.723

Table 4-9 Example of analysis of data from MB.

Day	Time between peaks (minutes)			lag to start generation (minutes)	lag to open sluice (minutes)	Pumping duration (minutes)		Generating duration (minutes)	
	All	Ebb	Flood			Ebb	Flood	Ebb	Flood
Average	372	391	353	207	393	24	68	252	192
Std Div	23	15	13	16	225	8	13	19	10
1	378	378		188	448	22		260	
	366		366	215	414		73		199
	383	383		197	449	20		252	
	363		363	208	411		71		203
2	385	385		197	459	26		262	
	359		359	201	407		69		206
	386	386		198	468	34		270	
	357		357	196	405		66		209
3	389	389		200	485	40		285	
	354		354	201	404		65		203
	389	389		202	486	40		284	
	352		352	202	408		63		206
4	394	394		207	499	39		292	
	349		349	210	408		63		198
	391	391		209	489	39		280	
	349		349	201	411		61		210
5	397	397		213	505	39		292	
	346		346	212	407		62		195
	393	393		213	490	38		277	
	346		346	200	410		62		210
6	400	400		217	509	39		292	
	345		345	213	404		65		191
	394	394		213	487	39		274	
	344		344	195	403		65		208
7	403	403		216	510	40		294	
	343		343	211	396		69		185
	395	395		212	479	39		267	
	344		344	187	395		70		208
8	404	404		213	503	41		290	
	343		343	203	390		76		187
	396	396		210	468	31		258	
9	344		344	186	392		77		206
	405	405		213	484	35		271	
	345		345	189	384		84		195
	396	396		207	461	26		254	
10	345		345	194	393		85		199
	406	406		214	471	23		257	
	348		348	199	387		57		188
	453	453		220	455	22		235	
11	357		357	149	339		65		190
	398	398		157	398	20		241	
	362		362	153	335		44		182
	323	323		162	385	22		223	
12	357		357	223	405		52		182
	398	398		228	456	18		228	
	362		362	228	405		42		177
	387	387		230	-990	21		220	

The highest tidal range during the period for MB is 9.306m and occurs on day six. The highest starting head of 4.47m occurs at the end of day 5 on the ebb tide, see Figure 4-33. The head increases during generation because the volume of water flowing through the turbines is less than optimum to match the natural tide flows, i.e., the gradient of the red line (impoundment level) is shallower than the blue line (sea level). At the time of the highest starting head the sea level is -3.924m OD, and the impoundment level is 1.467m OD.
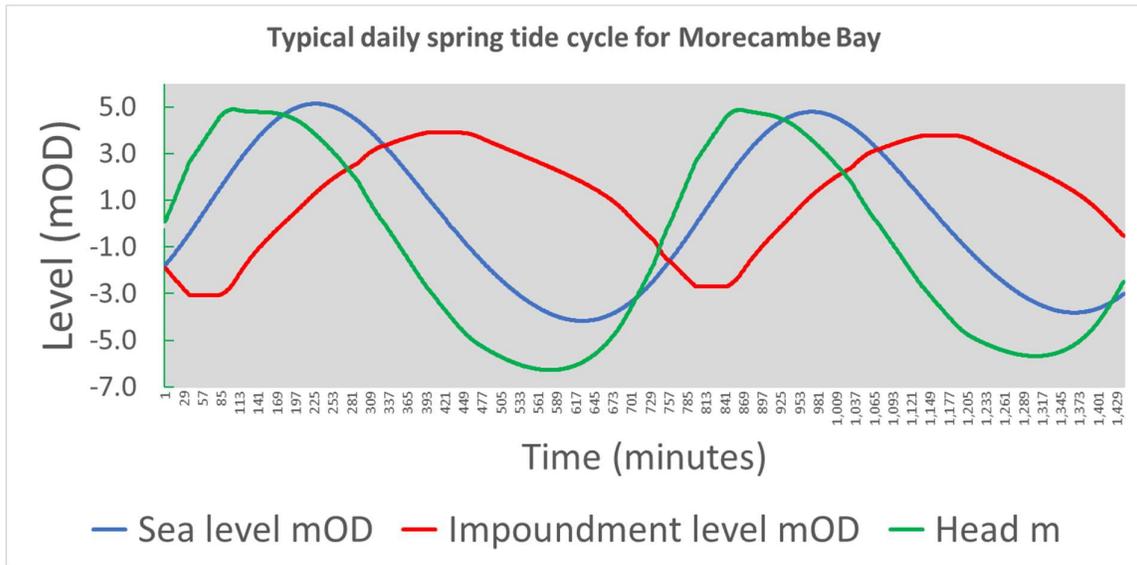
Figure 4-33 Example of highest tidal range of 9.31m and the highest starting head of 4.47m on day 6.

Figure 4-34 shows the flows in m³/s through the turbines (yellow line) and the sluices (red lines). The blue sea level line is for unrestricted sea levels.
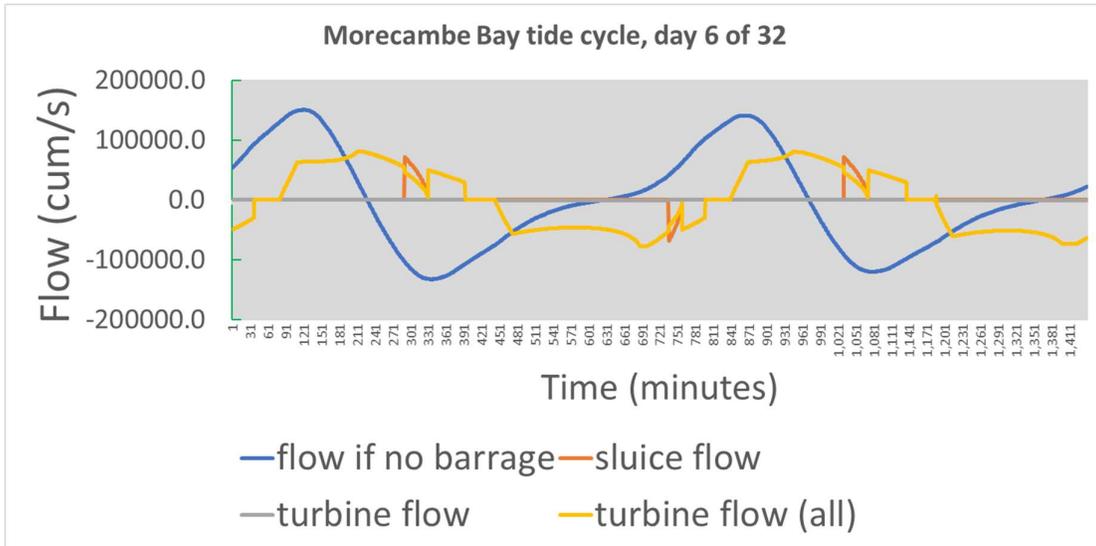
Figure 4-34 Example of flows on highest tidal range of 9.306 m on day 6.

Note also that the duration of the ebb is shorter than the flood, i.e. the blue line is not symmetrical, possibly due to the nature of the estuary.

Figure 4-35 shows the levels during a neap tide range on day 12, from Table 4-8.
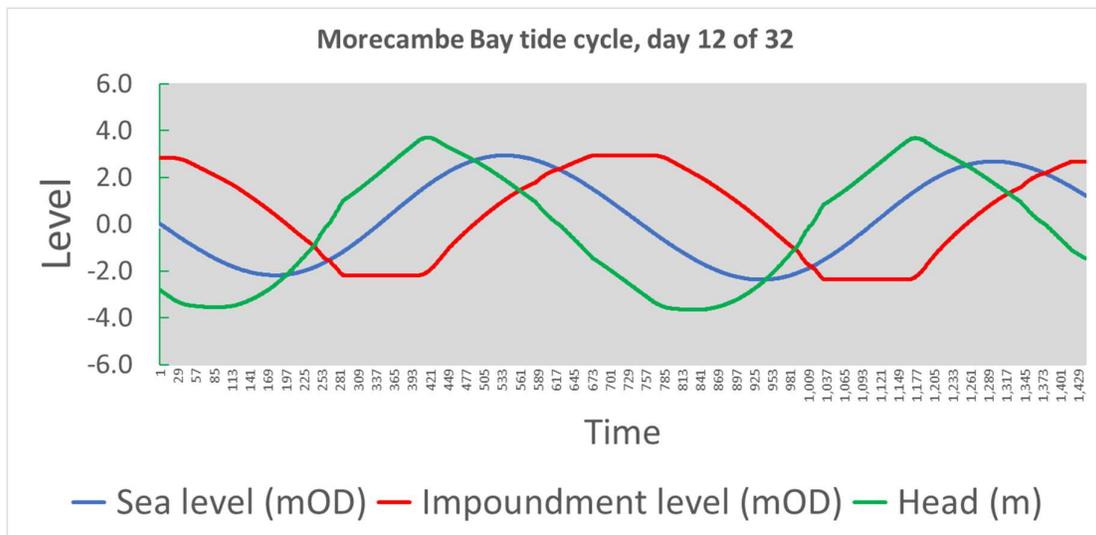
Figure 4-35 Example of a low tidal range of 5.85 m on day 8.

In Figure 4-36 we see a similar grouping of generation starting times as Figure 4-31 for NW except the range is wider. For ebb generation the starting times are mostly between 190 and 230 minutes after high tide. For flood generation the starting times vary from 185 to 245 minutes after low tide. Note that the scatter is greater at low tide than high tide.
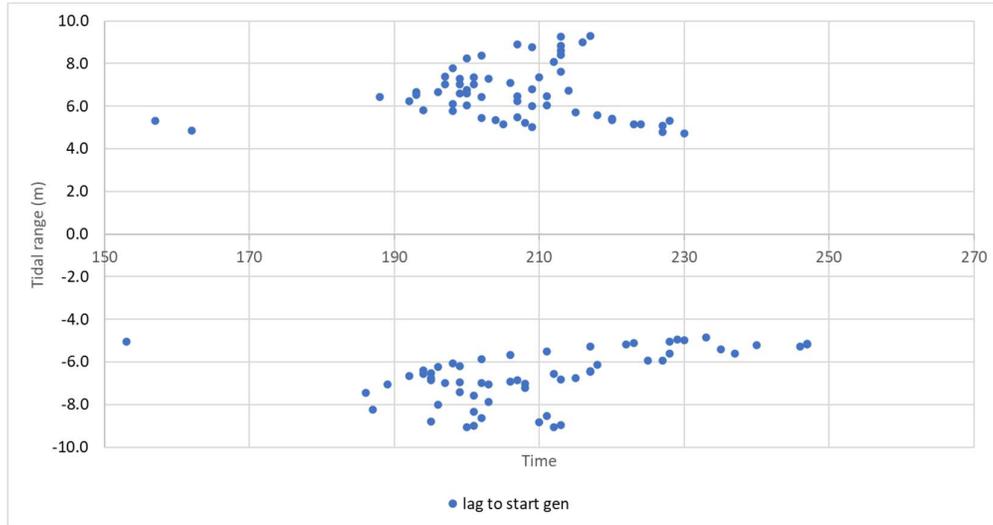
Figure 4-36 Scatter diagram for time lag to start generation after high and low tide.

The scatter diagram for the end of generation Figure 4-37 differs from NW in that the generation time for ebb tides extends from 430 minutes to 515 minutes. The time to stop generation on a falling tide (ebb) is almost a linear function from 390 minutes to 475 minutes after high tide; excluding one early finish at 375 minutes. The end of generation for the rising tide (flood) is clubbed together between 395 minutes and 475 minutes.
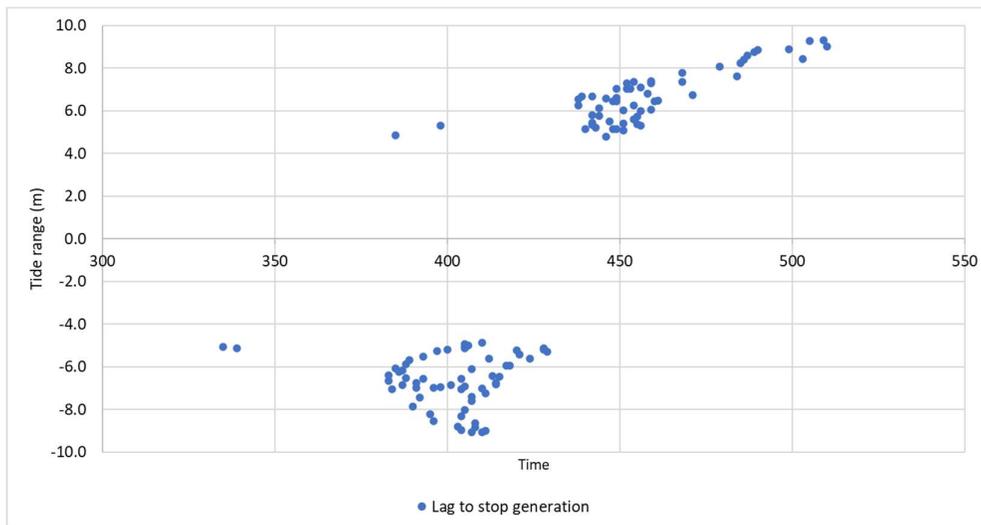
Figure 4-37 Scatter diagram for time lag to the end of generation after high and low tide.

Table 4-10 shows a summary of the data from the Morecambe Bay analysis. The maximum tidal range during the selected period is 9.31m, which is greater than the same period for North Wales and is probably due to the shape of the coastline and seabed levels.

Table 4-10 Range of parameters from MB.

Morecambe Bay, no SLR			Neap Tide		Spring Tide	
			Day 12	Range 4.72 m	Day 6	Range 9.31 m
			Max	Min non zero	Max	Min non zero
Tide height		td	2.940	-2.374	5.137	-4.169
Barrage height		BZ	2.948	-2.374	3.894	-3.065
Tide-barrage head diffeerence		dH	3.705	-3.664	4.892	-6.278
Power single turbine	4 Ebb gen	Pw1	1.39E+07	1.43E+06	2.00E+07	3.62E+06
	8 Flood gen		1.46E+07	1.48E+06	2.00E+07	3.87E+06
	Pumping		-7.50E+06	-7.50E+06	-7.50E+06	-7.50E+06
Power all turbines		PwA	1.75E+09	-1.06E+09	2.50E+09	-1.06E+09
turbine model speed (rpm)		n11	374.8	186.6	375.0	193.1
Nett energy		Enet	1.05E+11	-6.38E+10	1.50E+11	-6.38E+10
turbine model efficiency	4 Ebb gen	eta	0.896	0.528	0.916	0.537
	8 Flood gen		0.875	0.522	0.875	0.521
	Pumping		0.561	0.002	0.781	0.007
turbine model flow (m^3/s)		Q11	4.75	3.07	4.75	2.17
flow if no barrage (m^3/s)		Qb	6.51E+04	-5.75E+04	1.50E+05	-1.33E+05
total flow (m^3/s)		Qdt	8.55E+04	-8.33E+04	1.18E+05	-1.12E+05
sluice flow		Qs	5.20E+04	-5.07E+04	7.16E+04	-6.84E+04
turbine flow (all) (m^3/s)		Qt	5.97E+04	-5.86E+04	8.08E+04	-7.72E+04
turbine flow (m^3/s)	4 Ebb gen	Qt1	-289.7	-440.7	556.7	-580.2
	8 Flood gen		449.4	296.8	607.3	409.3
	Pumping		373.5	296.2	373.0	221.0
turbine speed (rpm)		Tspd	62.8	44.0	63.6	46.0

4.7.3 Comparison between the two different schemes.

For the spring tides at both sites the maximum generating head exceeds the starting head because the volume of water flowing through the turbines is less that the natural tidal flow. Thus, the generating head increases after the start of generation until the tide turns. This is not a problem as the head soon reduces; adding more turbines or starting generation earlier would avoid this but it may not be cost effective.

Table 4-7 shows a summary of the neap and spring tide data from the analysis for the North Wales lagoon. The maximum tidal range during this period is 7.81m, compared with Morecambe Bay in section 4.7.3. Table 4-10 shows a summary of the data from the Morecambe Bay analysis. The maximum tidal range during the selected period is 9.31m, which is greater than the same period for North Wales and is probably due to the shape of the coastline and seabed levels.

Tide/sea level

The mean tide levels from Llandudno (NW) is 0.78m below OD, whilst for Heysham (MB) the mean level is 0.38m above OD. The highest spring tide range from the 32-day dataset is 9.31m for MB and 7.81m for NW: a difference of 1.5m. The lowest neap tide range from the 32-day dataset is 4.72m for MB and 3.02m for NW: a difference of 1.7m.

Impoundment level

With a barrage installed, both sites match the natural tide range at neap tide. Whilst neither site matches the tide range at spring tide; the biggest difference is at high tide. NW is 0.62m below high tide while MB is 1.24m below.

Head

The head differences are larger for MB than NW as would be expected from the higher tidal range.

Power from a single turbine.

The maximum power generated for NW is 15-MW on spring tide for both ebb and flood generation. The lowest generation for NW is 1.3-MW which occurs on the flood of the neap tide. The maximum power generated for MB is 20-MW on spring tide for both ebb and flood generation. The lowest generation for MB is 1.4-MW which occurs on the ebb of the neap tide. For both sites the spring tide power reaches the generator rating. The pumping power is a constant 7.5-MW in all cases.

Turbine model speed n11.

The maximum model rotor has been set to 375 rpm which has been reached for neap and spring tides at MB and spring tide at NW. The maximum speed for NW neap tide is 340 rpm. The minimum rotor speeds for both sites and tides are within a narrow band between 182 and 193 rpm.

Turbine model efficiency.

The efficiency range for generation is in a similar range for both sites and tide directions, between 92% and 53%. For pumping the efficiency starts near 0% for zero head and increases to 78% on spring tides at both sites.

Turbine model flow Q11.

The maximum turbine model flows for both sites and all tides is about 4.8 m^3/s. The minimum turbine model flows for NW and all tides is about 2.3 m^3/s. For MB the minimum turbine model speed varies from 2.2 m^3/s to 3.1 m^3/s.

Turbine flow Qt1.

The single full-size turbine flows for NW at neap tides varies between 372 m^3/s to 207 m^3/s. For spring tides this increases to between 518 m^3/s to 329 m^3/s. For MB the single full-size turbine flows at neap tides varies between 450 m^3/s to 290 m^3/s and for spring tides between 607 m^3/s to 409 m^3/s.

Pumping flows for both sites and all tides are limited to a maximum of 373 m^3/s which is the turbine limit. Minimum pumping flows vary with site and tides. For NW the minimum pumping flow is 352 m^3/s at neap tide and 221 m^3/s at sprint tide. For MB the minimum pumping flow is 296 m^3/s at neap tide and 221 m^3/s at spring tide.

Flow without barrage Qb.

The average flow without the barrage is calculated as the difference between the impoundment volumes between high and low tide divided by the duration of the tide half cycle. This would be the average flow over the line of the barrage used in the bathymetry. From Table 4-7 for NW the flow at neap tide varies between 32,600 m^3/s to -32,700 m^3/s and between 77,800 m^3/s to -73,200 m^3/s for spring tides. From Table 4-10 for MB the flow at neap tide varies between 65,100 m^3/s to -57,500 m^3/s and between 150,000 m^3/s to -133,000 m^3/s for spring tides.

For NW the total flow through all sluices at neap tide varies between 42,100 m^3/s to -42,300 m^3/s and between 52,500 m^3/s to -54,200 m^3/s for spring tides. For MB the flow at neap tide varies between 52,0100 m^3/s to -50,700 m^3/s and between 71,600 m^3/s to -68,400 m^3/s for spring tides.

Turbine speed Tspd.

The turbine speeds are consistent between sites and tide ranges. Varying between 63 rpm to 31 or 46 rpm.

4.7.4 Proposed modifications to the Gen53 program

After using the program for 4-years the candidate suggests the following areas may benefit from further investigation: -

- The optimisation process involves many variables and is performed by a generic subroutine. It is time consuming and can produce false positive results if not handled with care. This is like finding a peak on a contour map but there are higher peaks elsewhere. This is apparent if you are plotting a range of scenarios and there is a blip in the curve, i.e. if you are plotting AEP against a range of turbine numbers the resulting curve should be fairly smooth. If this occurs It is necessary to manually reset some of the parameters and repeat the analysis until the results stabilise. It would be better if the optimisation routine could be improved or another method found.

- The estimated AEP is sensitive to the starting date used for the representative period. For example, the AEP for Morecambe Bay with 140 x 8m diameter turbines with 20-MW generators (no SLR, time interval 0.01h, pumping, cycle-by-cycle, sluice ratio=2, 63 sluices, triple regulated (RPM) is estimated at 6.1243-TWh from a 16-day period starting on 12-Jan-2018. Simply changing the start date to 30-Dec-2017 gives an AEP of 7.5019-TWh; a 22% increase. The user should be aware of this and select a time period that is more representative of the year, i.e. medium spring and neap tides. Figure 4-38 shows that the amplitude of spring tides around 4-Jan is significantly larger than around 20-Jan. The users should take care when selecting representative periods of tides.
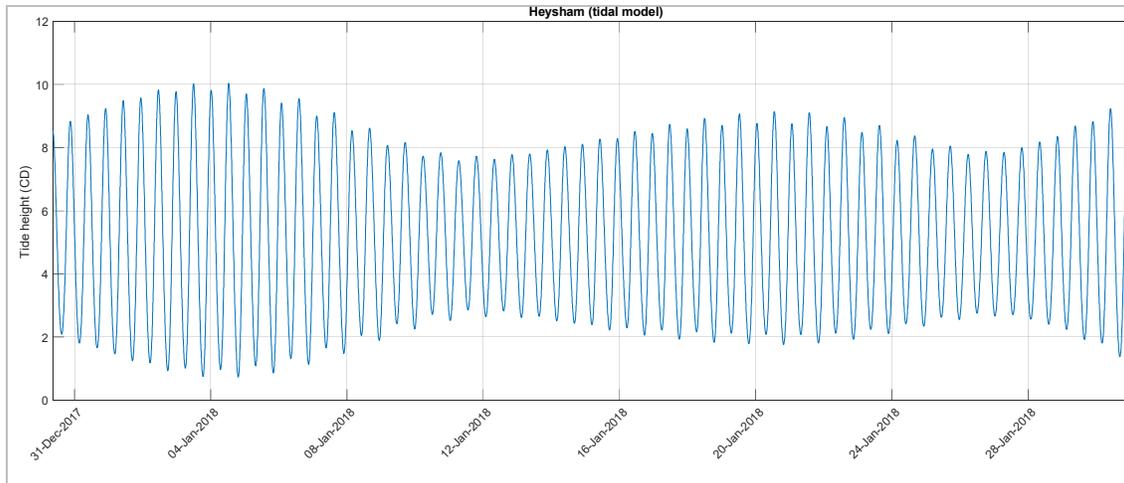
Figure 4-38 Tidal range for Hesham for 32-day periods.

- The efficiency of the turbine is based on the published hill chart from a double regulated, Andritz 3-blade, 7.5m diameter bulb turbine (Aggidis and Feather, 2012). This reference is now 13-years old and was published about the same time at the turbines were manufactured for the Lake Sihwa tidal range power station. The reference shows an initial efficiency of 90%, dropping linearly as rotational speed increases. The program extrapolates the published hill chart to give estimates from triple regulation, different turbine diameters and generator ratings. However, there is no reduction of efficiency in reverse flow conditions. Thus, the program overestimates flood generation by about 20% or 30%. Flood generation is less significant for estuarine barrages, where there is a small, wetted area at low tide, but more so for coastal lagoons where the flood generation is more significant. Whilst it would be possible to install some turbines in the reverse direction the overall efficiency would be less for two-way flow. If sea levels rise to the point where the flood tide has more energy, then the direction of bulb turbines could be reversed during a refit. It is also reasonable to assume that all manufacturers are seeking to improve the revers flow efficiency of their turbines.
- There is currently no program manual or listing of the main variables. To fully understand the program, it is proposed to draft a manual with subroutine and variable listings.
- Investigate a simplified time-based optimisation algorithm that will work on a full year of tide data. The one constant in tidal range is the period of the tides which is produced by the moon's rotation, approximately 12-hours 20-minutes. The flow rate for each tide must be related to the tidal range and the volume of water impounded between the tide extremes. To see if a time and flow rate optimisation is possible, the existing program data was analysed to determine the time

windows for start and end of generation and pumping, based on the time since high and low tides. A simplified optimisation would make it possible to estimate one year's generation at a time. So, comparisons with other years could be made to determine any annual variation.

- In the absence of specific data for bulb turbines in reverse flow a 20% reduction in efficiency will be applied to flood generation. Other turbines are in development which may give similar efficiencies in both directions, but no data is available.

- The investigations into the effects for SLR have shown the need for auxiliary pumps to assist draining impoundments to pre-SLR low tides. An additional sub-routine could be created to add submersible pumps when required to improve the pumping efficiency by increasing the pumping flow and reducing the total pumping time.

4.8   Summary

This chapter describes the method of operating and the workings of the Lancaster 0-D model. It includes details of pumping with turbines as pumps (TaP) and submersible pumps that can be used maintain existing low tide levels in the face of sea level rise. The function and operation of the Lancaster 0-D program has been described, and two case study sites were used to examine the results of the analysis and check the understanding and functioning of the program.

The possible need for independent pumps to reach existing low intertidal areas has been discussed and investigated to a limited extent.

The scatter diagrams show the start and end of generation times for the case study sites relative to the previous peak tide. They are important for the development of a simplified time-based model proposed in the following chapter.

5   SIMPLIFIED & DEMAND LED 0-D MODELS

To purpose of this chapter is to describe the development of a simplified analysis that could analyse a full year of tide data and thus avoid the need to extrapolate from optimised data obtained from a 16- or 32-day period. The following assumptions are made: -

- The basis of the new model will be the near constant period of the tides at approximately 6 hours and 10 minutes for each half cycle. From the sample data for North Wales (NW) the start of generation is between 180 and 210 minutes for the ebb tide and between 180 and 270 minutes for the flood tide. These results may be biased by the current model which optimises by head. A simple time step approach can be used to find the optimum start time rather than searching for optimum head.

- As the efficiency increases as the speed drops, the gradient of level change can be less than the maximum gradient of the sea level change. It should not be more than the natural peak flow as this may cause social or ecological problem. The gradient varies with tidal range and minimises changes to the environment.

- Include a target point for the equalisation of impoundment and sea levels, as discussed below. This will be set at half the maximum pumping head for ebb tides, i.e. 0.75m where the pumping head is limited to 1.50m. However, due to the larger surface area at high tide, the target point should be at a third of the maximum pumping head for flood tides, i.e. 0.5m below high tide level.

- An option for stand-alone submersible pumps will be included to take over pumping above 1.5m head, limited to 3.0m head as any more would not be efficient. Submersible pumps may only be required after 40 or 80 years when the turbines as pumps (TaP) cannot match existing low water levels due to sea level rise (SLR).

- The flow through the sluices approximates to a straight line. The sluices will open when the generation line intersects the sluice capacity and will be independent of the end of generation.

- Start of generation time will be incremented in steps until a maximum is achieved.

- Generation will stop when the minimum efficient head is reached, set at 1.5m, and the turbine races will supplement the sluice flows.

- Note that generation can continue after the sluice gates open, until the minimum head of 1.5m has been reached.

- In the absence of any published data of bulb turbines in reverse flow an assumed reduction in efficiency during reverse flow will be included in the program.

5.1 Turbine operation.

The turbine will be operated at maximum performance based on the 3 points highlighted in red in Figure 5-1. The maximum model flow Q_{11} will be limited to 4.75 m³/s, where the speed n_{11} is a maximum of 255 rpm, at this point the efficiency is a minimum of 77%.
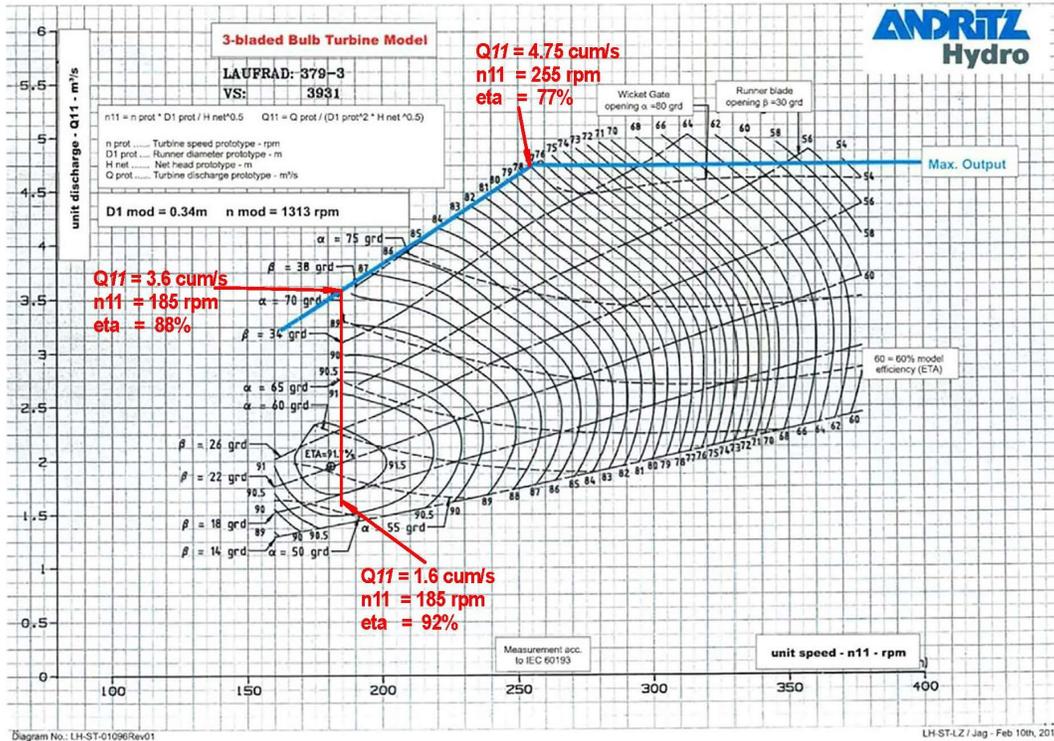
Figure 5-1 Operating limits for Andritz hill chart.

In Figure 5-1 the blue line is the maximum output between speeds of 185-rpm and 370-rpm; note that there is no increase in flow beyond 255-rpm, which is the maximum useful speed. The minimum speed of 185-rpm gives the highest efficiency as indicated by the red line. At the model flow of 3.6 m³/s the efficiency is 88%, increasing to 92% at the minimum flow rate of 1.6 m³/s. If the flow through the turbine is greater than 4.75 m³/s the sluice gates are opened to limit the flow through the turbines.

The model speed is similar given by Equation 5-1

$$3.6 \leq Q_{11} \leq 4.75, \quad n_{11} = 185 + 60.87(Q_{11} - 3.6)$$
$$1.6 \leq Q_{11} < 3.6, \quad n_{11} = 185 \; rpm$$

Equation 5-1 Model speed based on flow rate.

Efficiency is based on Q11 by Equation 5-2.

$$3.60 \leq Q_{11} \leq 4.75, \quad eta = 88 - 9.56(Q_{11} - 3.6)$$
$$1.60 \leq Q_{11} < 3.60, \quad eta = 92 - 2.00(Q_{11} - 1.6)$$

Equation 5-2 Efficiency based on flow rate.

The model speed is shown in Equation 5-3.

$$Q11 <= 3.6, \qquad then \qquad n11 = 180$$

else

$$3.6 < Q11 <= 4.75, \qquad n11 = 185 + (Q11 - 3.6)/1.15*40$$

Equation 5-3 Model speed n11 rpm.

It is assumed that the turbines are positioned for efficient flow on the ebb tide. The efficiency in reverse flow is not known but it will be assumed that there is a 20% reduction in the efficiency calculated with Equation 5-2. In the spreadsheet calculation the reverse flow reduction is held in a single cell that can be changed at any time. The effect of sea level rise (SLR) is to increase the flood tide and reduce the ebb tide generation so it may be appropriate to install half the turbines in each direction which would even out the generation between flood and ebb. Alternatively, the proposed reversible turret or counter rotating turbines could be used.

5.2 Target gradient.

The target gradient of the impoundment levels will be limited to the maximum gradient of the sea level for each tide. The gradient is calculated from the sea level at the start time to the target level and time for the end of the cycle. If the start time is early then the target gradient may be less than the tide gradient, this could occur where a lower starting head is balanced by a longer generation

time. If the target gradient is steeper than the maximum tide gradient, then it is limited to the tide and generation may have to be stopped early so that the sluices and pumps can reach the tide limit.

Table 5-1 gives the maximum and minimum gradients for a range of tides from the North Wales lagoon. Figure 5-2 shows a graphical representation of the same data.

Table 5-1 Sample of maximum gradient for different tidal ranges from NW.

Day	Direction	Tidal Range	max grad m/minute
4	Ebb	3.02	0.013
	Flood	-3.21	-0.014
	Ebb	3.56	0.014
	Flood	-3.51	-0.014
8	Flood	-5.48	-0.024
	Ebb	5.60	0.023
	Flood	-5.66	-0.025
	Ebb	5.85	0.024
12	Ebb	7.14	0.026
	Flood	-7.54	-0.032
	Ebb	7.81	0.031
	Flood	-7.42	-0.033
	Ebb	7.12	0.029
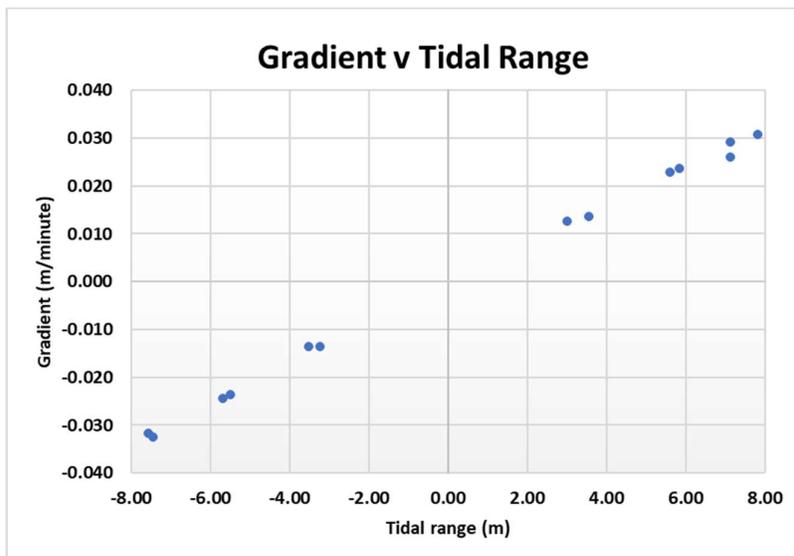
Figure 5-2 Graphical representation of Table 5-1.

Note the almost linear relationship between maximum/minimum gradient and the tidal range. However, it is a simple matter to calculate this for each tide.

Consider the areas between the lines in Figure 5-3 giving a rough indication of power generation, although not exactly true because the power is related to a higher exponential of head.
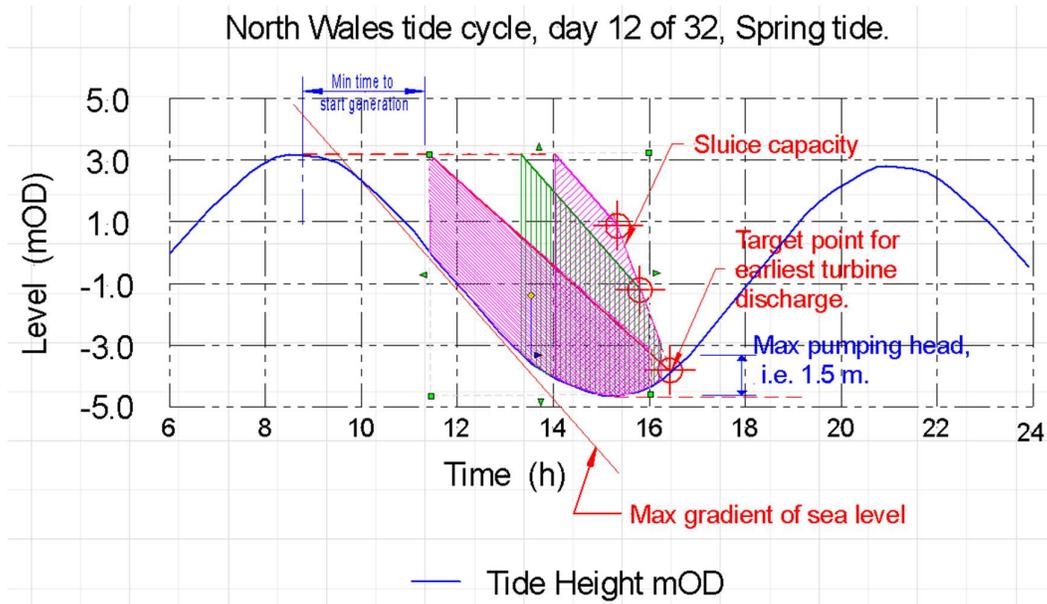
Figure 5-3 Example of ebb spring tide with 3 alternative generating lines.

Measuring from Figure 5-3 gives the relative areas in Table 5-2.

Table 5-2 Measured areas from Figure 5-3.

Generating option	Start time minutes	Generating time	Start head m	Relative area
Red	158	302	3.18	8.97
Green	273	226	6.38	8.56
Magenta	313	77	7.25	6.97

From Table 5-2 it appears that the early starting time, with the shallower gradient may generate more electricity. Also, the shallow gradient will have a higher turbine efficiency. The new program will start at a minimum starting time and calculate the generation for increasing time steps until the maximum energy conversion is reached. Initially steps will increase at 10-minute intervals to suit tide tables but can be reduced once the program is operational.

5.3 Bathymetry input.

A simplified input file in excel spreadsheet format has been created with impounded areas at 1m intervals, based on Ordnance Survey (OS) levels, see Table 5-3. The following sources have been used:-

- Morecambe Bay data has been taken from S Baker (Baker, 2021) and was developed using a combination of LIDAR and Admiralty charts.
- North Wales data has been taken from J Xue (Xue, 2021) and was developed using a combination of LIDAR and Admiralty charts.
- Solway Firth data has been taken from Burrows et al (Burrows et al., 2009), as referenced by Aggidis & Feather (Aggidis and Feather, 2012).

Table 5-3 Bathymetry input file.

Level mOD	-5	-4	-3	-2	-1	0	1	2	3	4	5
Morecambe Bay curved km^2	18.8	37.6	63.4	91.2	122.7	149.7	175.1	210.3	247.5	277.6	290.9
North Wales km^2	78.5	86.7	110.0	130.5	136.3	140.0	142.6	144.6	148.4	151.0	152.0
Solway Firth km2	400	530	634	694	741	778	812	842	870	894	910

Figure 5-4 shows a graphical representation of the data in Table 5-3. Note that the impounded volume for the Solway Firth would be at least four times higher than for NW and three times higher than MB.
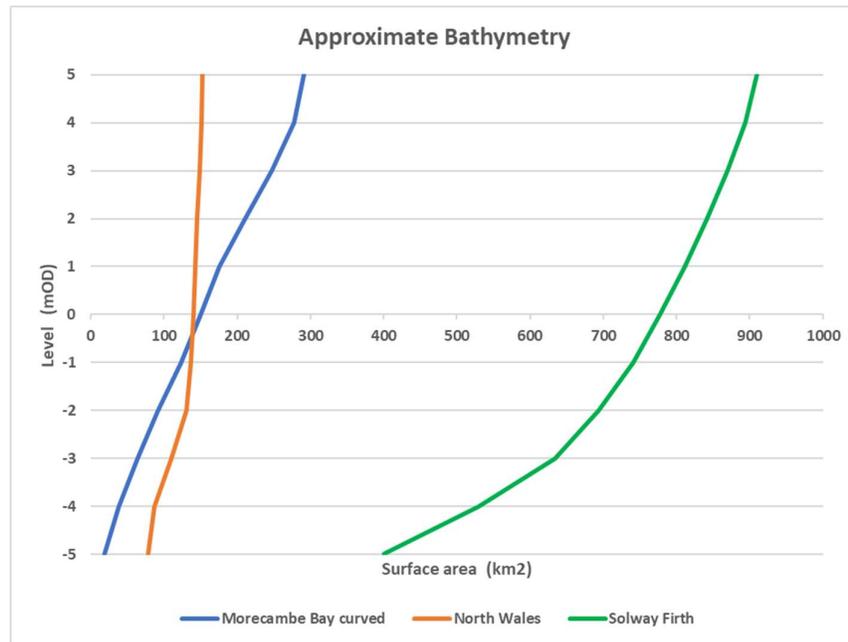
Figure 5-4 Simplified bathymetry for 3 sites used for input to the proposed program.

In Figure 5-4 the tides use data from Heysham, Llandudno and Whitehaven for Morecambe Bay (Baker, 2025) , North Wales (Xue, 2021) and the Solway Firth (Aggidis and Feather, 2012) respectively. Site specific readings will need to be recorded during the feasibility studies. For example, for North Wales there is a partial recording station at Colwyn Bay, and it is found the high tides are slightly higher than at Llandudno and occur slightly later.

5.4   Tide input.

For simplicity tide data is exported from *Tide Plotter* by Belfield (Belfield Software Ltd, 2025). Tide levels can be exported for many tide gauges at 5- or 10-minute intervals base on Greenwich Mean Time (GMT) and chart datum. A pre-processer program converts the sea levels to ordnance datum (OD) and adds the wholesale electricity price for each half-hour slot.

Tide data from *Tide Plotter* (Belfield Software Ltd, 2025) has been purchased for the years 2016, 2017, 2023 to 2026. The 2016 data was used by General Electric to estimate the annual electricity production (AEP) for North Wales Tidal Energy and was used as a control.

Price data from Elexon (Elexon, 2025) is available to download from March 2001 and has been tracked since 2016 for this research.

Table 5-4 Tide level data every 10 minutes exported from Tide Plotter for Llandudno.

Date/Time	Sea Level mOD	Wholesale Price £/MWh
01/01/2023 00:00	-1.97	-8.07
01/01/2023 00:10	-1.98	-8.07
01/01/2023 00:20	-1.97	-8.07
01/01/2023 00:30	-1.95	200.00
01/01/2023 00:40	-1.92	200.00
01/01/2023 00:50	-1.87	200.00
01/01/2023 01:00	-1.80	199.00
01/01/2023 01:10	-1.72	199.00
01/01/2023 01:20	-1.63	199.00
01/01/2023 01:30	-1.53	-17.14
01/01/2023 01:40	-1.41	-17.14
01/01/2023 01:50	-1.28	-17.14
01/01/2023 02:00	-1.15	-32.61
01/01/2023 02:10	-1.00	-32.61

5.5 Simplified Model.

First it is necessary to calculate the target gradient from the impoundment level at the start of generation to the target point which is half the maximum pumping head above or below the next tide limit.

The total flow Q_t is thus the target gradient times the surface area of the impoundment divided by the time step T_s (5 or 10 minutes). The total flow through the turbines' during generation is required to match the maximum sea level gradient, see Equation 5-4.

$$Q_t = \frac{(Area_n + Area_{n+1}) \times level\ change}{2 \times T_s \times 60}\ m^3/s$$

Equation 5-4 Total flow through turbines.

Where

      Q_t is the total flow through all turbines

      N   is the row number in the spreadsheet.

The flow through a single turbine needs to include the 95% availability figure and drag coefficient Cd = 1.1. The Cd figure is greater than 1.0 because the flow is calculated using the diameter of the turbine runner (8m) whilst the intake and outfall of the draft tube is larger (15 x 15m square). Thus, the water is accelerated through the turbine. The flow through a single turbine is given by Equation 5-5.

$$Q_{t1} = \frac{Q_t \times 1.1}{No.\,of\ turbines \ \times 0.95} \ \ m^3/s$$

Equation 5-5 Flow through a single turbine.

Where

      Q_{t1} is the flow through a single turbine

      Q_t is the total flow through all turbines

Q_{11} can now be calculated using the affinity relationship given in Equation 5-6.

$$Q_{11} = \frac{Q_{t1}}{D^2\sqrt{H}} \ \ m^3/s$$

Equation 5-6 Flow through model turbine.

Where Q_{t1} is the flow through a single turbine

       Q_{11} is the flow the model turbine

       D   is the diameter of the turbine blades

       H   is the head of water across the turbine.

The flow must be within the working range of the turbine as shown in Figure 5-1, 1.6 to 4.75 m^3/s. If the flow is above the maximum, then several sluice gates can be opened to share the flow; and the blade angle on the turbines can be adjusted to keep the turbines within the operating parameters. This maintains the planned level for the next time step. If the flow is below the minimum, then generation should not start. The sluice overflow is easily calculated Equation 5-7.

$$Q_s = Q_t - 4.75 \times number\ of\ turbines \times D^2 \times \sqrt{H} \times \frac{0.95}{1.1}\ \ m^3/s$$

Equation 5-7 Overflow through sluice whilst generating.

Where Q_s is the total flow through the sluices

Q_t is the flow the turbine

D   is the diameter of the turbine blades

H   is the head of water across the turbine.

Qs must be within the total sluicing capacity. Generation continues with some of the sluices open until the head reduces to 1.5m when generation stops and all sluices open. The turbines are allowed to run free providing additional sluicing capacity. For turbines running free (no load) see Equation 5-8.

$$Q_s = A_s \times C_d \times \sqrt{2gH}\ \ m^3/s$$

Equation 5-8 Total flow through sluices without generation.

Where Q_s is the total flow through the sluices

As   is the total area of the turbine runners

Cd   is the drag coefficient through the sluices, typically 0.90.

G   is the acceleration due to gravity, 9.81 m/s².

H   is the head of water across the turbine.

Power is given by Equation 5-9.

$$P = \rho \times g \times H \times Q_t \times \eta\ \ Watts$$

Equation 5-9 Power.

Where P   is the total power

ρ is the density of sea water at 1,025 kg/m³.

H   is the head of water across the turbine.

Q_t is the total flow through the turbines

η is the turbine efficiency.

5.6   Pumping

Pumping flows using Equation 4-2 are shown in Equation 5-10.

$$Q_p = 380 \times \frac{(2.2 - H)}{2.2} \ m^3/s$$

Equation 5-10 flow through Andritz turbine used as pump, 7.5 MW power.

Where Q_p is the pumped flow through a single turbine.

   H   is the head of water across the turbine.

5.7   Spreadsheet calculation.

To provide check data for the simplified program a spreadsheet was developed to cover the first 22-days of 2023. This year was selected as it was the latest year with complete price data at the time of development. The spreadsheet is based on North Wales with 125 turbines with 15-MW generators and 56-sluices @ 15 x 15m square. The 22-day period covers two neap and spring tides.

The calculation is carried out using a simple spreadsheet which starts with Tide data from *Tide Plotter* (Belfield Software Ltd, 2025) which has been purchased for the years 2016, 2017, 2023 to 2026.

Price data from Elexon (Elexon, 2025) is available to download from March 2001, tracked since 2016. A simple pre-processor program was written to combine 10-minute tide levels from *Tide Plotter* with the half-hourly price data from Elexon. See the first three columns in Table 5-5.

Three generation start times were selected as 200, 230 and 260 minutes after each high or low tide. Time slots of 10-minutes are used but the time interval will be reduced for the final program. If the initial model flow rate exceeds 4.75 m³/s, generation needs to start earlier, or sluices are opened to keep the turbine flow within limit. Similarly, if the model flow rate is less than 1.6 m³/s generation will not start. This situation does not occur in the following examples. Also, if the power generated exceed the installed capacity times the availability factor, the sluicing must be increased to limit the flow through the turbines.

The formulae for first two tides in the spreadsheet were created manually. See appendix A.2 for full spreadsheets and details of the construction. For the following tides, the formulae were mainly a cut and paste operation although the target point and gradient had to be set for each tide. The formulae

for the surface area had to be checked and copied from the bathymetry sheet. Changing the start of generation time and target gradient has little effect on the sluicing and pumping times.

For neap tides, Tables 5-5 to 5-7, the turbine model speeds are all at the minimum of 185 rpm and the flow rate and generation are all within the machines capabilities. When it gets to the spring tides, tables 5-8 to 5-10, the power generation must be limited from the start of generation by sluicing. Then later in the generation cycle the model turbine flow rate must be limited to 4.75 m³/s by sluicing as expected as the installation was sized to maximise the price per MWh rather than the maximum generation.

Table 5-11 gives a summary of the generation and income for each half tide cycle during the 22-day period. Flood and ebb tides are listed separately. The 20% reduction in turbine efficiency for reverse flow has been included in the flood generation. Without reduction the flood tide total is about 85% of the ebb tide because the ratio of low tide impoundment area to high tide is greater for a lagoon rather than an estuary. With sea level rise the flood generation is likely to increase, and the turbines may be better suited for maximum generation on the flood. Table 5-11 also shows that there are several examples of generating at negative income which need not occur in practice. It can also be seen that the target gradient for the 260-minute start time often exceeds the natural maximum sea gradient; possibly having negative environmental consequences.

Table 5-12 summarises the generation and income for each of the three start times and shows the maximum for each tide. The data is taken from Table 5-11 and any negative income has been shown in red. The highest generation and income for each start time has a green highlight. The maximum predicted generation of 22 days is 182.333-GWh; which equates to an annual electricity production (AEP) 3.03-TWh. This figure is lower than previous prediction using the Gen53 model as it includes a 20% reduction in efficiency for reverse flow. If the reverse flow efficiency reduction is set to 0% the 22-day generation becomes 211.5-GWh, equating to an AEP of 3.51-TWh. Still significantly less than the AEP of 4.37-TWh reported for the same installation in Table 2 of (Vandercruyssen et al., 2023b). Some of the difference is likely due to the limited optimisation by selecting only three starting times. The proposed computer program will optimise over starting times at five-minute intervals or less and should produce a higher AEP. The maximum income predicted, with the 20% reduction for reverse flow, is £26.2m for the 22 days, equivalent to £435m for 2023.

Table 5-5 Example of simplified program for neap ebb tide in January 2023, with generation starting 200 minutes after high tide.

Date/Time	Sea Level mOD	Price £/MWh	Sea level change in 10 minutes	Tide	Mode	Lagoon level	Head	Surface area km2	All sluices Qs	All turbines Qt	Single turbine Qt1	Q11 m3/s	n11 rpm	Efficiency %	Turbine speed nt rpm	Net power MW	Ebb	Flood	Income £
Number of turbines	dia. (m)	Gen rating (MW)	Availability	max installed capacity (MW)		min gen head (m)	low tide target (m)	high tide target (m)				limit Q11 1.6<= 4.75		reverse flow eff reduction.	max net power (MW)	468	1,027	0	110,303
125	8.00	15.00	0.95	1,781		1.50	0.75	-0.5						20%	min	-937.5			
16/01/2023 06:30	1.53	51.00	#REF!	target	Hold	2.06	0.53	144.81											
16/01/2023 06:40	1.41	51.00	-0.12			2.06	0.65					Start gen time	200						
16/01/2023 06:50	1.29	51.00	-0.12			2.06	0.77					Start level	2.056						
16/01/2023 07:00	1.16	50.00	-0.13			2.06	0.90					target time	490						
16/01/2023 07:10	1.03	50.00	-0.13			2.06	1.03					target level	-0.820						
16/01/2023 07:20	0.89	50.00	-0.14			2.06	1.17					Drop in 10 mins	-0.099						
16/01/2023 07:30	0.75	185.76	-0.14			2.06	1.31												
16/01/2023 07:40	0.60	185.76	-0.15			2.06	1.46												
16/01/2023 07:50	0.45	185.76	-0.15	maxGrad		2.06	1.61												
16/01/2023 08:00	0.30	60.10	-0.15			2.06	1.76												
16/01/2023 08:10	0.16	60.10	-0.14			2.06	1.90	144.81											
16/01/2023 08:20	0.01	60.10	-0.15		Generate	1.96	1.95	144.43		23,901	221	2.48	185	90.2%	32.26	422	70		4,228
16/01/2023 08:30	-0.14	60.10	-0.15			1.86	2.00	144.31		23,860	221	2.44	185	90.3%	32.68	433	72		4,335
16/01/2023 08:40	-0.28	60.10	-0.14			1.76	2.04	144.12		23,834	221	2.42	185	90.4%	33.01	441	74		4,421
16/01/2023 08:50	-0.41	60.10	-0.13			1.66	2.07	143.92		23,801	220	2.39	185	90.4%	33.26	448	75		4,484
16/01/2023 09:00	-0.55	230.00	-0.14			1.56	2.11	143.72		23,768	220	2.37	185	90.5%	33.59	456	76		17,486
16/01/2023 09:10	-0.67	230.00	-0.12			1.46	2.13	143.52		23,735	220	2.35	185	90.5%	33.76	460	77		17,640
16/01/2023 09:20	-0.79	230.00	-0.12			1.36	2.15	143.32		23,703	220	2.34	185	90.5%	33.92	464	77		17,794
16/01/2023 09:30	-0.91	58.00	-0.12			1.26	2.17	143.12		23,670	219	2.32	185	90.6%	34.08	468	78		4,526
16/01/2023 09:40	-1.01	58.00	-0.10			1.16	2.17	142.93		23,637	219	2.32	185	90.6%	34.09	468	78		4,522
16/01/2023 09:50	-1.11	58.00	-0.10			1.06	2.17	142.73		23,604	219	2.32	185	90.6%	34.10	467	78		4,517
16/01/2023 10:00	-1.20	223.54	-0.09			0.96	2.16	142.51		23,570	218	2.32	185	90.6%	34.02	465	77		17,311
16/01/2023 10:10	-1.28	223.54	-0.08			0.87	2.15	142.25		23,530	218	2.33	185	90.5%	33.87	460	77		17,127
16/01/2023 10:20	-1.35	223.54	-0.07			0.77	2.12	141.99		23,488	218	2.34	185	90.5%	33.64	453	75		16,859
16/01/2023 10:30	-1.41	60.00	-0.06			0.67	2.08	141.74		23,445	217	2.35	185	90.5%	33.33	443	74		4,432
16/01/2023 10:40	-1.46	60.00	-0.05			0.57	2.03	141.48		23,403	217	2.38	185	90.4%	32.93	432	72		4,317
16/01/2023 10:50	-1.50	60.00	-0.04			0.47	1.97	141.22		23,360	216	2.41	185	90.4%	32.45	418	70		4,180
16/01/2023 11:00	-1.52	230.00	-0.02			0.37	1.89	140.96		23,317	216	2.45	185	90.3%	31.79	400	67		15,337
16/01/2023 11:10	-1.53	230.00	-0.01	low		0.27	1.80	140.70		23,275	216	2.51	185	90.2%	31.03	380	63		14,569
16/01/2023 11:20	-1.53	230.00	0.00			0.17	1.70	140.45		23,232	215	2.58	185	90.0%	30.17	358	60		13,721
16/01/2023 11:30	-1.52	225.00	0.01			0.07	1.59	140.19		23,190	215	2.66	185	89.9%	29.18	334	56		12,515
16/01/2023 11:40	-1.49	225.00	0.03			-0.03	1.46	139.93		23,147	214	2.77	185	89.7%	27.97	305	51		11,451
16/01/2023 11:50	-1.45	225.00	0.04		Sluice	-0.43	1.02	138.40	57,392	37,032									
16/01/2023 12:00	-1.40	225.00	0.05			-0.77	0.63	137.14	47,879	30,894									
16/01/2023 12:10	-1.33	225.00	0.07			-1.04	0.29	136.05	37,565	24,239									
16/01/2023 12:20	-1.25	225.00	0.08			-1.23	0.02	134.98	25,395	16,386									
16/01/2023 12:30	-1.16	225.00	0.09		Pump	-1.33	-0.17	134.36		-47,980						-938	-156		-35,156
16/01/2023 12:40	-1.06	225.00	0.10			-1.43	-0.37	133.79		-43,734						-938	-156		-35,156
16/01/2023 12:50	-0.95	225.00	0.11			-1.52	-0.57	133.28		-39,467						-938	-156		-35,156
16/01/2023 13:00	-0.82	67.00	0.13	target	Hold	-1.52	-0.70	133.28											
16/01/2023 13:10	-0.69	67.00	0.13			-1.52	-0.83									sums	1,027	0	110,303
16/01/2023 13:20	-0.55	67.00	0.14			-1.52	-0.97												
16/01/2023 13:30	-0.40	67.00	0.15			-1.52	-1.12												

Table 5-6 Example of simplified program for neap ebb tide in January 2023, with generation starting 230 minutes after high tide.

Date/Time	Sea Level mOD	Price £/MWh	Sea level change in 10 minutes	Tide	Mode	Lagoon level	Head	Surface area km2	Flows m3/s All sluices Qs	Flows m3/s All turbines Qt	Single turbine Qt1	Model Q11 m3/s	Model n11 rpm	Model Efficiency %	Turbine speed nt rpm	Net power MW	Net Energy (MWh) Ebb	Net Energy (MWh) Flood	Income £
Number of turbines	dia. (m)	Gen rating (MW)	Availability	max installed capacity (MW)			min gen head (m)	low tide target (m)	high tide target (m)			limit Q11 1.6 <= 4.75		reverse flow eff reduction.	max net power (MW)	571	1,069	0	137,856
125	8.00	15.00	0.95	1,781			1.50	0.75	-0.5					20%	min	-937.5			
16/01/2023 06:30	1.53	51.00	#REF!	target	Hold	2.03	0.50	144.72											
16/01/2023 06:40	1.41	51.00	-0.12			2.03	0.62					Start gen time		230					
16/01/2023 06:50	1.29	51.00	-0.12			2.03	0.74					Start level		2.032					
16/01/2023 07:00	1.16	50.00	-0.13			2.03	0.87					target time		490					
16/01/2023 07:10	1.03	50.00	-0.13			2.03	1.00					target level		-0.820					
16/01/2023 07:20	0.89	50.00	-0.14			2.03	1.14					Drop in 10 mins		-0.110					
16/01/2023 07:30	0.75	185.76	-0.14			2.03	1.28												
16/01/2023 07:40	0.60	185.76	-0.15			2.03	1.43												
16/01/2023 07:50	0.45	185.76	-0.15	maxGrad		2.03	1.58												
16/01/2023 08:00	0.30	60.10	-0.15			2.03	1.73												
16/01/2023 08:10	0.16	60.10	-0.14			2.03	1.87												
16/01/2023 08:20	0.01	60.10	-0.15			2.03	2.02												
16/01/2023 08:30	-0.14	60.10	-0.15			2.03	2.17												
16/01/2023 08:40	-0.28	60.10	-0.14			2.03	2.31	144.72											
16/01/2023 08:50	-0.41	60.10	-0.13		Generate	1.92	2.33	144.44		26,430	245	2.50	185	90.2%	35.31	559	93		5,599
16/01/2023 09:00	-0.55	230.00	-0.14			1.81	2.36	144.22		26,385	244	2.48	185	90.2%	35.54	566	94		21,678
16/01/2023 09:10	-0.67	230.00	-0.12			1.70	2.37	144.01		26,344	244	2.48	185	90.2%	35.62	567	95		21,744
16/01/2023 09:20	-0.79	230.00	-0.12			1.59	2.38	143.79		26,304	244	2.47	185	90.3%	35.70	569	95		21,810
16/01/2023 09:30	-0.91	58.00	-0.12			1.48	2.39	143.57		26,264	243	2.46	185	90.3%	35.78	571	95		5,516
16/01/2023 09:40	-1.01	58.00	-0.10			1.37	2.38	143.35		26,224	243	2.46	185	90.3%	35.70	567	95		5,485
16/01/2023 09:50	-1.11	58.00	-0.10			1.26	2.37	143.13		26,184	243	2.46	185	90.3%	35.63	564	94		5,455
16/01/2023 10:00	-1.20	223.54	-0.09			1.15	2.35	143.00		26,152	242	2.47	185	90.3%	35.48	559	93		20,820
16/01/2023 10:10	-1.28	223.54	-0.08			1.04	2.32	142.72		26,115	242	2.48	185	90.2%	35.26	551	92		20,523
16/01/2023 10:20	-1.35	223.54	-0.07			0.93	2.28	142.43		26,063	241	2.50	185	90.2%	34.96	540	90		20,125
16/01/2023 10:30	-1.41	60.00	-0.06			0.83	2.24	142.15		26,011	241	2.52	185	90.2%	34.57	527	88		5,271
16/01/2023 10:40	-1.46	60.00	-0.05			0.72	2.18	141.86		25,958	240	2.55	185	90.1%	34.11	512	85		5,117
16/01/2023 10:50	-1.50	60.00	-0.04			0.61	2.11	141.58		25,906	240	2.58	185	90.0%	33.56	494	82		4,939
16/01/2023 11:00	-1.52	230.00	-0.02			0.50	2.02	141.29		25,854	239	2.64	185	89.9%	32.84	471	79		18,069
16/01/2023 11:10	-1.53	230.00	-0.01	low		0.39	1.92	141.00		25,802	239	2.70	185	89.8%	32.01	447	74		17,117
16/01/2023 11:20	-1.53	230.00	0.00			0.28	1.81	140.72		25,750	239	2.77	185	89.7%	31.08	419	70		16,078
16/01/2023 11:30	-1.52	225.00	0.01			0.17	1.69	140.43		25,698	238	2.86	185	89.5%	30.04	390	65		14,627
16/01/2023 11:40	-1.49	225.00	0.03			0.06	1.55	140.15		25,646	238	2.98	185	89.2%	28.77	356	59		13,353
16/01/2023 11:50	-1.45	225.00	0.04		Sluice	-0.36	1.09	138.67	59,020	38,083									
16/01/2023 12:00	-1.40	225.00	0.05			-0.71	0.69	137.37	49,573	31,987									
16/01/2023 12:10	-1.33	225.00	0.07			-0.99	0.34	136.33	39,378	25,409									
16/01/2023 12:20	-1.25	225.00	0.08			-1.19	0.06	135.18	27,497	17,742									
16/01/2023 12:30	-1.16	225.00	0.09		Pump	-1.30	-0.14	134.55		-48,726						-938	-156		-35,156
16/01/2023 12:40	-1.06	225.00	0.10			-1.40	-0.34	133.98		-44,448						-938	-156		-35,156
16/01/2023 12:50	-0.95	225.00	0.11			-1.49	-0.54	133.46		-40,149						-938	-156		-35,156
16/01/2023 13:00	-0.82	67.00	0.13	target	Hold	-1.49	-0.67	133.46											
16/01/2023 13:10	-0.69	67.00	0.13			-1.49	-0.80									sums	1,069	0	137,856
16/01/2023 13:20	-0.55	67.00	0.14			-1.49	-0.94												
16/01/2023 13:30	-0.40	67.00	0.15			-1.49	-1.09												

Table 5-7 Example of simplified program for neap ebb tide in January 2023, with generation starting 260 minutes after high tide.

Date/Time	Sea Level mOD	Price £/MWh	Sea level change in 10 minutes	Tide	Mode	Lagoon level	Head	Surface area km2	All sluices Qs	All turbines Qt	Single turbine Qt1	Q11 m3/s	n11 rpm	Efficiency %	Turbine speed nt rpm	Net power MW	Ebb	Flood	Income £
Number of turbines	dia. (m)	Gen rating (MW)	Availability	max installed capacity (MW)			min gen head (m)	low tide target (m)	high tide target (m)			limit Q11 1.6 <= 4.75		reverse flow eff reduction.	max net power (MW)	706	1,049	0	128,753
125	8.00	15.00	0.95	1,781			1.50	0.75	-0.5					20%	min	-937.5			
16/01/2023 06:30	1.53	51.00	#REF!	target	Hold	1.99	0.46	144.57											
16/01/2023 06:40	1.41	51.00	-0.12			1.99	0.58					Start gen time	260						
16/01/2023 06:50	1.29	51.00	-0.12			1.99	0.70					Start level	1.987						
16/01/2023 07:00	1.16	50.00	-0.13			1.99	0.83					target time	490						
16/01/2023 07:10	1.03	50.00	-0.13			1.99	0.96					target level	-0.820						
16/01/2023 07:20	0.89	50.00	-0.14			1.99	1.10					Drop in 10 mins	-0.122						
16/01/2023 07:30	0.75	185.76	-0.14			1.99	1.24												
16/01/2023 07:40	0.60	185.76	-0.15			1.99	1.39												
16/01/2023 07:50	0.45	185.76	-0.15	maxGrad		1.99	1.54												
16/01/2023 08:00	0.30	60.10	-0.15			1.99	1.69												
16/01/2023 08:10	0.16	60.10	-0.14			1.99	1.83												
16/01/2023 08:20	0.01	60.10	-0.15			1.99	1.98												
16/01/2023 08:30	-0.14	60.10	-0.15			1.99	2.13												
16/01/2023 08:40	-0.28	60.10	-0.14			1.99	2.27												
16/01/2023 08:50	-0.41	60.10	-0.13			1.99	2.40												
16/01/2023 09:00	-0.55	230.00	-0.14			1.99	2.54												
16/01/2023 09:10	-0.67	230.00	-0.12			1.99	2.66	144.57											
16/01/2023 09:20	-0.79	230.00	-0.12		Generate	1.87	2.66	144.33		29,384	272	2.61	185	90.0%	37.68	706	118		27,059
16/01/2023 09:30	-0.91	58.00	-0.12			1.74	2.65	144.09		29,334	272	2.61	185	90.0%	37.67	704	117		6,807
16/01/2023 09:40	-1.01	58.00	-0.10			1.62	2.63	143.84		29,285	271	2.61	185	90.0%	37.51	697	116		6,738
16/01/2023 09:50	-1.11	58.00	-0.10			1.50	2.61	143.60		29,235	271	2.62	185	90.0%	37.35	690	115		6,670
16/01/2023 10:00	-1.20	223.54	-0.09			1.38	2.58	143.35		29,185	270	2.63	185	89.9%	37.12	680	113		25,340
16/01/2023 10:10	-1.28	223.54	-0.08			1.25	2.53	143.11		29,136	270	2.65	185	89.9%	36.82	668	111		24,874
16/01/2023 10:20	-1.35	223.54	-0.07			1.13	2.48	142.87		29,086	269	2.67	185	89.9%	36.44	652	109		24,309
16/01/2023 10:30	-1.41	60.00	-0.06			1.01	2.42	142.62		29,036	269	2.70	185	89.8%	35.98	635	106		6,347
16/01/2023 10:40	-1.46	60.00	-0.05			0.89	2.35	142.31		28,980	268	2.74	185	89.7%	35.44	614	102		6,141
16/01/2023 10:50	-1.50	60.00	-0.04			0.77	2.27	141.99		28,916	268	2.78	185	89.6%	34.82	591	98		5,908
16/01/2023 11:00	-1.52	230.00	-0.02			0.64	2.16	141.68		28,852	267	2.84	185	89.5%	34.02	562	94		21,550
16/01/2023 11:10	-1.53	230.00	-0.01	low		0.52	2.05	141.36		28,787	267	2.91	185	89.4%	33.13	531	89		20,357
16/01/2023 11:20	-1.53	230.00	0.00			0.40	1.93	141.04		28,723	266	2.99	185	89.2%	32.13	497	83		19,068
16/01/2023 11:30	-1.52	225.00	0.01			0.28	1.80	140.72		28,658	265	3.09	185	89.0%	31.01	461	77		17,299
16/01/2023 11:40	-1.49	225.00	0.03			0.16	1.65	140.41		28,593	265	3.23	185	88.7%	29.67	420	70		15,754
16/01/2023 11:50	-1.45	225.00	0.04		Sluice	-0.27	1.18	139.00	60,878	39,282									
16/01/2023 12:00	-1.40	225.00	0.05			-0.64	0.76	137.64	51,503	33,233									
16/01/2023 12:10	-1.33	225.00	0.07			-0.93	0.40	136.68	41,433	26,734									
16/01/2023 12:20	-1.25	225.00	0.08			-1.15	0.10	135.43	29,836	19,252									
16/01/2023 12:30	-1.16	225.00	0.09		Pump	-1.26	-0.10	134.79		-49,659						-938	-156		-35,156
16/01/2023 12:40	-1.06	225.00	0.10			-1.36	-0.30	134.21		-45,340						-938	-156		-35,156
16/01/2023 12:50	-0.95	225.00	0.11			-1.45	-0.50	133.67		-41,002						-938	-156		-35,156
16/01/2023 13:00	-0.82	67.00	0.13	target	Hold	-1.45	-0.63	133.67											
16/01/2023 13:10	-0.69	67.00	0.13			-1.45	-0.76									sums	1,049	0	128,753
16/01/2023 13:20	-0.55	67.00	0.14			-1.45	-0.90												
16/01/2023 13:30	-0.40	67.00	0.15			-1.45	-1.05												

Table 5-8 Example of simplified program for spring ebb tide in January 2023, with generation starting 200 minutes after high tide.

Date/Time	Sea Level mOD	Price £/MWh	Sea level change in 10 minutes	Tide	Mode	Lagoon level	Head	Surface area km2	All sluices Qs	All turbines Qt	Single turbine Qt1	Q11 m3/s	n11 rpm	Efficiency %	Turbine speed nt rpm	Net power MW	Ebb	Flood	Income £
Number of turbines	dia. (m)	Gen rating (MW)	Availability	max installed capacity (MW)		min gen head (m)	low tide target (m)	high tide target (m)				limit Q11 1.6 <= 4.75		reverse flow eff reduction.	max net power (MW)	1,781	5,730	0	918,517
125	8.00	15.00	0.95	1,781		1.50	0.75	-0.5						20%	min	-937.5			
22/01/2023 13:00	2.42	100.00	2.42		Hold	4.13	1.71	151.13											
22/01/2023 13:10	2.13	100.00	-0.29			4.13	2.00					Start gen time		200					
22/01/2023 13:20	1.83	100.00	-0.30			4.13	2.30					Start level		4.134					
22/01/2023 13:30	1.53	100.00	-0.30			4.13	2.60					target time		480					
22/01/2023 13:40	1.22	100.00	-0.31			4.13	2.91					target level		-2.900					
22/01/2023 13:50	0.91	100.00	-0.31			4.13	3.22					Drop in 10 mins		-0.251					
22/01/2023 14:00	0.59	190.00	-0.32	maxGrad		4.13	3.54												
22/01/2023 14:10	0.28	190.00	-0.31			4.13	3.85	151.13											
22/01/2023 14:20	-0.02	190.00	-0.30		Generate	3.88	3.90	150.69	11,390	51,794	480	3.79	197	87.6%	48.61	1,781	297		56,388
22/01/2023 14:30	-0.32	100.00	-0.30			3.63	3.95	150.04	11,890	51,066	473	3.72	192	87.8%	47.76	1,781	297		29,678
22/01/2023 14:40	-0.62	100.00	-0.30			3.38	4.00	149.39	12,300	50,382	467	3.65	188	87.9%	46.95	1,781	297		29,691
22/01/2023 14:50	-0.90	100.00	-0.28			3.13	4.03	148.74	12,450	49,959	463	3.60	185	88.0%	46.45	1,781	297		29,683
22/01/2023 15:00	-1.18	99.65	-0.28			2.88	4.06	147.94	12,550	49,555	459	3.56	185	88.1%	46.58	1,781	297		29,578
22/01/2023 15:10	-1.45	99.65	-0.27			2.63	4.08	146.98	12,450	49,288	457	3.53	185	88.1%	46.69	1,781	297		29,573
22/01/2023 15:20	-1.70	99.65	-0.25			2.38	4.08	146.03	12,030	49,308	457	3.54	185	88.1%	46.68	1,781	297		29,575
22/01/2023 15:30	-1.95	99.65	-0.25			2.12	4.07	145.07	11,600	49,338	457	3.54	185	88.1%	46.68	1,781	297		29,582
22/01/2023 15:40	-2.18	99.65	-0.23			1.87	4.05	144.35	10,950	49,636	460	3.57	185	88.1%	46.55	1,781	297		29,586
22/01/2023 15:50	-2.40	99.65	-0.22			1.62	4.02	143.84	10,260	50,069	464	3.61	186	88.0%	46.58	1,781	297		29,584
22/01/2023 16:00	-2.61	102.20	-0.21			1.37	3.98	143.34	9,460	50,659	469	3.68	190	87.8%	47.28	1,781	297		30,341
22/01/2023 16:10	-2.81	102.20	-0.20			1.12	3.93	142.84	8,500	51,409	476	3.75	194	87.7%	48.16	1,781	297		30,339
22/01/2023 16:20	-2.99	102.20	-0.18			0.87	3.86	142.26	7,200	52,482	486	3.87	201	87.5%	49.42	1,781	297		30,333
22/01/2023 16:30	-3.15	246.50	-0.16			0.62	3.77	141.60	5,460	53,963	500	4.02	211	87.2%	51.15	1,781	297		73,184
22/01/2023 16:40	-3.29	246.50	-0.14			0.37	3.66	140.95	3,280	55,870	518	4.23	223	86.7%	53.37	1,781	297		73,186
22/01/2023 16:50	-3.42	246.50	-0.13			0.11	3.53	140.30	790	58,086	538	4.47	238	86.3%	55.95	1,781	297		73,156
22/01/2023 17:00	-3.52	259.88	-0.10			-0.14	3.38	139.49		58,571	543	4.61	246	86.0%	56.65	1,713	286		74,207
22/01/2023 17:10	-3.61	259.88	-0.09			-0.39	3.22	138.56		58,209	539	4.69	252	85.8%	56.44	1,618	270		70,095
22/01/2023 17:20	-3.66	259.88	-0.05			-0.64	3.02	137.64	800	57,019	528	4.75	255	85.7%	55.38	1,484	247		64,293
22/01/2023 17:30	-3.69	250.00	-0.03	low		-0.89	2.80	136.71	2,500	54,930	509	4.75	255	85.7%	53.35	1,325	221		55,216
22/01/2023 17:40	-3.69	250.00	0.00			-1.14	2.55	135.48	4,600	52,379	485	4.75	255	85.7%	50.87	1,150	192		47,930
22/01/2023 17:50	-3.67	250.00	0.02			-1.39	2.28	134.02	6,900	49,517	459	4.75	255	85.7%	48.09	972	162		40,489
22/01/2023 18:00	-3.61	250.00	0.06			-1.64	1.97	132.56	9,800	46,007	426	4.75	255	85.7%	44.68	779	130		32,478
22/01/2023 18:10	-3.53	250.00	0.08			-1.90	1.63	131.11	13,200	41,997	389	4.75	255	85.7%	40.79	592	99		24,650
22/01/2023 18:20	-3.41	250.00	0.12		Sluice	-2.35	1.06	123.29	60,663	39,143									
22/01/2023 18:30	-3.27	105.50	0.14			-2.74	0.53	115.27	48,803	31,490									
22/01/2023 18:40	-3.10	105.50	0.17			-3.04	0.06	109.23	34,453	22,231									
22/01/2023 18:50	-2.90	105.50	0.20	target	Pump	-3.17	-0.27	106.48		-48,845						-938	-156		-16,484
22/01/2023 19:00	-2.67	230.00	0.23			-3.29	-0.62	104.07		-41,630						-938	-156		-35,938
22/01/2023 19:10	-2.42	230.00	0.25			-3.39	-0.97	102.05		-34,131						-938	-156		-35,938
22/01/2023 19:20	-2.15	230.00	0.27			-3.47	-1.32	99.15		-26,609						-938	-156		-35,938
22/01/2023 19:30	-1.86	106.10	0.29		Hold	-3.47	-1.61	99.15											
22/01/2023 19:40	-1.56	106.10	0.30			-3.47	-1.91									sums	5,730	0	918,517
22/01/2023 19:50	-1.24	106.10	0.32			-3.47	-2.23												
22/01/2023 20:00	-0.91	106.10	0.33			-3.47	-2.56												

Table 5-9 Example of simplified program for spring ebb tide in January 2023, with generation starting 230 minutes after high tide.

Date/Time	Sea Level mOD	Price £/MWh	Sea level change in 10 minutes	Tide	Mode	Lagoon level	Head	Surface area km2	All sluices Qs	All turbines Qt	Single turbine Qt1	Q11 m3/s	n11 rpm	Efficiency %	Turbine speed nt rpm	Net power MW	Ebb	Flood	Income £
Number of turbines	dia. (m)	Gen rating (MW)	Availability	max installed capacity (MW)		min gen head (m)	low tide target (m)	high tide target (m)				limit Q11 1.6 <= 4.75		reverse flow eff reduction.	max net power (MW)	1,781	5,000	0	843,552
125	8.00	15.00	0.95	1,781		1.50	0.75	-0.5						20%	min	#REF!			
22/01/2023 13:00	2.42	100.00	2.42		Hold	4.07	1.65	151.07											
22/01/2023 13:10	2.13	100.00	-0.29			4.07	1.94					Start gen time	230						
22/01/2023 13:20	1.83	100.00	-0.30			4.07	2.24					Start level	4.069						
22/01/2023 13:30	1.53	100.00	-0.30			4.07	2.54					target time	480						
22/01/2023 13:40	1.22	100.00	-0.31			4.07	2.85					target level	-2.900						
22/01/2023 13:50	0.91	100.00	-0.31			4.07	3.16					Drop in 10 mins	-0.279						
22/01/2023 14:00	0.59	190.00	-0.32	maxGrad		4.07	3.48												
22/01/2023 14:10	0.28	190.00	-0.31			4.07	3.79												
22/01/2023 14:20	-0.02	190.00	-0.30			4.07	4.09												
22/01/2023 14:30	-0.32	100.00	-0.30			4.07	4.39												
22/01/2023 14:40	-0.62	100.00	-0.30			4.07	4.69	151.07											
22/01/2023 14:50	-0.90	100.00	-0.28		sluice Generate	3.79	4.69	150.46	27880	42,166	391	2.82	185	89.6%	50.08	1,781	297		29,685
22/01/2023 15:00	-1.18	99.65	-0.28			3.51	4.69	150.34	27730	42,147	390	2.82	185	89.6%	50.09	1,781	297		29,577
22/01/2023 15:10	-1.45	99.65	-0.27			3.23	4.68	149.28	27360	42,245	391	2.83	185	89.5%	50.04	1,781	297		29,585
22/01/2023 15:20	-1.70	99.65	-0.25			2.95	4.65	148.23	26600	42,513	394	2.85	185	89.5%	49.89	1,781	297		29,572
22/01/2023 15:30	-1.95	99.65	-0.25			2.68	4.63	147.17	25800	42,821	397	2.88	185	89.4%	49.73	1,781	297		29,582
22/01/2023 15:40	-2.18	99.65	-0.23			2.40	4.58	145.39	24650	43,313	401	2.93	185	89.3%	49.47	1,781	297		29,575
22/01/2023 15:50	-2.40	99.65	-0.22			2.12	4.52	144.84	23470	43,952	407	2.99	185	89.2%	49.15	1,781	297		29,584
22/01/2023 16:00	-2.61	102.20	-0.21			1.84	4.45	144.28	22470	44,693	414	3.07	185	89.1%	48.78	1,781	297		30,332
22/01/2023 16:10	-2.81	102.20	-0.20			1.56	4.37	143.72	21300	45,604	422	3.16	185	88.9%	48.34	1,781	297		30,341
22/01/2023 16:20	-2.99	102.20	-0.18			1.28	4.27	143.33	19900	46,784	433	3.28	185	88.6%	47.79	1,781	297		30,341
22/01/2023 16:30	-3.15	246.50	-0.16			1.00	4.15	142.61	18150	48,275	447	3.43	185	88.3%	47.12	1,781	297		73,162
22/01/2023 16:40	-3.29	246.50	-0.14			0.72	4.01	141.88	15930	50,158	465	3.62	186	88.0%	46.69	1,781	297		73,152
22/01/2023 16:50	-3.42	246.50	-0.13			0.45	3.87	141.16	13360	52,392	485	3.86	201	87.5%	49.31	1,781	297		73,186
22/01/2023 17:00	-3.52	259.88	-0.10			0.17	3.69	140.62	10150	55,307	512	4.17	220	86.9%	52.72	1,781	297		77,131
22/01/2023 17:10	-3.61	259.88	-0.09			-0.11	3.50	139.58	6260	58,832	545	4.55	243	86.1%	56.81	1,781	297		77,157
22/01/2023 17:20	-3.66	259.88	-0.05			-0.39	3.27	138.55	5300	59,313	549	4.75	255	85.7%	57.61	1,671	278		72,371
22/01/2023 17:30	-3.69	250.00	-0.03	low		-0.67	3.02	137.52	7100	57,033	528	4.75	255	85.7%	55.39	1,484	247		61,847
22/01/2023 17:40	-3.69	250.00	0.00			-0.95	2.74	136.60	9300	54,379	504	4.75	255	85.7%	52.82	1,285	214		53,521
22/01/2023 17:50	-3.67	250.00	0.02			-1.23	2.44	134.98	11800	51,289	475	4.75	255	85.7%	49.81	1,080	180		44,982
22/01/2023 18:00	-3.61	250.00	0.06			-1.51	2.10	133.36	14700	47,638	441	4.75	255	85.7%	46.27	864	144		35,982
22/01/2023 18:10	-3.53	250.00	0.08			-1.78	1.75	131.75	18200	43,387	402	4.75	255	85.7%	42.14	652	109		27,183
22/01/2023 18:20	-3.41	250.00	0.12		Sluice	-2.25	1.16	125.28	62,675	40,441									
22/01/2023 18:30	-3.27	105.50	0.14			-2.66	0.61	117.04	51,000	32,908									
22/01/2023 18:40	-3.10	105.50	0.17			-2.97	0.13	110.62	37,165	23,981									
22/01/2023 18:50	-2.90	105.50	0.20	target	Pump	-3.11	-0.21	107.52		-50,310						-938	-156		-16,484
22/01/2023 19:00	-2.67	230.00	0.23			-3.23	-0.56	104.73		-43,046						-938	-156		-35,938
22/01/2023 19:10	-2.42	230.00	0.25			-3.33	-0.91	102.36		-35,487						-938	-156		-35,938
22/01/2023 19:20	-2.15	230.00	0.27			-3.41	-1.26	100.45		-27,894						-938	-156		-35,938
22/01/2023 19:30	-1.86	106.10	0.29		Hold	-3.41	-1.55	100.49											
22/01/2023 19:40	-1.56	106.10	0.30			-3.41	-1.85									sums	5,000	0	843,552
22/01/2023 19:50	-1.24	106.10	0.32			-3.41	-2.17												
22/01/2023 20:00	-0.91	106.10	0.33			-3.41	-2.50												

Table 5-10 Example of simplified program for spring ebb tide in January 2023, with generation starting 260 minutes after high tide.

Date/Time	Sea Level mOD	Price £/MWh	Sea level change in 10 minutes	Tide	Mode	Lagoon level	Head	Surface area km2	All sluices Qs	All turbines Qt	Single turbine Qt1	Q11 m3/s	n11 rpm	Efficiency %	Turbine speed nt rpm	Net power MW	Ebb	Flood	Income £
Number of turbines	dia. (m)	Gen rating (MW)	Availability	max installed capacity (MW)		min gen head (m)	low tide target (m)	high tide target (m)				limit Q11 1.6 <= 4.75		reverse flow eff reduction.	max net power (MW)	1,781	4,229	0	784,695
125	8.00	15.00	0.95	1,781		1.50	0.75	-0.5						20%	min	-938			
22/01/2023 13:10	2.13	100.00	#REF!		Hold	3.89	1.76												
22/01/2023 13:20	1.83	100.00	-0.30			3.89	2.06												
22/01/2023 13:30	1.53	100.00	-0.30			3.89	2.36												
22/01/2023 13:40	1.22	100.00	-0.31			3.89	2.67												
22/01/2023 13:50	0.91	100.00	-0.31			3.89	2.98					Start gen time	260						
22/01/2023 14:00	0.59	190.00	-0.32	maxGrad		3.89	3.30					Start level	3.885						
22/01/2023 14:10	0.28	190.00	-0.31			3.89	3.61					target time	480						
22/01/2023 14:20	-0.02	190.00	-0.30			3.89	3.91					target level	-2.900						
22/01/2023 14:30	-0.32	100.00	-0.30			3.89	4.21					Drop in 10 mins	-0.308						
22/01/2023 14:40	-0.62	100.00	-0.30			3.89	4.51												
22/01/2023 14:50	-0.90	100.00	-0.28			3.89	4.79												
22/01/2023 15:00	-1.18	99.65	-0.28			3.89	5.07												
22/01/2023 15:10	-1.45	99.65	-0.27			3.89	5.34	150.70											
22/01/2023 15:20	-1.70	99.65	-0.25		sluice Generate	3.58	5.28	149.90	40,180	37,078	343	2.34	185	90.5%	53.12	1,781	297		29,578
22/01/2023 15:30	-1.95	99.65	-0.25			3.27	5.22	149.10	39,320	37,525	348	2.38	185	90.4%	52.83	1,781	297		29,577
22/01/2023 15:40	-2.18	99.65	-0.23			2.96	5.14	148.25	38,270	38,151	353	2.44	185	90.3%	52.43	1,781	297		29,580
22/01/2023 15:50	-2.40	99.65	-0.22			2.65	5.05	147.08	37,030	38,871	360	2.50	185	90.2%	51.97	1,781	297		29,576
22/01/2023 16:00	-2.61	102.20	-0.21			2.34	4.95	145.29	35,430	39,710	368	2.58	185	90.0%	51.47	1,781	297		30,330
22/01/2023 16:10	-2.81	102.20	-0.20			2.03	4.84	144.67	33,830	40,692	377	2.68	185	89.8%	50.90	1,781	297		30,336
22/01/2023 16:20	-2.99	102.20	-0.18			1.73	4.72	144.49	32,400	41,916	388	2.79	185	89.6%	50.22	1,781	297		30,342
22/01/2023 16:30	-3.15	246.50	-0.16			1.42	4.57	143.69	30,650	43,414	402	2.94	185	89.3%	49.42	1,781	297		73,171
22/01/2023 16:40	-3.29	246.50	-0.14			1.11	4.40	142.88	28,400	45,252	419	3.12	185	89.0%	48.50	1,781	297		73,156
22/01/2023 16:50	-3.42	246.50	-0.13			0.80	4.22	142.08	25,830	47,409	439	3.34	185	88.5%	47.51	1,781	297		73,177
22/01/2023 17:00	-3.52	259.88	-0.10			0.49	4.01	141.82	22,770	50,197	465	3.63	187	87.9%	46.73	1,781	297		77,148
22/01/2023 17:10	-3.61	259.88	-0.09			0.18	3.79	140.68	19,100	53,506	496	3.98	208	87.2%	50.61	1,781	297		77,142
22/01/2023 17:20	-3.66	259.88	-0.05			-0.12	3.54	139.54	13,950	58,070	538	4.47	238	86.3%	55.93	1,781	297		77,135
22/01/2023 17:30	-3.69	250.00	-0.03	low		-0.43	3.26	138.40	12,200	59,233	549	4.75	255	85.7%	57.53	1,663	277		69,276
22/01/2023 17:40	-3.69	250.00	0.00			-0.74	2.95	137.80	14,600	56,386	522	4.75	255	85.7%	54.77	1,433	239		59,699
22/01/2023 17:50	-3.67	250.00	0.02			-1.05	2.62	136.01	17,300	53,073	492	4.75	255	85.7%	51.54	1,199	200		49,942
22/01/2023 18:00	-3.61	250.00	0.06			-1.36	2.25	134.22	20,200	49,254	456	4.75	255	85.7%	47.84	956	159		39,827
22/01/2023 18:10	-3.53	250.00	0.08			-1.67	1.86	132.44	23,700	44,834	415	4.75	255	85.7%	43.55	720	120		29,999
22/01/2023 18:20	-3.41	250.00	0.12		Sluice	-2.15	1.26	127.44	64,770	41,793									
22/01/2023 18:30	-3.27	105.50	0.14			-2.56	0.71	118.98	53,275	34,376									
22/01/2023 18:40	-3.10	105.50	0.17			-2.89	0.21	112.19	39,927	25,763									
22/01/2023 18:50	-2.90	105.50	0.20	target		-3.03	-0.13	109.25		-51,968						-938	-156		-16,484
22/01/2023 19:00	-2.67	230.00	0.23		Pump	-3.15	-0.48	106.40		-44,650						-938	-156		-35,938
22/01/2023 19:10	-2.42	230.00	0.25			-3.26	-0.84	103.96		-37,037						-938	-156		-35,938
22/01/2023 19:20	-2.15	230.00	0.27			-3.34	-1.19	101.99		-29,384						-938	-156		-35,938
22/01/2023 19:30	-1.86	106.10	0.29		Hold	-3.41	-1.55	100.49											
22/01/2023 19:40	-1.56	106.10	0.30			-3.41	-1.85									sums	4,229	0	784,695
22/01/2023 19:50	-1.24	106.10	0.32			-3.41	-2.17												
22/01/2023 20:00	-0.91	106.10	0.33			-3.41	-2.50												

Table 5-11 Summary of generation and income from 22 days in January 2023, with generation starting 200, 230 & 260 minutes after high tide.

NW 2023, 125 tur, 56 sluices				Start lag 200				Start lag 230				Start lag 260			
Date Time	Sea Level mOD	Range	Max sea grad	Initial target Grad	ebb gen MWh	flood gen MWh	income £	Initial target Grad	ebb gen MWh	flood gen MWh	income £	Initial target Grad	ebb gen MWh	flood gen MWh	income £
Max Range	7.91		0.34	TOTALS	107,153	64,204	23,788,645	TOTALS	111,507	66,516	24,747,883	TOTALS	106,296	61,325	22,980,055
Min Range	3.58		0.15		171,356				178,024				167,621		
01/01/2023 00:10	-1.98	4.14	0.18	0.116	0	607	-24,590	0.130	0	678	-24,946	0.147	0	707	-23,547
01/01/2023 06:20	2.16	-3.71	-0.16	-0.101	1,095	0	221,683	-0.113	1,161	0	235,686	-0.126	1,168	0	237,409
01/01/2023 12:40	-1.55	3.92	0.17	0.110	0	701	159,757	0.124	0	755	174,059	0.137	0	535	111,993
01/01/2023 18:40	2.37	-4.29	-0.18	-0.120	1,514	0	309,960	-0.134	1,628	0	374,063	-0.149	1,620	0	326,434
02/01/2023 01:10	-1.92	4.14	0.18	0.116	0	685	-43,850	0.130	0	753	-31,025	0.142	0	698	-16,355
02/01/2023 07:30	2.22	-3.83	-0.16	-0.112	1,237	0	29,543	-0.126	1,307	0	49,222	-0.140	1,258	0	73,472
02/01/2023 13:40	-1.61	3.98	0.17	0.113	0	667	244,857	0.126	0	750	263,164	0.140	0	731	250,191
02/01/2023 19:40	2.37	-4.33	-0.18	-0.120	1,549	0	261,740	-0.133	1,680	0	313,956	-0.147	1,685	0	362,404
03/01/2023 02:10	-1.96	4.33	0.19	0.129	0	895	124,660	0.144	0	974	116,910	0.161	0	952	86,707
03/01/2023 08:20	2.37	-4.15	-0.17	-0.115	1,381	0	389,189	-0.128	1,484	0	408,193	-0.142	1,456	0	399,360
03/01/2023 14:40	-1.78	4.25	0.19	0.128	0	664	159,229	0.144	0	678	143,301	0.161	0	690	122,992
03/01/2023 20:40	2.47	-4.53	-0.19	-0.129	1,570	0	-44,312	-0.144	1,652	0	-44,586	-0.160	1,667	0	-61,993
04/01/2023 03:00	-2.06	4.64	0.20	0.145	0	908	50,534	0.163	0	986	55,621	0.188	0	1,067	48,316
04/01/2023 09:10	2.58	-4.58	-0.19	-0.133	1,696	0	37,130	-0.155	1,850	0	79,916	-0.175	1,993	0	25,540
04/01/2023 15:30	-2.00	4.61	0.19	0.148	0	838	199,749	0.167	0	923	200,692	0.189	0	881	213,101
04/01/2023 21:20	2.61	-4.80	-0.20	-0.139	2,033	0	248,615	-0.155	2,193	0	252,250	-0.173	2,298	0	242,890
05/01/2023 03:50	-2.19	4.99	0.22	0.163	0	1,138	169,419	0.184	0	1,241	147,716	0.207	0	1,182	110,178
05/01/2023 09:50	2.80	-5.03	-0.21	-0.153	2,230	0	123,249	-0.170	2,376	0	136,268	-0.191	2,407	0	143,689
05/01/2023 16:10	-2.23	5.00	0.22	0.164	0	1,178	214,150	0.185	0	1,285	226,625	0.209	0	1,246	207,070
05/01/2023 22:10	2.77	-5.09	-0.21	-0.169	2,574	0	354,155	-0.191	2,769	0	349,849	-0.215	2,741	0	298,936
06/01/2023 04:20	-2.32	5.34	0.24	0.167	0	1,557	148,063	0.218	0	1,704	150,422	0.248	0	1,610	78,900
06/01/2023 10:30	3.02	-5.47	-0.22	-0.162	2,618	0	437,503	-0.189	3,082	0	469,199	-0.212	3,081	0	485,140
06/01/2023 16:50	-2.45	5.36	0.24	0.187	0	1,531	186,775	0.244	0	1,686	250,698	0.284	0	1,563	176,914
06/01/2023 22:50	2.91	-5.34	-0.22	-0.167	2,511	0	142,768	-0.193	2,900	0	195,511	-0.217	2,835	0	262,189
07/01/2023 05:00	-2.43	5.62	0.25	0.187	0	1,764	494,173	0.223	0	1,954	534,001	0.254	0	1,898	523,841
07/01/2023 11:00	3.19	-5.80	-0.24	-0.175	2,816	0	264,668	-0.201	3,286	0	274,417	-0.225	3,226	0	297,901

Table 5-11 continued.

NW 2023, 125 tur, 56 sluices				Start lag 200				Start lag 230				Start lag 260			
Date Time	Sea Level mOD	Range	Max sea grad	Initial target Grad	ebb gen MWh	flood gen MWh	income £	Initial target Grad	ebb gen MWh	flood gen MWh	income £	Initial target Grad	ebb gen MWh	flood gen MWh	income £
07/01/2023 17:30	-2.61	5.58	0.25	0.225	0	1,931	223,701	0.259	0	2,010	243,572	0.298	0	1,798	172,165
07/01/2023 23:20	2.97	-5.45	-0.23	-0.176	2,726	0	201,177	-0.198	2,952	0	134,634	-0.221	2,882	0	-2,951
08/01/2023 05:40	-2.48	5.79	0.26	0.233	0	1,974	-79,074	0.267	0	1,946	-52,515	0.308	0	1,816	-32,865
08/01/2023 11:40	3.31	-6.02	-0.24	-0.199	3,451	0	701,902	-0.224	3,719	0	763,682	-0.250	3,248	0	678,897
08/01/2023 18:00	-2.71	5.71	0.25	0.216	0	2,047	230,734	0.246	0	2,081	177,915	0.280	0	2,181	85,066
09/01/2023 00:00	3.00	-5.48	-0.23	-0.175	2,690	0	52,600	-0.196	2,907	0	99,729	-0.214	2,692	0	125,066
09/01/2023 06:10	-2.48	5.83	0.16	0.220	0	2,119	419,891	0.252	0	2,232	442,286	0.288	0	2,078	411,569
09/01/2023 12:10	3.35	-6.07	-0.25	-0.192	3,418	0	583,303	-0.215	3,706	0	606,934	-0.238	3,342	0	513,496
09/01/2023 18:40	-2.72	5.65	0.25	0.227	0	2,069	405,346	0.261	0	2,155	409,200	0.300	0	1,939	438,133
10/01/2023 00:30	2.93	-5.34	-0.22	-0.172	2,463	0	144,713	-0.194	2,690	0	172,378	-0.219	2,706	0	178,762
10/01/2023 06:50	-2.41	5.72	0.25	0.231	0	1,910	483,900	0.266	0	1,953	493,174	0.306	0	1,895	483,517
10/01/2023 12:50	3.31	-5.97	-0.24	-0.199	3,468	0	824,840	-0.224	3,725	0	883,968	-0.249	3,231	0	784,417
10/01/2023 19:10	-2.66	5.48	0.25	0.208	0	1,402	94,030	0.235	0	1,346	109,292	0.270	0	1,036	131,841
11/01/2023 01:10	2.82	-5.12	-0.22	-0.174	2,342	0	193,712	-0.197	2,589	0	311,666	-0.223	2,552	0	259,427
11/01/2023 07:20	-2.30	5.51	0.25	0.210	0	1,837	170,990	0.243	0	1,937	200,713	0.281	0	1,928	323,938
11/01/2023 13:20	3.21	-5.76	-0.23	-0.172	3,228	0	744,075	-0.194	3,624	0	824,719	-0.213	3,479	0	789,385
11/01/2023 19:50	-2.55	5.21	0.23	0.190	0	1,601	6,346	0.217	0	1,702	2,916	0.253	0	1,474	591
12/01/2023 01:50	2.66	-4.79	-0.19	-0.128	1,896	0	428,334	-0.140	1,894	0	501,740	-0.154	2,135	0	555,466
12/01/2023 07:50	-2.13	5.19	0.23	0.182	0	1,459	197,648	0.199	0	1,491	172,208	0.225	0	1,419	108,947
12/01/2023 14:00	3.06	-5.45	-0.22	-0.162	2,688	0	593,073	-0.180	2,924	0	633,978	-0.204	3,067	0	656,160
12/01/2023 20:30	-2.39	4.85	0.22	0.178	0	1,275	7,921	0.204	0	1,419	12,665	0.238	0	1,403	15,601
13/01/2023 02:20	2.46	-4.40	-0.19	-0.133	1,396	0	129,295	-0.149	1,576	0	152,827	-0.169	1,642	0	202,904
13/01/2023 08:30	-1.94	4.81	0.21	0.164	0	1,405	283,535	0.185	0	1,527	306,122	0.213	0	1,567	311,617
13/01/2023 14:40	2.87	-5.07	-0.21	-0.152	2,431	0	511,019	-0.169	2,629	0	544,775	-0.186	2,585	0	536,854
13/01/2023 21:10	-2.20	4.48	0.20	0.160	0	1,115	271,234	0.182	0	1,194	262,333	0.207	0	981	233,522
14/01/2023 03:10	2.28	-4.05	-0.17	-0.119	1,357	0	241,609	-0.133	1,450	0	229,960	-0.144	1,163	0	179,416
14/01/2023 09:20	-1.77	4.45	0.20	0.150	0	1,113	-51,429	0.168	0	1,168	-37,648	0.195	0	1,221	-13,966
14/01/2023 15:20	2.68	-4.73	-0.19	-0.127	1,986	0	283,576	-0.141	2,149	0	296,796	-0.152	2,067	0	264,940
14/01/2023 22:00	-2.05	4.19	0.19	0.148	0	820	139,651	0.168	0	875	173,867	0.191	0	815	219,580
15/01/2023 04:00	2.14	-3.76	-0.16	-0.116	1,352	0	184,138	-0.130	1,425	0	248,008	-0.144	1,176	0	224,721

Table 5-11 continued.

Date Time	Sea Level mOD	Range	Max sea grad	Initial target Grad	ebb gen MWh	flood gen MWh	income £	Initial target Grad	ebb gen MWh	flood gen MWh	income £	Initial target Grad	ebb gen MWh	flood gen MWh	income £
	NW 2023, 125 tur, 56 sluices			Start lag 200				Start lag 230				Start lag 260			
15/01/2023 10:10	-1.62	4.12	0.18	0.140	0	1,096	-14,201	0.158	0	1,165	-6,495	0.181	0	1,174	20,963
15/01/2023 16:20	2.50	-4.39	-0.18	-0.117	1,716	0	401,087	-0.130	1,801	0	413,389	-0.141	1,767	0	396,045
15/01/2023 22:50	-1.89	3.94	0.17	0.124	0	966	65,539	0.138	0	991	68,885	0.158	0	1,020	73,964
16/01/2023 05:00	2.05	-3.58	-0.15	-0.099	1,027	0	110,303	-0.110	1,069	0	137,856	-0.122	1,049	0	128,753
16/01/2023 11:10	-1.53	3.92	0.17	0.127	0	970	120,060	0.141	0	1,018	135,478	0.160	0	1,013	153,657
16/01/2023 17:20	2.39	-4.24	-0.17	-0.116	1,591	0	247,147	-0.127	1,684	0	257,079	-0.141	1,712	0	255,358
17/01/2023 00:00	-1.85	3.96	0.17	0.126	0	1,012	138,490	0.140	0	1,047	156,836	0.158	0	1,029	158,476
17/01/2023 06:10	2.11	-3.72	-0.15	-0.104	1,062	0	199,415	-0.115	1,122	0	190,780	-0.129	1,126	0	161,531
17/01/2023 12:20	-1.61	4.04	0.18	0.133	0	906	157,364	0.148	0	959	155,053	0.167	0	953	158,798
17/01/2023 18:30	2.43	-4.38	-0.18	-0.117	1,657	0	190,443	-0.128	1,724	0	180,380	-0.140	1,717	0	178,786
18/01/2023 01:10	-1.95	4.32	0.19	0.122	0	822	110,513	0.134	0	861	116,979	0.148	0	844	110,980
18/01/2023 07:20	2.37	-4.27	-0.17	-0.129	1,614	0	187,312	-0.143	1,682	0	175,888	-0.160	1,678	0	155,790
18/01/2023 13:40	-1.90	4.56	0.20	0.155	0	1,182	213,683	0.173	0	1,247	224,822	0.197	0	1,235	223,411
18/01/2023 19:40	2.66	-4.87	-0.20	-0.147	2,192	0	347,308	-0.162	2,306	0	356,198	-0.180	2,322	0	343,745
19/01/2023 02:10	-2.21	5.01	0.22	0.184	0	1,636	251,062	0.207	0	1,726	289,079	0.237	0	1,546	284,041
19/01/2023 08:20	2.80	-5.15	-0.21	-0.160	2,589	0	349,566	-0.177	2,715	0	368,543	-0.201	2,832	0	361,165
19/01/2023 14:40	-2.35	5.36	0.23	0.194	0	1,886	229,222	0.220	0	1,948	237,498	0.251	0	1,693	208,466
19/01/2023 20:50	3.01	-5.56	-0.23	-0.172	2,976	0	401,497	-0.190	3,137	0	397,032	-0.214	3,235	0	362,556
20/01/2023 03:10	-2.55	5.85	0.26	0.213	0	2,251	546,533	0.241	0	2,215	534,807	0.275	0	2,154	525,944
20/01/2023 09:20	3.30	-6.16	-0.25	-0.192	3,793	0	506,061	-0.215	4,100	0	557,678	-0.241	4,136	0	546,090
20/01/2023 15:50	-2.86	6.27	0.28	0.235	0	2,327	372,584	0.267	0	2,615	437,750	0.309	0	2,368	405,073
20/01/2023 21:50	3.41	-6.33	-0.26	-0.179	4,047	0	409,210	-0.195	4,088	0	406,063	-0.220	3,885	0	378,570
21/01/2023 04:10	-2.92	6.73	0.30	0.258	0	2,497	487,438	0.294	0	2,349	457,813	0.342	0	1,876	357,561
21/01/2023 10:10	3.81	-7.15	-0.28	-0.229	5,362	0	693,538	-0.253	4,883	0	656,239	-0.285	3,945	0	535,288
21/01/2023 16:50	-3.34	7.10	0.32	0.295	0	2,925	489,608	0.339	0	2,908	484,739	0.402	0	2,139	384,673
21/01/2023 22:40	3.76	-6.99	-0.29	-0.229	5,085	0	739,739	-0.255	4,552	0	617,143	-0.286	3,662	0	469,161
22/01/2023 05:00	-3.23	7.45	0.33	0.295	0	3,172	464,403	0.337	0	2,987	405,314	0.396	0	2,491	319,969
22/01/2023 11:00	4.22	-7.91	-0.32	-0.251	5,730	0	918,517	-0.279	5,000	0	843,552	-0.308	4,229	0	784,695
22/01/2023 17:30	-3.69	7.67	0.34	0.303	0	3,347	412,990	0.346	0	3,077	396,574	0.407	0	2,479	340,263
22/01/2023 23:30	3.98	-7.39	-0.30	-0.256	4,996	0	561,614	-0.286	4,317	0	471,857	-0.324	3,602	0	376,398

Table 5 12 summarises the generation and income for each of the three start times and shows the maximum for each tide. The data is taken from Table 5-11 and any negative income has been shown in red. The highest generation and income for each start time has a green highlight.

Table 5-12 Maximum generation and income from 22 days in January 2023 over a range of starting times.

NW 2023, 125 tur, 56 sluices				Start lag 200		Start lag 230		Start lag 260		Maximum Simplified model	
Date Time	Sea Level mOD	Range	Max sea grad	Generation MWh	income £	Generation MWh	income £	Generation MWh	income £	Generation MWh	income £
Max Range		7.91	TOTALS	171,181	23,756,397	177,639	24,689,596	167,186	22,922,700	182,333	26,116,746
Min Range		3.58									
01/01/2023 00:10	-1.98	4.14	0.18	607	-24,590	678	-24,946	707	-23,547	707	-23,547
01/01/2023 06:20	2.16	-3.71	-0.16	1,095	221,683	1,161	235,686	1,168	237,409	1,168	237,409
01/01/2023 12:40	-1.55	3.92	0.17	701	159,757	755	174,059	535	111,993	755	174,059
01/01/2023 18:40	2.37	-4.29	-0.18	1,514	309,960	1,628	374,063	1,620	326,434	1,628	374,063
02/01/2023 01:10	-1.92	4.14	0.18	685	-43,850	753	-31,025	698	-16,355	753	-16,355
02/01/2023 07:30	2.22	-3.83	-0.16	1,237	29,543	1,307	49,222	1,258	73,472	1,307	73,472
02/01/2023 13:40	-1.61	3.98	0.17	667	244,857	750	263,164	731	250,191	750	263,164
02/01/2023 19:40	2.37	-4.33	-0.18	1,549	261,740	1,680	313,956	1,685	362,404	1,685	362,404
03/01/2023 02:10	-1.96	4.33	0.19	895	124,660	974	116,910	952	86,707	974	124,660
03/01/2023 08:20	2.37	-4.15	-0.17	1,381	389,189	1,484	408,193	1,456	399,360	1,484	408,193
03/01/2023 14:40	-1.78	4.25	0.19	664	159,229	678	143,301	690	122,992	690	159,229
03/01/2023 20:40	2.47	-4.53	-0.19	1,570	-44,312	1,652	-44,586	1,667	-61,993	1,667	-44,312
04/01/2023 03:00	-2.06	4.64	0.20	908	50,534	985	55,611	1,058	48,230	1,058	55,611
04/01/2023 09:10	2.58	-4.58	-0.19	1,696	37,130	1,850	79,916	1,993	25,540	1,993	79,916
04/01/2023 15:30	-2.00	4.61	0.19	838	199,749	923	200,692	880	213,083	923	213,083
04/01/2023 21:20	2.61	-4.80	-0.20	2,033	248,615	2,193	252,250	2,298	242,890	2,298	252,250
05/01/2023 03:50	-2.19	4.99	0.22	1,138	169,419	1,241	147,716	1,175	108,627	1,241	169,419
05/01/2023 09:50	2.80	-5.03	-0.21	2,230	123,249	2,376	136,268	2,406	143,551	2,406	143,551
05/01/2023 16:10	-2.23	5.00	0.22	1,178	214,150	1,284	226,599	1,237	206,369	1,284	226,599
05/01/2023 22:10	2.77	-5.09	-0.21	2,574	354,155	2,763	350,018	2,741	298,936	2,763	354,155
06/01/2023 04:20	-2.32	5.34	0.24	1,557	148,063	1,662	149,867	1,610	78,900	1,662	149,867
06/01/2023 10:30	3.02	-5.47	-0.22	2,618	437,503	3,082	469,199	3,081	485,140	3,082	485,140
06/01/2023 16:50	-2.45	5.36	0.24	1,531	186,775	1,686	250,698	1,563	176,914	1,686	250,698
06/01/2023 22:50	2.91	-5.34	-0.22	2,511	142,768	2,899	195,383	2,835	262,189	2,899	262,189
07/01/2023 05:00	-2.43	5.62	0.25	1,757	494,095	1,954	534,001	1,898	523,841	1,954	534,001
07/01/2023 11:00	3.19	-5.80	-0.24	2,816	264,668	3,286	274,417	3,226	297,901	3,286	297,901
07/01/2023 17:30	-2.61	5.58	0.25	1,931	223,701	2,010	243,572	1,798	172,165	2,010	243,572
07/01/2023 23:20	2.97	-5.45	-0.23	2,724	201,198	2,952	134,634	2,882	-2,951	2,952	201,198
08/01/2023 05:40	-2.48	5.79	0.26	1,974	-79,005	1,946	-52,515	1,816	-32,865	1,974	-32,865
08/01/2023 11:40	3.31	-6.02	-0.24	3,451	701,902	3,705	760,879	3,248	678,897	3,705	760,879
08/01/2023 18:00	-2.71	5.71	0.25	2,047	230,719	2,081	177,915	2,181	85,066	2,181	230,719
09/01/2023 00:00	3.00	-5.48	-0.23	2,690	52,600	2,907	99,729	2,692	125,066	2,907	125,066
09/01/2023 06:10	-2.48	5.83	0.16	2,119	419,813	2,232	442,286	2,078	411,569	2,232	442,286
09/01/2023 12:10	3.35	-6.07	-0.25	3,418	583,261	3,706	606,934	3,342	513,496	3,706	606,934
09/01/2023 18:40	-2.72	5.65	0.25	2,069	405,350	2,155	409,200	1,939	438,133	2,155	438,133
10/01/2023 00:30	2.93	-5.34	-0.22	2,463	144,713	2,681	170,231	2,706	178,762	2,706	178,762
10/01/2023 06:50	-2.41	5.72	0.25	1,910	483,786	1,953	493,174	1,895	483,517	1,953	493,174
10/01/2023 12:50	3.31	-5.97	-0.24	3,468	824,840	3,707	880,433	3,231	784,417	3,707	880,433
10/01/2023 19:10	-2.66	5.48	0.25	1,402	93,980	1,346	109,292	1,036	131,841	1,402	131,841
11/01/2023 01:10	2.82	-5.12	-0.22	2,342	193,712	2,589	311,666	2,552	259,427	2,589	311,666
11/01/2023 07:20	-2.30	5.51	0.25	1,837	170,986	1,937	200,713	1,928	323,938	1,937	323,938

Table 5-12 continued.

NW 2023, 125 tur, 56 sluices				Start lag 200		Start lag 230		Start lag 260		Maximum Simplified model	
Date Time	Sea Level mOD	Range	Max sea grad	Generation MWh	income £	Generation MWh	income £	Generation MWh	income £	Generation MWh	income £
11/01/2023 13:20	3.21	-5.76	-0.23	3,228	744,075	3,624	824,719	3,479	789,385	3,624	824,719
11/01/2023 19:50	-2.55	5.21	0.23	1,601	6,346	1,702	2,916	1,474	591	1,702	6,346
12/01/2023 01:50	2.66	-4.79	-0.19	1,896	428,334	1,894	501,740	2,135	555,466	2,135	555,466
12/01/2023 07:50	-2.13	5.19	0.23	1,459	197,648	1,491	172,208	1,419	108,947	1,491	197,648
12/01/2023 14:00	3.06	-5.45	-0.22	2,688	593,073	2,921	633,523	3,067	656,160	3,067	656,160
12/01/2023 20:30	-2.39	4.85	0.22	1,275	7,919	1,419	12,665	1,403	15,601	1,419	15,601
13/01/2023 02:20	2.46	-4.40	-0.19	1,396	129,295	1,576	152,827	1,642	202,904	1,642	202,904
13/01/2023 08:30	-1.94	4.81	0.21	1,405	283,535	1,527	306,122	1,567	311,617	1,567	311,617
13/01/2023 14:40	2.87	-5.07	-0.21	2,431	511,019	2,629	544,775	2,585	536,854	2,629	544,775
13/01/2023 21:10	-2.20	4.48	0.20	1,115	271,234	1,194	262,333	981	233,522	1,194	271,234
14/01/2023 03:10	2.28	-4.05	-0.17	1,357	241,609	1,450	229,960	1,163	179,416	1,450	241,609
14/01/2023 09:20	-1.77	4.45	0.20	1,113	-51,429	1,168	-37,648	1,221	-13,966	1,221	-13,966
14/01/2023 15:20	2.68	-4.73	-0.19	1,986	283,576	2,149	296,796	2,067	264,940	2,149	296,796
14/01/2023 22:00	-2.05	4.19	0.19	820	139,651	875	173,867	815	219,580	875	219,580
15/01/2023 04:00	2.14	-3.76	-0.16	1,352	184,138	1,425	248,008	1,176	224,721	1,425	248,008
15/01/2023 10:10	-1.62	4.12	0.18	1,096	-14,201	1,165	-6,495	1,174	20,963	1,174	20,963
15/01/2023 16:20	2.50	-4.39	-0.18	1,716	401,087	1,801	413,389	1,767	396,045	1,801	413,389
15/01/2023 22:50	-1.89	3.94	0.17	966	65,539	991	68,885	1,020	73,964	1,020	73,964
16/01/2023 05:00	2.05	-3.58	-0.15	1,027	110,303	1,069	137,856	1,049	128,753	1,069	137,856
16/01/2023 11:10	-1.53	3.92	0.17	970	120,060	1,018	135,478	1,013	153,657	1,018	153,657
16/01/2023 17:20	2.39	-4.24	-0.17	1,591	247,147	1,684	257,079	1,712	255,358	1,712	257,079
17/01/2023 00:00	-1.85	3.96	0.17	1,012	138,490	1,047	156,836	1,029	158,476	1,047	158,476
17/01/2023 06:10	2.11	-3.72	-0.15	1,062	199,415	1,122	190,780	1,126	161,531	1,126	199,415
17/01/2023 12:20	-1.61	4.04	0.18	906	157,364	959	155,053	953	158,798	959	158,798
17/01/2023 18:30	2.43	-4.38	-0.18	1,657	190,443	1,724	180,380	1,717	178,786	1,724	190,443
18/01/2023 01:10	-1.95	4.32	0.19	822	110,513	861	116,979	844	110,980	861	116,979
18/01/2023 07:20	2.37	-4.27	-0.17	1,614	187,312	1,682	175,888	1,678	155,790	1,682	187,312
18/01/2023 13:40	-1.90	4.56	0.20	1,182	213,683	1,247	224,822	1,235	223,411	1,247	224,822
18/01/2023 19:40	2.66	-4.87	-0.20	2,192	347,308	2,306	356,198	2,322	343,745	2,322	356,198
19/01/2023 02:10	-2.21	5.01	0.22	1,636	251,082	1,726	289,079	1,546	284,041	1,726	289,079
19/01/2023 08:20	2.80	-5.15	-0.21	2,589	349,566	2,715	368,543	2,832	361,165	2,832	368,543
19/01/2023 14:40	-2.35	5.36	0.23	1,886	229,222	1,948	237,498	1,693	208,466	1,948	237,498
19/01/2023 20:50	3.01	-5.56	-0.23	2,976	401,497	3,137	397,032	3,235	362,556	3,235	401,497
20/01/2023 03:10	-2.55	5.85	0.26	2,251	546,533	2,215	534,807	2,154	525,944	2,251	546,533
20/01/2023 09:20	3.30	-6.16	-0.25	3,809	507,897	4,100	557,678	3,728	491,229	4,100	557,678
20/01/2023 15:50	-2.86	6.27	0.28	2,327	372,584	2,615	437,750	2,368	405,073	2,615	437,750
20/01/2023 21:50	3.41	-6.33	-0.26	4,047	409,210	4,088	406,063	3,885	378,570	4,088	409,210
21/01/2023 04:10	-2.92	6.73	0.30	2,313	453,284	2,349	457,813	1,876	357,561	2,349	457,813
21/01/2023 10:10	3.81	-7.15	-0.28	5,363	693,787	4,816	640,279	3,945	535,288	5,363	693,787
21/01/2023 16:50	-3.34	7.10	0.32	2,925	489,608	2,697	453,019	2,139	384,673	2,925	489,608
21/01/2023 22:40	3.76	-6.99	-0.29	5,085	739,828	4,540	616,025	3,662	469,161	5,085	739,828
22/01/2023 05:00	-3.23	7.45	0.33	3,172	464,403	2,987	405,314	2,491	319,969	3,172	464,403
22/01/2023 11:00	4.22	-7.91	-0.32	5,730	918,517	5,000	843,552	4,229	784,695	5,730	918,517
22/01/2023 17:30	-3.69	7.67	0.34	3,347	412,990	3,077	396,574	2,479	340,263	3,347	412,990
22/01/2023 23:30	3.98	-7.39	-0.30	4,996	561,614	4,317	471,857	3,602	376,398	4,996	561,614

The total income for the 22-days in Table 5-12 is £26.1m, this would equate to an annual income of £433m per annum but is not representative of the real solution for two reasons: -

1. The price varies all the time so extrapolation will only be appropriate.

2. The highest generation total will require much finer time steps to determine the optimum times to start generation.

5.8 Results from the simplified model.

The spreadsheet sample developed to check the simplified model showed the idea works reasonably well to maximise the generation but there were several areas for improvement. The half hourly prices vary randomly which is probably due to the availability of demand, wind and sunlight. This has highlighted an opportunity to provide a balancing service to the grid as shown in the following demand led model. In particular: -

- For the first flood tide on 01/01/2023, the price is negative throughout the whole of the generating period. It may be best to cancel the generation and leave sluices and turbines open. The price is still negative during what would have been the subsequent pumping phase so there is potential to pump slightly above the high tide to gain some income and produce a higher head for the subsequent tide. The grid could request more pumping if needed to balance the system.

- For the first flood tide on 02/01/2023, starting at 01:10 the price is negative for the first 1.5 hours of generation. The previous hold period could be extended, which would increase the head and gradient.

- Table 5-12 summarises the generation and income for each of the three start times and shows the maximum for each tide. The data is taken from Table 5-11 and any negative income has been shown in red. The highest generation and income for each start time has a green highlight.

- Table 5-12 shows numerous instances of negative income from tides and there is no reason to generate in these circumstances.

Therefor it was decided to stop further work on the simplified model and develop a demand led model as described in the next section.

5.9   Demand led 0-D model

It has been shown (Harcourt et al., 2019) that optimising for price gave a 23% improvement on revenue for Swansea Bay. There will be no generation at negative rates because the turbines can be set to run free, in fact, they could be run in pump mode to balance the system and take advantage of the negative price. It remains to be seen if demand increases significantly due to the drive to reach net zero, if so the economics of tidal range are improved significantly.

Consider a hydro turbine functioning in the same way as a tap in a water pipe, where the valve can be turned on or off. The maximum flow is governed by the diameter of the turbine or pipe and the pressure head. The flow through the turbine or pipe can be varied infinitely between zero and the maximum, fully opened position. Earlier work by Cardiff University linked generation to the day ahead prices to try increasing income (Zhang et al., 2022). For a demand/price-based model, the flow through the turbine will be increased when the electricity price is high and reduced when it is low. The system must meet the constraints dictated by the pressure head, maximum flow through the turbine, maximum generator rating and meeting the natural tide limits wherever possible.

The spreadsheet calculations for the simplified model in the previous section has highlighted many instances where generation is not optimal for price or supporting the grid. The price fluctuates enormously and randomly which is assumed to be more related to the availability of renewable generation than demand fluctuation.

The simplified model performs well where the price is fairly constant throughout the generation period. However, where the price fluctuates or goes negative the simple model does not give the optimum income. By seeking to maximise the income the priced based model is also more responsive to supply and demand on the grid. Table 5-13 shows the annual fluctuation in average price and standard deviation (SD). In 2017 & 2020 the SD is less than in 2016 where the average price is higher. The 22-day sample period in section 5.5 was taken from 2023 as there was a complete year of price data available at the time of analysis. The average price and SD is higher than in 2024 so the benefit of the price-based model may be more than in 2024. However, the 2023 figures are less than the average price and SD since 2020. As the percentage of renewable energy increases the SD may be expected to increase due to the intermittency of the supply.

Table 5-13 Half hourly sell price data for recent years, including standard deviation of the mean.

Year	Sell price, £/MWh			
	Mean	Std. Deviation	Maximum	Minimum
2016	40	47	1,529	-100
2017	45	31	1,510	-73
2018	57	30	990	-150
2019	42	23	375	-88
2020	35	37	2,242	-70
2021	113	151	4,038	-70
2022	200	148	4,036	-90
2023	95	63	1,950	-185
2024	71	42	669	-92
2025	81	77	2,900	-95
Mean 2016 to 2020	44	33	1,329	-96
Mean since 2020	112	96	2,719	-106

The investigation of the price-based model will use the same 22-day period from 2023 to be comparable with the simplified model. For this period the average price is £128.79/MWh with a standard deviation of 89.70. Both are slightly higher than the annual figures which is most likely due to the winter period selected. The benefits of increased revenue and response to the grid will be tested. The benefits may change for different periods of time, but the principle will be the same.

To be useful, it is necessary to estimate the price of electricity for the next tide cycle. Forward price estimating is already done in the energy market where the generators bid their prices a day ahead. These "day-ahead" prices are not publicly available but as an example Octopus Energy publish their day ahead prices for their customers *(Octopus, 2024)*. These are retail prices not wholesale prices, but the forecasting principle is the same.

Tidal range schemes will be looking for government subsidies in the early years as happened for the development of solar and wind energy, at least for the initial years of construction and operation. Whether it takes the form of Contract for Difference (CfD) or Regulated Asset Base (RAB) (Vandercruyssen et al., 2023a) the generator will most likely be paid a fixed price. If so, it does not negate the benefit to the grid which derives from the flexible operation of tidal range during generation.

In this section the spreadsheet from the simplified model is modified to allow the change in level of the impoundment to be varied for each 10-minute time slot: -

- If the price is zero or negative the change in level can be set to zero, causing a halt in generation and raising the head.
- Where the prices vary significantly, the average change in level can be weighted by the individual half-hourly price to increase or decrease the flow.
- If the pumping price is high compared with the generating price, the sluicing can be brought forward to reduce the amount of pumping. Conversely if the pumping price is relatively low, then it can be delayed until close to the maximum pumping head.
- If the price is negative for the whole of the generation cycle, then sluicing and pumping can be used instead of generation.

The spreadsheet will be developed manually to estimate the first 22 days for 2023 for comparison with the simplified model. The example is based on the same North Wales installation.

5.10 Fixed constraints.

- Each cycle to be within 0.10m of tide peaks.
- Minimum generating head is 1.5m.
- Minimum starting head is 2.0m.
- Efficiency on flood tide is set by a cell in the spreadsheet, typically 20% less than ebb tide.
- Limit max Q11 to 4.75 m3/s, if exceeded reduce the flow or partially open sluices to share the flow and reduce Q11 to max.
- Check that the weighted flow does not exceed the maximum capacity through the turbines for the given head. If it does the change in level for that time step needs to be reduced manually, there may be scope for increasing the change in level for subsequent steps. See columns L & M in the spreadsheet.
- Check that the maximum power generation does not exceed the installed capacity, or sluicing is requited to reduce the flow through the turbines.

5.11 Operational guidance rules for control program.

From the manual spreadsheet calculations, the following guidelines for control have been determined:-

- Do not generate if the price is less than £5/MWh as this price may not cover the wear and tear on the turbine and generator.
- The target level 0.75m above low tide allows pumps to reach low tide. For high tide without sea level rise, the target should be limited to 0.5m below high tide because of the greater surface area.
- Aim to meet tide peaks within +/- 100 mm.
- Pumps can run with negative head when sluices are open if the price is negative, which would generate income and help balance the grid system.
- Sluicing can be used in conjunction with generation if the maximum speed is reached or it is necessary to reach next tide peak or trough. Alternatively, the gradient can be reduced to give max Q11 if subsequent periods are below max Q11.
- If the generation price is negative, then stop the flow. Increase the gradient of following periods if the price returns to positive.
- Assume generation starts 200 minutes after high or low tide but the change in level can be set to zero if the head is less than 2.0m or the price is low.

5.12 Weighting system

It is proposed to weight the change in level by the price for each timeslot, i.e. Increase the change in level where the price is above the average price for the half tide cycle and reduce where the price is lower. There must be limits on this for the generation phase, ie:-

- Zero change for negative or zero price, ie no generation but hold.
- Maximum change must be adjusted so as not to exceed installed capacity,
- The price range is so large that it needs to be reduced to fit within the zero and maximum gradient range.

The procedure adopted is:-

- Set any negative price to zero.
- Divide each price by the maximum price in the generation period, producing a "price factor" between 0 and 1.
- Sum the individual price factors over the generation period.
- Calculate the target change in level over the generation period.

- The weighted change in level is then the price factor divided by the sum of the price factors, multiplied by the change in level required over the generation phase.
- The volume flowing over the time slot is then calculated by the average surface area multiplied by the change in level.

This is illustrated in Table 5-14, consider the generation period which starts at 22:00 hours on 1-Jan-23. The electricity price during generation changes from £42/MWh to £290/MWh.

Table 5-14 Example of generation period with significant changes in price.

A	B	C	D	F	G H	
Date/Time	Sea Level mOD	Price £/MWh	Sea level change in 10 minutes	Tide	Mode	Ch
01/01/2023 21:30	0.63	217.00	-0.17			
01/01/2023 21:40	0.47	217.00	-0.16			
01/01/2023 21:50	0.29	217.00	-0.18	minGrad		
01/01/2023 22:00	0.12	42.00	-0.17			
01/01/2023 22:10	-0.04	42.00	-0.16			
01/01/2023 22:20	-0.21	42.00	-0.17			
01/01/2023 22:30	-0.37	290.00	-0.16			
01/01/2023 22:40	-0.53	290.00	-0.16			
01/01/2023 22:50	-0.69	290.00	-0.16			
01/01/2023 23:00	-0.84	236.00	-0.15			
01/01/2023 23:10	-0.98	236.00	-0.14		Generate	
01/01/2023 23:20	-1.11	236.00	-0.13			
01/01/2023 23:30	-1.24	151.35	-0.13			
01/01/2023 23:40	-1.36	151.35	-0.12			
01/01/2023 23:50	-1.47	151.35	-0.11			
02/01/2023 00:00	-1.57	172.68	-0.10			
02/01/2023 00:10	-1.65	172.68	-0.08			
02/01/2023 00:20	-1.73	172.68	-0.08			
02/01/2023 00:30	-1.80	182.34	-0.07			
02/01/2023 00:40	-1.85	182.34	-0.05			
02/01/2023 00:50	-1.89	182.34	-0.04			
02/01/2023 01:00	-1.91	42.00	-0.02			

Note in Table 5-14 any expected storm surge can be added or subtracted from column B.

The first three columns (date/time, sea level and price) are copied from the main generation spreadsheet just for the generation period into columns A to C on the weighting sheet shown in Figure

5-5 as 18 x 10-minute slots. Generation is starting with a head of 2.42m but the initial price is £42/MWh and changes several times through the generation cycle. The price factors in column D are calculated as the individual prices divided by the maximum price.

The total level change (TLC) is -2.91m, giving an average change of -0.16m every 10-minutes. The individual weighted level changes (WLC) are calculated as the price factor divided by the sum of all price factors, times the target level change (TLC) in the impoundment (highlighted in yellow) is calculated by Equation 5-11.

$$WLC = ABS(Intial\ lagoon\ level - sea\ level\ at\ end\ of\ generation) - Min\ gen\ head\ (1.5\ m)$$

Equation 5-11 Weighted level change in impoundment.

Where   ABS is the absolute value.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Date/Time	Sea Level	Price £/MWh	Price factor	weighted change in 10							
2												
3	01/01/2023 22:00	0.12	42.00	0.145	-0.038							
4	01/01/2023 22:10	-0.04	42.00	0.145	-0.038							
5	01/01/2023 22:20	-0.21	42.00	0.145	-0.038							
6	01/01/2023 22:30	-0.37	290.00	1.000	-0.262							
7	01/01/2023 22:40	-0.53	290.00	1.000	-0.262							
8	01/01/2023 22:50	-0.69	290.00	1.000	-0.262							
9	01/01/2023 23:00	-0.84	236.00	0.814	-0.213							
10	01/01/2023 23:10	-0.98	236.00	0.814	-0.213							
11	01/01/2023 23:20	-1.11	236.00	0.814	-0.213							
12	01/01/2023 23:30	-1.24	151.35	0.522	-0.137							
13	01/01/2023 23:40	-1.36	151.35	0.522	-0.137							
14	01/01/2023 23:50	-1.47	151.35	0.522	-0.137							
15	02/01/2023 00:00	-1.57	172.68	0.595	-0.156							
16	02/01/2023 00:10	-1.65	172.68	0.595	-0.156							
17	02/01/2023 00:20	-1.73	172.68	0.595	-0.156							
18	02/01/2023 00:30	-1.80	182.34	0.629	-0.165							
19	02/01/2023 00:40	-1.85	182.34	0.629	-0.165							
20	02/01/2023 00:50	-1.89	182.34	0.629	-0.165							
21				0.000	0.000		Count		18			
22				0.000	0.000		Maximum price		£290.00		total change	-2.91
23				0.000	0.000		Average price		£179.06		average drop	-0.16
24				0.000	0.000		Minimum Price		£42.00			
25				0.000	0.000		Total price factor		11.114			
26				0.000	0.000							

Figure 5-5 Example of weighted level change during generation phase.

For this example, the figures are shown in Equation 5-12.

$$TLC = ABS(2.52 -(-1.89)) – 1.5 = 2.91\ m$$

Equation 5-12 example level change in impoundment.

The resulting WLC (column E as highlighted in Figure 5-5) is then copied back to column I in Table 5-15. This gives a good starting point for optimum price generation but there are several adjustments and checks to be made. The income is increased by setting WLC for the first three 10-minute periods to zero to increase the initial generating head. Then it is necessary to check that the targeted flow through the turbines does not exceed the maximum flow for the given head. If the flows for the price of £290/MWh and £236/MWh exceeded the maximum Qt, highlighted in red in Table 5-15, the change in lagoon level is reduced manually until the target flow became less than the maximum.

Table 5-15 shows a section of the spreadsheet with the WLC from Figure 5-5 inserted in column I. The income from this generation is valued at £416,749. Note that the head at the end of generation is the minimum generating head of 1.5m as planned. The flows for the second and third half hour in column N are highlighted in red as they exceed the maximum Qt for the given head shown in column O. It is necessary to manually reduce the WLC or open sluices to pass the excess flow. As there are following generation slots that are below max Qt it is better to manually reduce WLC for the red slots and to increase those on later slots.

Table 5-15 Example of price change through generation.

Date/Time	Sea Level mOD	Price £/MWh	Sea level change in 10 minutes	Tide	Mode	Change in Lagoon level	Lagoon level	Head	Surface area km2	All sluices Qs	All turbines Qt	Max Qt	Single turbine Qt1	Q11 m3/s	n11 rpm	Efficiency %	Turbine speed nt rpm	Net power MW	Ebb	Flood	Income £
01/01/2023 21:30	0.63	217.00	-0.17				2.52	1.89	146.58												
01/01/2023 21:40	0.47	217.00	-0.16				2.52	2.05	146.58												
01/01/2023 21:50	0.29	217.00	-0.18	minGrad			2.52	2.23	146.58												
01/01/2023 22:00	0.12	42.00	-0.17			-0.038	2.48	2.36	146.43		9,259	47,057	74	0.75	185	93.7%	35.54	206	34		1,442
01/01/2023 22:10	-0.04	42.00	-0.16			-0.038	2.44	2.48	146.29		9,250	48,257	74	0.73	185	93.7%	36.45	217	36		1,516
01/01/2023 22:20	-0.21	42.00	-0.17			-0.038	2.41	2.62	146.14		9,241	49,524	74	0.71	185	93.8%	37.40	228	38		1,596
01/01/2023 22:30	-0.37	290.00	-0.16			-0.262	2.14	2.51	145.15		63,557	48,550	508	5.01	271	74.5%	53.68	1,197	199		57,832
01/01/2023 22:40	-0.53	290.00	-0.16			-0.262	1.88	2.41	144.15		63,123	47,557	505	5.08	275	73.8%	53.41	1,130	188		54,615
01/01/2023 22:50	-0.69	290.00	-0.16			-0.262	1.62	2.31	143.84		62,838	46,543	503	5.17	280	73.0%	53.28	1,065	178		51,482
01/01/2023 23:00	-0.84	236.00	-0.15			-0.213	1.41	2.25	143.42		51,006	45,903	408	4.25	225	81.7%	42.11	942	157		37,060
01/01/2023 23:10	-0.98	236.00	-0.14		Generate	-0.213	1.19	2.17	142.99		50,854	45,151	407	4.31	228	81.2%	42.08	903	150		35,505
01/01/2023 23:20	-1.11	236.00	-0.13			-0.213	0.98	2.09	142.56		50,703	44,280	406	4.38	233	80.5%	42.05	858	143		33,758
01/01/2023 23:30	-1.24	151.35	-0.13			-0.137	0.84	2.08	142.29		32,437	44,209	259	2.81	185	89.6%	33.39	609	102		15,366
01/01/2023 23:40	-1.36	151.35	-0.12			-0.137	0.71	2.07	141.84		32,355	44,033	259	2.81	185	89.6%	33.26	603	100		15,204
01/01/2023 23:50	-1.47	151.35	-0.11			-0.137	0.57	2.04	141.49		32,263	43,748	258	2.82	185	89.6%	33.04	593	99		14,962
02/01/2023 00:00	-1.57	172.68	-0.10			-0.156	0.42	1.99	141.08		36,711	43,145	294	3.26	185	88.7%	32.59	650	108		18,709
02/01/2023 00:10	-1.65	172.68	-0.08			-0.156	0.26	1.91	140.68		36,606	42,312	293	3.31	185	88.6%	31.96	623	104		17,920
02/01/2023 00:20	-1.73	172.68	-0.08			-0.156	0.10	1.83	140.27		36,501	41,463	292	3.37	185	88.5%	31.32	595	99		17,136
02/01/2023 00:30	-1.80	182.34	-0.07			-0.165	-0.06	1.74	139.78		38,419	40,379	307	3.64	188	87.6%	30.91	589	98		17,887
02/01/2023 00:40	-1.85	182.34	-0.05			-0.165	-0.23	1.62	139.17		38,268	39,026	306	3.75	194	86.5%	30.96	541	90		16,439
02/01/2023 00:50	-1.89	182.34	-0.04			-0.165	-0.39	1.50	138.56		38,100	37,499	305	3.89	203	85.2%	31.01	490	82		14,884
02/01/2023 01:00	-1.91	42.00	-0.02			-0.413	-0.80	1.11	137.91	57,953	37,499										
02/01/2023 01:10	-1.92	42.00	-0.01	low	Sluice	-0.357	-1.16	0.76	136.98	49,778	32,209										
02/01/2023 01:20	-1.92	42.00	0.00			-0.298	-1.46	0.46	136.21	41,250	26,691										
02/01/2023 01:30	-1.91	42.00	0.01			-0.233	-1.69	0.22	135.60	32,175	20,819										
02/01/2023 01:40	-1.87	42.00	0.04			-0.161	-1.85	0.02	135.18	22,139	14,325										
02/01/2023 01:50	-1.83	42.00	0.04		Pump	-0.213	-2.06	-0.23	130.12		47,879							-938	-156		-6,563
02/01/2023 02:00	-1.77	42.00	0.06				-2.06	-0.29	129.17												
02/01/2023 02:10	-1.70	42.00	0.07				-2.06	-0.36	129.17									sums	1,850	0	416,749

In Table 5-16 the WLC for the first half hour has been set to zero so that the initial generating head increased to 2.73m. Also, the WLC (column I) for the next hour has been manually changed to -0.200 to reduce the target flow in column N to within the turbine Qt limit in column O. The TLC for the last hour has been manually increased to just below max Qt. The final slot exceeded the Qt limit, so sluices were partially opened to allow a flow of 700m³/s. The generation income has increased by 11% to £463,982; the final head has increased to 1.74m. Because the end of generation is close to low tide only one pumping slot is needed and takes the level in the impoundment just below the natural low tide. If the price were higher the generation period could be extended towards 0.75m above low tide.

Table 5-16 Manual changes to TLC to increase price and limit TLC to turbine capacity.

Date/Time	Sea Level mOD	Price £/MWh	Sea level change in 10 minutes	Tide	Mode	Change in Lagoon level	Lagoon level	Head	Surface area km2	All sluices Qs	All turbines Qt	Max Qt	Single turbine Qt1	Q11 m3/s	n11 rpm	Efficiency %	Turbine speed nt rpm	Net power MW	Ebb	Flood	Income £
01/01/2023 21:30	0.63	217.00	-0.17					2.52	1.89	146.58											
01/01/2023 21:40	0.47	217.00	-0.16					2.52	2.05	146.58											
01/01/2023 21:50	0.29	217.00	-0.18	minGrad				2.52	2.23	146.58											
01/01/2023 22:00	0.12	42.00	-0.17			0.000	2.52	2.40	146.58		0	47,433	0	0.00	185	95.2%	35.82	0	0		0
01/01/2023 22:10	-0.04	42.00	-0.16			0.000	2.52	2.56	146.58		0	48,989	0	0.00	185	95.2%	37.00	0	0		0
01/01/2023 22:20	-0.21	42.00	-0.17			0.000	2.52	2.73	146.58		0	50,589	0	0.00	185	95.2%	38.21	0	0		0
01/01/2023 22:30	-0.37	290.00	-0.16		Generate	-0.200	2.32	2.69	145.82		48,732	50,217	390	3.71	192	86.9%	39.35	1,146	191		55,366
01/01/2023 22:40	-0.53	290.00	-0.16			-0.200	2.12	2.65	145.06		48,479	49,842	388	3.72	192	86.8%	39.16	1,122	187		54,208
01/01/2023 22:50	-0.69	290.00	-0.16			-0.200	1.92	2.61	144.44		48,249	49,465	386	3.73	193	86.7%	39.00	1,098	183		53,075
41/01/2023 23:00	-0.84	236.00	-0.15			-0.200	1.72	2.56	144.04		48,080	48,989	385	3.76	195	86.5%	38.90	1,071	178		42,108
40/01/2023 23:10	-0.98	236.00	-0.14			-0.200	1.52	2.50	143.64		47,947	48,411	384	3.79	197	86.2%	38.86	1,039	173		40,851
01/01/2023 23:20	-1.11	236.00	-0.13			-0.195	1.32	2.43	143.25		46,620	47,778	373	3.73	193	86.7%	37.68	990	165		38,929
18/01/2023 23:30	-1.24	151.35	-0.13			-0.137	1.19	2.43	142.98		32,593	47,712	261	2.61	185	90.0%	36.04	716	119		18,062
01/01/2023 23:40	-1.36	151.35	-0.12			-0.137	1.05	2.41	142.73		32,535	47,549	260	2.62	185	90.0%	35.91	710	118		17,904
01/01/2023 23:50	-1.47	151.35	-0.11			-0.137	0.92	2.39	142.38		32,467	47,285	260	2.63	185	89.9%	35.71	700	117		17,666
02/01/2023 00:00	-1.57	172.68	-0.10			-0.180	0.74	2.31	141.91		42,644	46,485	341	3.51	185	88.2%	35.11	872	145		25,083
02/01/2023 00:10	-1.65	172.68	-0.08			-0.180	0.56	2.21	141.44		42,503	45,466	340	3.58	185	88.0%	34.34	830	138		23,879
02/01/2023 00:20	-1.73	172.68	-0.08			-0.180	0.38	2.11	140.98		42,363	44,423	339	3.65	188	87.5%	34.10	785	131		22,586
02/01/2023 00:30	-1.80	182.34	-0.07			-0.176	0.20	2.00	140.74		41,318	43,290	331	3.65	188	87.5%	33.26	727	121		22,082
20/01/2023 00:40	-1.85	182.34	-0.05			-0.176	0.02	1.87	140.09		41,187	41,903	329	3.76	195	86.4%	33.33	671	112		20,379
02/01/2023 00:50	-1.89	182.34	-0.04			-0.176	-0.15	1.74	139.43	700	40,296	40,353	322	3.82	199	85.9%	32.70	604	101		18,367
02/01/2023 01:00	-1.91	42.00	-0.02			-0.442	-0.59	1.32	138.45	62,364	40,353										
02/01/2023 01:10	-1.92	42.00	-0.01	low	Sluice	-0.387	-0.98	0.94	137.45	54,262	35,111										
02/01/2023 01:20	-1.92	42.00	0.00			-0.329	-1.31	0.61	136.59	45,821	29,649										
02/01/2023 01:30	-1.91	42.00	0.01			-0.267	-1.58	0.33	135.90	36,904	23,879										
02/01/2023 01:40	-1.87	42.00	0.04			-0.198	-1.78	0.09	135.38	27,234	17,622										
02/01/2023 01:50	-1.83	42.00	0.04		Pump	-0.219	-2.00	-0.17	130.52		49,512							-938	-156		-6,563
02/01/2023 02:00	-1.77	42.00	0.06				-2.00	-0.23	130.58												
02/01/2023 02:10	-1.70	42.00	0.07				-2.00	-0.30	130.58									sums	2,023	0	463,982

18-Jan-26

5.13 Results from the demand led model

The demand/priced based model shows significant increased income over the simplified model when electricity prices vary during the generation cycle; 21% for the period selected. Providing the additional benefit of helping to balance the grid between supply and demand. The flow of water through the turbines is regulated just like the flow through a tap. Between zero flow and the maximum there is infinite control over the flow of water, the same as controlling the flow through the turbines.

During operation it is only necessary to consider the price for the next one or two generation periods. However, to estimate the full effect of the demand led model for long term operation it would be useful to develop a computer program which would calculate the possible income from previous years where the tide levels and prices are known.

Table 5-17 shows a summary of the results from both the simplified model and the demand led model. The negative figures, shown in red, are much reduced in the demand led model. By weighting the flow to the higher price, the income has been increased by 25% and a 13% drop in electrical generation, which reduces wear and tear on the turbines. These figures will change depending on the period selected. It is hoped to further develop the model into a computer program which will assess a whole year of data, but the algorithm will be complex and cannot be completed within this study.

Table 5-17 Summary comparing generation and income from simplified and demand led model.

NW 2023, 125 tur, 56 sluices				Maximum Simplified model		Demand led model		
						Generation MWh		
Date Time	Sea Level mOD	Range	Max sea grad	Generation MWh	income £	Ebb	Flood	income £
Max Range		7.91	TOTALS	182,333	26,116,746	109,007	48,948	32,592,308
Min Range		3.58				157,955		
01/01/2023 00:10	-1.98	4.14	0.18	707	-23,547	0	-4,531	165,675
01/01/2023 06:20	2.16	-3.71	-0.16	1,168	237,409	1,226	0	248,578
01/01/2023 12:40	-1.55	3.92	0.17	755	174,059	0	1,407	360,441
01/01/2023 18:40	2.37	-4.29	-0.18	1,628	374,063	2,023	0	463,982
02/01/2023 01:10	-1.92	4.14	0.18	753	-16,355	0	-2,344	168,872
02/01/2023 07:30	2.22	-3.83	-0.16	1,307	73,472	1,201	0	212,140
02/01/2023 13:40	-1.61	3.98	0.17	750	263,164	0	933	274,270
02/01/2023 19:40	2.37	-4.33	-0.18	1,685	362,404	2,398	0	510,467
03/01/2023 02:10	-1.96	4.33	0.19	974	124,660	0	1,050	250,271
03/01/2023 08:20	2.37	-4.15	-0.17	1,484	408,193	2,011	0	485,260
03/01/2023 14:40	-1.78	4.25	0.19	690	159,229	0	1,535	294,157
03/01/2023 20:40	2.47	-4.53	-0.19	1,667	-44,312	-3,281	0	130,500
04/01/2023 03:00	-2.06	4.64	0.20	1,058	55,611	0	1,371	79,355
04/01/2023 09:10	2.58	-4.58	-0.19	1,993	79,916	1,893	0	150,040
04/01/2023 15:30	-2.00	4.61	0.19	923	213,083	0	1,707	299,734
04/01/2023 21:20	2.61	-4.80	-0.20	2,298	252,250	1,990	0	350,415
05/01/2023 03:50	-2.19	4.99	0.22	1,241	169,419	0	1,683	256,452
05/01/2023 09:50	2.80	-5.03	-0.21	2,406	143,551	2,634	0	230,710
05/01/2023 16:10	-2.23	5.00	0.22	1,284	226,599	0	1,708	322,744
05/01/2023 22:10	2.77	-5.09	-0.21	2,763	354,155	1,985	0	426,047
06/01/2023 04:20	-2.32	5.34	0.24	1,662	149,867	0	1,723	285,423
06/01/2023 10:30	3.02	-5.47	-0.22	3,082	485,140	2,963	0	446,332
06/01/2023 16:50	-2.45	5.36	0.24	1,686	250,698	0	977	242,831
06/01/2023 22:50	2.91	-5.34	-0.22	2,899	262,189	2,470	0	449,972
07/01/2023 05:00	-2.43	5.62	0.25	1,954	534,001	0	2,149	500,549
07/01/2023 11:00	3.19	-5.80	-0.24	3,286	297,901	3,981	0	834,969
07/01/2023 17:30	-2.61	5.58	0.25	2,010	243,572	0	1,107	303,894
07/01/2023 23:20	2.97	-5.45	-0.23	2,952	201,198	-81	0	378,637
08/01/2023 05:40	-2.48	5.79	0.26	1,974	-32,865	0	1,188	101,210
08/01/2023 11:40	3.31	-6.02	-0.24	3,705	760,879	4,057	0	829,007
08/01/2023 18:00	-2.71	5.71	0.25	2,181	230,719	0	1,624	276,657
09/01/2023 00:00	3.00	-5.48	-0.23	2,907	125,066	2,913	0	228,413
09/01/2023 06:10	-2.48	5.83	0.16	2,232	442,286	0	2,482	491,474
09/01/2023 12:10	3.35	-6.07	-0.25	3,706	606,934	3,772	0	758,495
09/01/2023 18:40	-2.72	5.65	0.25	2,155	438,133	0	2,519	520,944
10/01/2023 00:30	2.93	-5.34	-0.22	2,706	178,762	2,497	0	353,826
10/01/2023 06:50	-2.41	5.72	0.25	1,953	493,174	0	2,537	579,180
10/01/2023 12:50	3.31	-5.97	-0.24	3,707	880,433	3,984	0	895,621
10/01/2023 19:10	-2.66	5.48	0.25	1,402	131,841	0	-990	204,942
11/01/2023 01:10	2.82	-5.12	-0.22	2,589	311,666	2,871	0	599,108

Table 5-17 continued

NW 2023, 125 tur, 56 sluices				Maximum Simplified model		Demand led model		
							Generation MWh	
Date Time	Sea Level mOD	Range	Max sea grad	Generation MWh	income £	Ebb	Flood	income £
11/01/2023 07:20	-2.30	5.51	0.25	1,937	323,938	0	1,882	456,432
11/01/2023 13:20	3.21	-5.76	-0.23	3,624	824,719	4,082	0	811,263
11/01/2023 19:50	-2.55	5.21	0.23	1,702	6,346	0	0	0
12/01/2023 01:50	2.66	-4.79	-0.19	2,135	555,466	2,407	0	600,785
12/01/2023 07:50	-2.13	5.19	0.23	1,491	197,648	0	868	196,534
12/01/2023 14:00	3.06	-5.45	-0.22	3,067	656,160	3,534	0	725,953
12/01/2023 20:30	-2.39	4.85	0.22	1,419	15,601	0	1,247	23,192
13/01/2023 02:20	2.46	-4.40	-0.19	1,642	202,904	1,651	0	324,480
13/01/2023 08:30	-1.94	4.81	0.21	1,567	311,617	0	1,198	291,771
13/01/2023 14:40	2.87	-5.07	-0.21	2,629	544,775	2,851	0	587,662
13/01/2023 21:10	-2.20	4.48	0.20	1,194	271,234	0	-417	258,840
14/01/2023 03:10	2.28	-4.05	-0.17	1,450	241,609	1,991	0	473,979
14/01/2023 09:20	-1.77	4.45	0.20	1,221	-13,966	0	765	116,442
14/01/2023 15:20	2.68	-4.73	-0.19	2,149	296,796	1,789	0	432,933
14/01/2023 22:00	-2.05	4.19	0.19	875	219,580	0	499	208,512
15/01/2023 04:00	2.14	-3.76	-0.16	1,425	248,008	1,830	0	347,189
15/01/2023 10:10	-1.62	4.12	0.18	1,174	20,963	0	1,087	127,530
15/01/2023 16:20	2.50	-4.39	-0.18	1,801	413,389	1,997	0	453,305
15/01/2023 22:50	-1.89	3.94	0.17	1,020	73,964	0	897	133,071
16/01/2023 05:00	2.05	-3.58	-0.15	1,069	137,856	777	0	251,417
16/01/2023 11:10	-1.53	3.92	0.17	1,018	153,657	0	849	155,360
16/01/2023 17:20	2.39	-4.24	-0.17	1,712	257,079	1,568	0	330,945
17/01/2023 00:00	-1.85	3.96	0.17	1,047	158,476	0	943	164,037
17/01/2023 06:10	2.11	-3.72	-0.15	1,126	199,415	1,298	0	226,456
17/01/2023 12:20	-1.61	4.04	0.18	959	158,798	0	1,117	192,501
17/01/2023 18:30	2.43	-4.38	-0.18	1,724	190,443	1,793	0	245,060
18/01/2023 01:10	-1.95	4.32	0.19	861	116,979	0	513	67,964
18/01/2023 07:20	2.37	-4.27	-0.17	1,682	187,312	1,460	0	208,488
18/01/2023 13:40	-1.90	4.56	0.20	1,247	224,822	0	1,030	236,639
18/01/2023 19:40	2.66	-4.87	-0.20	2,322	356,198	2,383	0	389,669
19/01/2023 02:10	-2.21	5.01	0.22	1,726	289,079	0	1,756	353,950
19/01/2023 08:20	2.80	-5.15	-0.21	2,832	368,543	2,899	0	484,513
19/01/2023 14:40	-2.35	5.36	0.23	1,948	237,498	0	2,458	317,819
19/01/2023 20:50	3.01	-5.56	-0.23	3,235	401,497	2,811	0	381,416
20/01/2023 03:10	-2.55	5.85	0.26	2,251	546,533	0	-2,369	534,383
20/01/2023 09:20	3.30	-6.16	-0.25	4,100	557,678	3,874	0	612,511
20/01/2023 15:50	-2.86	6.27	0.28	2,615	437,750	0	2,368	413,748
20/01/2023 21:50	3.41	-6.33	-0.26	4,088	409,210	3,719	0	464,268
21/01/2023 04:10	-2.92	6.73	0.30	2,349	457,813	0	2,801	543,125
21/01/2023 10:10	3.81	-7.15	-0.28	5,363	693,787	5,355	0	742,190
21/01/2023 16:50	-3.34	7.10	0.32	2,925	489,608	0	3,379	576,663
21/01/2023 22:40	3.76	-6.99	-0.29	5,085	739,828	4,766	0	741,723
22/01/2023 05:00	-3.23	7.45	0.33	3,172	464,403	0	2,772	401,202
22/01/2023 11:00	4.22	-7.91	-0.32	5,730	918,517	6,320	0	1,094,139
22/01/2023 17:30	-3.69	7.67	0.34	3,347	412,990	0	3,470	428,706
22/01/2023 23:30	3.98	-7.39	-0.30	4,996	561,614	4,345	0	501,945

5.14 Summary

The simplified model works reasonably well to maximise the generation but does not come close to maximising the revenue which is related to demand and price fluctuations. The half hourly prices appear to vary randomly which is probably due to the availability of wind and sunlight. The demand led model demonstrates how the flows can be modified to help match the electricity demand which maximising the income at the same time. This can be used to help stabilise the grid. The benefit will be greater during periods of fluctuating demand, i.e. high standard deviation of price.

6 ECONOMICS OF TIDAL RANGE

Economics of tidal range has been investigated and published in three papers as follows:

- A model of the costs for tidal range power generation schemes (Vandercruyssen et al., 2022a) gives an approximate CAPEX cost model for tidal range schemes and was developed by updating a previous study from MIT (Fay and Smachlo, 1983). It has been benchmarked against the total CAPEX of Lake Sihwa. The costs are estimate under five major components:-

  - Turbo-generating equipment
  - Powerhouse
  - Sluices
  - Cofferdam
  - Bund

  Lake Sihwa was built into an existing bund so excluded the bund cost element. Alternative designs were considered and costs estimated as reported in (Vandercruyssen et al., 2024).

- Tidal range generation: combining the Lancaster zero-dimension generation and cost models (Vandercruyssen et al., 2023a) uses the economic model proposed in the previous paper to examine the CAPEX for the two case study schemes of Morecambe Bay and the North Wales coastal lagoon. It highlights the generator ratings giving the best value of generation/CAPEX.

- Economic methods for the selection of renewable energy sources, a case study (DiLellio et al., 2025) includes an explanation of the levelised cost of energy (LCOE) for 10 forms of generation.

  - Seven of them use UK government figures,
  - there is also an update of nuclear based on published rising construction costs for Hinkley Point C,
  - estimates have been made of the two tidal range schemes in this case study.

The paper gives a critical review of LCOE and proposes a new sustained cost of energy (SCOE) over continuous generation for 120-years. An analysis by internal rate of return is also included.

The last paper stems from previous experience in estimating the most economic form of bridges. All new bridges had to consider several alternative forms of construction and compare their net present values (NPV). NPV analysis was required by the Department of Transport at the time for *approval in principle* process. The NPV method required the costs of construction (CAPEX) and maintenance (OPEX) to be tabulated for each year of the standard design life of 120 years. Invariably the lowest NPV came from the lowest CAPEX and the subsequent OPEX could be more than the other alternatives. This may be satisfactory for a single bridge, but the country requires several hundred new and replacement bridges every year for the foreseeable future. The NPV method is storing up higher maintenance costs for future generations. For renewable energy schemes a similar metric LCOE is being widely used. This is discussed in detail in (DiLellio et al., 2025) but the full spreadsheets were not included in the paper but are included in Appendix A.2 and are shown below.

Table 6-1 shows the CAPEX & OPEX cost used to derive LCOE for a nuclear plant commissioning in 2030. The assumptions are taken from government published figures except that the CAPEX has been increased to reported construction costs.

Table 6-1 Extract of LCOE for nuclear from spreadsheet located in Appendix A.2.

Levelised Cost Of Energy	Units	Value	Nuclear PWR, Lancaster assessment, commissioning in 2030
Reference plant size	MW	3,260	
Turbine size	MW	1,630	
Average load factor	%	90%	
Hours per year	hours	8,760	
Annual Electricity Production (AEP)	MWh	25,701,840	
Operating lifetime	years	60	
Pre-development cost	£/kW	240	
Pre-development period	years	5	
pre-development phasing	year	1	2 3
%	%	20%	20% 20%
Construction cost	£/kW	14,110	
Construction period	years	10	
Construction phasing %	year	1	2 3 6 7 8 9
	%	5%	5% 13% 13% 13% 13% 5%
Infrastructure	£k	17,300	
Fixed O&M	£/MW/year	72,900	
Insurance	£/MW/year	11,500	
Connection and use of system charges	£/MW/year	500	
Variable O&M	£/MWh	5	
Fuel price	£/MWh	5	
Average fuel efficiency (LHV)	%	100%	
Carbon	£/MWh	0	
Decommisioning & Demolition	£/kW	19	
Hurdle/ discount rate	%	10.0%	
Technology level	MW	NOAK	

				Pre-development			Construction		Construction		Operation & Maintenance		
			Year	2015	2018	2019	2020	2021	2028	2029	2030	2031	2032
			Discount factor	1.00	0.751	0.683	0.621	0.564	0.290	0.263	0.239	0.218	0.198
Discounted generation	MWh	67,478,903									6,152,816	5,593,469	5,084,972

	Total discounted costs £m	LCOE £/MWh	2015	2018	2019	2020	2021	2028	2029	2030	2031	2032
Total Pre-development	652.50	9.67		156.48	117.57	106.88						
Total Construtiion (incl infrastructure)	19,039.12	282.15					1,428	1,298	666	606		
Fixed O&M (incl Insurance, connection & UofS)	726.66	10.77									66.3	60.2	54.8
Variable O&M	337.39	5.00									30.8	28.0	25.4
Fuel costs	337.39	5.00									30.8	28.0	25.4
Carbon	0.00	0.00									0	0	0
waste processing & decommissioning	162.62	2.41									14.8	13.5	12.3
Totals	21,255.68	315.00		156	118	107	1,428	1,298	666	606	143	130	118

Table 6-2 shows extract of the calculation for the sustained cost of energy (SCOE) for 10 generation options. Which are based on 120-years of continuous generation from each type, i.e. two consecutive nuclear plants or four consecutive CCGTs etc.

Table 6-2 Extract of SCOE from spreadsheet located in Appendix A.2 with 2% inflation per annum.

Technology	AEP MWh		Total cost lifetime £m	£/MWh	Construction years 2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	Operation & Maintenance years 2030	2031	2032	2033
					1.000	1.000	1.000	1.000	1.020	1.040	1.061	1.082	1.104	1.126	1.149	1.172	1.195	1.219
North Wales Tidal Lagoon	4,478,204	Base costs	18,377	34				855	855	855	855	855	855	570	47	47	47	47
		1st Plant	61,331	114				855	872	890	908	926	944	642	54	55	56	57
Morecambe Bay Esturaine Barrage	7,178,894	Base costs	24,181	28				1,050	1,050	1,050	1,050	1,050	1,050	700	71	71	71	71
		1st Plant	82,856	96				1,050	1,071	1,093	1,115	1,137	1,160	789	81	83	85	86
Nuclear PWR	AEP (MWh) 25,701,840	Base costs	60,492	39	2,300	2,300	6,118	6,118	6,118	6,118	6,118	6,118	2,300	2,300	277	277	277	277
		1st Plant	82,689	116	2,300	2,300	6,118	6,118	6,240	6,365	6,493	6,622	2,539	2,590	318	324	331	337
	operating yrs 60	2nd Plant	276,372															
Offshore wind	AEP (MWh) 5,694,000	Base costs	4,293	25									732	732	94	94	94	94
		1st Plant	6,027										808	825	108	110	113	115
	operating yrs 30	2nd Plant	10,917	106														
		3rd plant	19,775															
		4th plant	35,819															
Floating Offshore wind	AEP (MWh) 5,645,645	Base costs	6,523	39								1,296	1,296	494	115	115	115	115
		1st Plant	8,730									1,403	1,431	556	132	134	137	140
	operating yrs 30	2nd Plant	15,813	155														
		3rd plant	28,643															
		4th plant	51,882															
CCGT H Class	AEP (MWh) 9,776,160	Base costs	39,115	133								290	290	145	1,280	1,280	1,280	1,280
		1st Plant	60,430									314	321	163	1,470	1,499	1,529	1,560
	operating yrs 30	2nd Plant	109,460	620														
		3rd plant	198,272															
		4th plant	359,142															
Hydrogen CCGT	AEP (MWh) 9,776,160	Base costs	32,259	110								339	339	169	963	963	963	963
		1st Plant	50,618									367	374	191	1,106	1,128	1,150	1,173
	operating yrs 30	2nd Plant	91,687	519														
		3rd plant	166,078															
		4th plant	300,827															
Tidal Stream	AEP (MWh) 64,824	Base costs	146	90							18	18	18	18	3	3	3	3
		1st Plant	187								19	19	20	20	3	3	4	4
	operating yrs 25	2nd Plant	307															
		3rd plant	504	385														
		4th plant	828															
		5th plant	1,168															
Wave	AEP (MWh) 23,652	Base costs	67	142									19	19	1	1	1	1
		1st Plant	83										21	22	2	2	2	2
	operating yrs 20	2nd Plant	123															
		3rd plant	182	585														
		4th plant	271															
		5th plant	403															
		6th plant	599															
Large scale solar	AEP (MWh) 19,272	Base costs	15	22										7.4	0.2	0.2	0.2	0.2
		1st Plant	21											8.3	0.2	0.2	0.3	0.3
	operating life 35	2nd Plant	41	106														
		3rd plant	82															
		4th plant	100															

Table 6-2 Continued.

Technology		Operation & Maintenance years														Operation & Maintenance years				
		2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057	2058	2059	2060	2145	2146	2147	2148	2149
		1.608	1.641	1.673	1.707	1.741	1.776	1.811	1.848	1.885	1.922	1.961	2.000	2.040	2.081	11.200	11.424	11.653	11.886	12.123
North Wales Tidal Lagoon	Base costs	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47
	1st Plant	75	77	78	80	81	83	85	86	88	90	92	93	95	97	524	534	545	556	567
Morecambe Bay Esturaine Barrage	Base costs	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71
	1st Plant	114	116	118	121	123	126	128	131	133	136	139	142	144	147	793	809	825	841	858
Nuclear PWR	Base costs	277	277	277	277	277	277	277	277	277	277	277	277	277	277					
	1st Plant	445	454	463	472	482	492	501	511	522	532	543	554	565	576					
	2nd Plant															3,100	3,162	3,225	3,290	3,355
Offshore wind	Base costs	94	94	94	94	94	94	94	94	94	94	94	94	94						
	1st Plant	152	155	158	161	164	167	171	174	178	181	185	189	192						
	2nd Plant												1,464	1,494	196					
	3rd plant																			
	4th plant															1,056	1,077	1,099	1,121	1,143
Floating Offshore wind	Base costs	115	115	115	115	115	115	115	115	115	115	115	115	115						
	1st Plant	184	188	192	196	200	204	208	212	216	220	225	229	234						
	2nd Plant											2,541	2,592	1,007	238					
	3rd plant																			
	4th plant															1,284	1,309	1,335	1,362	1,389
CCGT H Class	Base costs	1,280	1,280	1,280	1,280	1,280	1,280	1,280	1,280	1,280	1,280	1,280	1,280	1,280						
	1st Plant	2,058	2,099	2,141	2,184	2,228	2,272	2,318	2,364	2,412	2,460	2,509	2,559	2,610						
	2nd Plant											569	581	296	2,663					
	3rd plant																			
	4th plant															14,332	14,619	14,911	15,209	15,514
Hydrogen CCGT	Base costs	963	963	963	963	963	1,279	1,279	1,279	1,279	1,279	1,279	1,279	1,279						
	1st Plant	1,548	1,579	1,611	1,643	1,676	2,272	2,318	2,364	2,411	2,459	2,509	2,559	2,610						
	2nd Plant											664	677	345	2,003					
	3rd plant																			
	4th plant															14,330	14,617	14,909	15,207	15,511
Tidal Stream	Base costs	3	3	3	3	3	3	3	3											
	1st Plant	5	5	5	5	5	5	5	5											
	2nd Plant					31	32	33	33	6	6	6	6	6	6					
	3rd plant																			
	4th plant																			
	5th plant															33	34	34	35	36
Wave	Base costs	1	1	1																
	1st Plant	2	2	2																
	2nd Plant		32	33	2	2	2	3	3	3	3	3	3	3	3					
	3rd plant																			
	4th plant																			
	5th plant																			
	6th plant															16	16	16	17	17
Large scale solar	Base costs	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2					
	1st Plant	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4					
	2nd Plant																			
	3rd plant																			
	4th plant															2.4	2.4	2.5	2.5	2.6

In

Table 6-2 the base cost is the estimated CAPEX and OPEX for the first scheme constructed. For any subsequent replacements within the 120-year period the base costs are index linked to the assumed inflation rate. For example, the second nuclear PWR plant will need to start construction in 2145 to maintain continuous generation after the first plant has life expired.

The internal rate of return (IRR) is the discount rate that makes an investment's net present value (NPV) of cash flows equal to zero, estimating its annual growth rate. Table 6-3 shows the IRR for all 10 generating options, see the third column. See appendix A.2 for a copy of the full spreadsheet. The future assumed inflation rate can be set to see how the figures change under different scenarios. The main conclusion is that the ranking for longer lived forms of generation is better reflected in the sustainable cost of energy (SCOE) (DiLellio et al., 2025) and IRR methods of analysis than the levelised cost of energy (LCOE).

Table 6-3 Extract of IRR analysis from spreadsheet located in Appendix A.2.

Cost of electricity Average since 2020 £/MWh	120		Inflation rate	2.0%														

Technology	AEP MWh	Internal rate of return		lifetime costs £m	Construction years										Operation & Maintenance years			
					2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
					1.000	1.000	1.000	1.000	1.020	1.040	1.061	1.082	1.104	1.126	1.149	1.172	1.195	1.219
North Wales Tidal Lagoon	4,434,750	9.0%	Total base costs	18,377				855	855	855	855	855	855	570	47	47	47	47
			Indexed costs	-61,331				-855	-872	-890	-908	-926	-944	-642	-54	-55	-56	-57
			Indexed revenue	298,776										306	611	624	636	649
			Balance	237,445				-855	-872	-890	-908	-926	-944	-337	558	569	580	592
Morecambe Bay Esturaine Barrage	7,113,120	10.9%	Total base costs	24,181				1,050	1,050	1,050	1,050	1,050	1,050	700	71	71	71	71
			Indexed costs	-82,856				-1,050	-1,071	-1,093	-1,115	-1,137	-1,160	-789	-81	-83	-85	-86
			Indexed revenue	479,222										490	980	1,000	1,020	1,041
			Balance	396,366				-1,050	-1,071	-1,093	-1,115	-1,137	-1,160	-298	899	917	936	954
North Wales Tidal Lagoon with flood protection	4,434,750	12.0%	Total base costs	18,377				855	855	855	855	855	855	570	47	47	47	47
			Indexed costs	-61,331				-855	-872	-890	-908	-926	-944	-642	-54	-55	-56	-57
			Indexed revenue	438,572										449	897	915	934	952
			Balance	377,241				-855	-872	-890	-908	-926	-944	-194	844	860	878	895
Morecambe Bay Esturaine Barrage with flood protection	7,113,120	13.2%	Total base costs	24,181				1,050	1,050	1,050	1,050	1,050	1,050	700	71	71	71	71
			Indexed costs	-82,856				-1,050	-1,071	-1,093	-1,115	-1,137	-1,160	-789	-81	-83	-85	-86
			Indexed revenue	619,018										633	1,267	1,292	1,318	1,344
			Balance	536,161				-1,050	-1,071	-1,093	-1,115	-1,137	-1,160	-155	1,185	1,209	1,233	1,258
Nuclear PWR	25,701,840	7.7%	Total base costs	122,730	2,300	2,300	6,118	6,118	6,118	6,118	6,118	6,118	2,300	2,300	277	277	277	277
			Indexed costs	147,741	-2,300	-2,300	-6,118	-6,118	-6,240	-6,365	-6,493	-6,622	-2,539	-2,590	-318	-324	-331	-337
			Indexed revenue	1,729,801											3,543	3,614	3,686	3,760
			Balance	1,875,242	-2,300	-2,300	-6,118	-6,118	-6,240	-6,365	-6,493	-6,622	-2,539	-2,590	3,225	3,289	3,355	3,422
Offshore wind	5,694,000	37.0%	Total base costs	17,172	0	0	0	0	0	0	0	0	732	732	94	94	94	94
			Indexed costs	-72,538									-808	-825	-108	-110	-113	-115
			Indexed revenue	383,221											785	801	817	833
			Balance	310,683									-808	-825	677	690	704	718
Floating Offshore wind	5,645,645	17.3%	Total base costs	26,094	0	0	0	0	0	0	0	1,296	1,296	494	115	115	115	115
			Indexed costs	-105,067								-1,403	-1,431	-556	-132	-134	-137	-140
			Indexed revenue	379,967											778	794	810	826
			Balance	274,899								-1,403	-1,431	-556	647	659	673	686
CCGT H Class	9,776,160	#NUM!	Total base costs	156,461	0	0	0	0	0	0	0	290	290	145	1,280	1,280	1,280	1,280
			Indexed costs	-727,303								-314	-321	-163	-1,470	-1,499	-1,529	-1,560
			Indexed revenue	657,961											1,348	1,375	1,402	1,430
			Balance	-69,342								-314	-321	-163	-122	-125	-127	-130
Hydrogen CCGT	9,776,160	21.8%	Total base costs	129,037	0	0	0	0	0	0	0	339	339	169	963	963	963	963
			Indexed costs	-609,209								-367	-374	-191	-1,106	-1,128	-1,150	-1,173
			Indexed revenue	657,961											1,348	1,375	1,402	1,430
			Balance	48,752								-367	-374	-191	242	247	252	257
Tidal Stream	64,824	8.0%	Total base costs	696	0	0	0	0	0	0	18	18	18	18	3	3	3	3
			Indexed costs	-2,975							-19	-19	-20	-20	-3	-3	-4	-4
			Indexed revenue	4,363											9	9	9	9
			Balance	1,387								-19	-20	-20	6	6	6	6
Wave	23,652	-0.7%	Total base costs	402	0	0	0	0	0	0	0	0	19	19	1	1	1	1
			Indexed costs	-1,661									-21	-22	-1.6	-2	-2	-2
			Indexed revenue	1,592											3.3	3	3	3
			Balance	-69									-21	-22	1.6	2	2	2
Large scale solar	19,272	30.9%	Total base costs	55	0	0	0	0	0	0	0	0	0	7	0	0	0	0
			Indexed costs	-244										-8	-0.2	0	0	0
			Indexed revenue	1,297											2.7	3	3	3
			Balance	1,053										-8	2.4	2	3	3

6.1 Electricity demand & prices

Total electricity consumption in the UK increased by 233% between 1965 and 2005 as shown in Figure 6-1. Since 2005 it has decreased gradually, partly due to the decline in manufacturing and record high annual average temperature (UK Gov Digest of UK Energy Statistics (DUKES), 2024a).
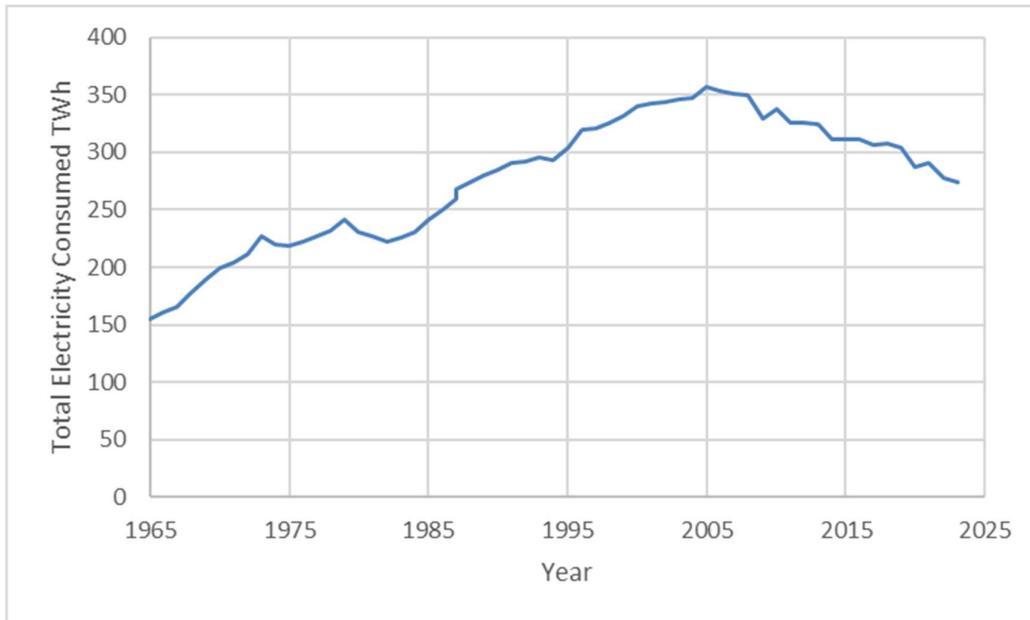

Figure 6-1 Total annual electricity consumption from 1965 to 2023 from (UK Gov Digest of UK Energy Statistics (DUKES), 2024b).

6.2 Variations in Demand

Electricity demand in the UK is constantly changing. The UK National Grid is charged with maintaining adequate generation capacity to meet all conceivable demands on the electricity system. The main factures which affect demand are:-

- Daily cycle
- Weekly cycle
- Seasonal cycle
- Long-term trends

The traditional daily cycle shows low demand at night, rising in the morning for breakfast. There are slight peaks in demand around lunchtimes and the highest demand in early evening.

The weekly cycle is changing from the traditional 5-day working week, most shops and many businesses are now open 7-days a week. Internet shopping is increasing rapidly and requires 24-hour, 7-days a week warehouse operation and transport.

The seasonal cycle is related to the reduced daylight hours and lower average temperatures in winter. The highest demand in the UK is during the winter even though only a small proportion of electricity is used for heating. In hotter countries the peak season can occur in the summer due to the extensive use of air conditioning. Figure 6-2 from (Aggidis and Benzon, 2013) shows a polynomial curve fit to the UK demand for the whole of 2009.
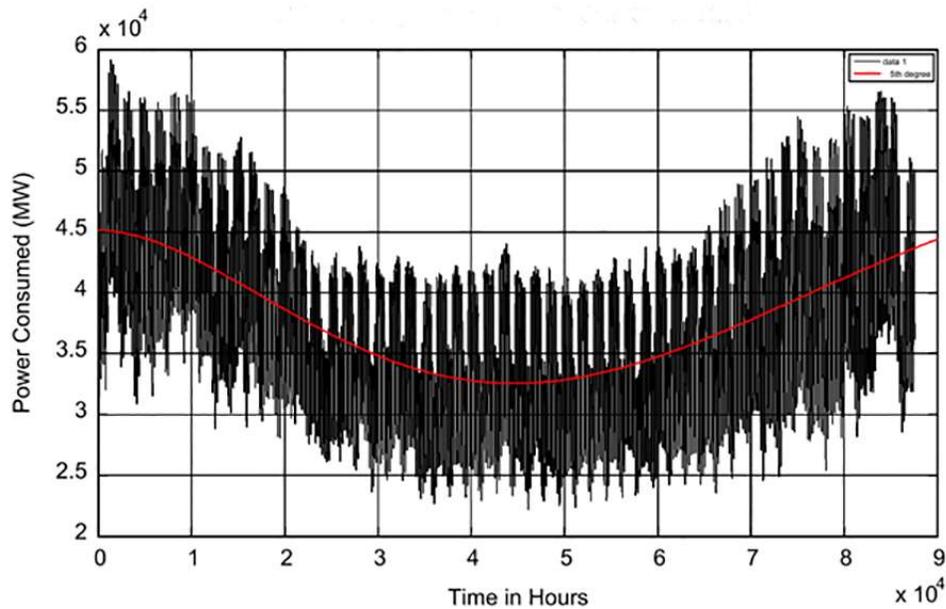
Figure 6-2 Annual electricity consumption for the whole of 2009 (Aggidis and Benzon, 2013).

Long term trends are due to the rising development of technology in countries throughout the world. Generally increasing demand, possibly following the UK's 73 times increase in 98-years as stated

above. The UK's current intention to move away from fossil fuels for heating and transport is going to produce an unprecedented increase in demand for electricity, possibly fivefold (Amble, 2023). If battery cars become significant it is assumed that the bulk of charging will occur during evenings and overnight.

6.3   Wholesale Price

Prior to privatisation of the electricity industry in 1990 the UK Central Electricity Generating Board (CEGB) was a publicly owned body which set the price of electricity, planned, and built the power stations and distribution networks. Since privatisation there is a free market in pricing. Initially the six main generating companies bid prices to the National Grid and were paid for the power accepted at the highest price bid for half-hour slots. As demand increases the less efficient power stations would be brought online, increasing the price. The market was further opened to competition by allowing non-generating companies to block purchase electricity at a future date and price (forwards market), then sell directly to consumers. This was a purely financial arrangement and worked until the 2021 Covid-19 pandemic when several of these non-generating companies were bankrupted and the government had to step in to pay the generating companies to take on the displaced customers (The Times, 2021).

Also, the price was linked to the cost of fuels such as coal, oil and petroleum gas. The use of coal has now stopped in the UK and oil is used only in emergencies. The gas price can be volatile. As renewable energy increases the price is less dependent on gas but is linked to the gap between demand and the availability of renewable energy. Mainstream renewable energy is intermittent whether from wind, solar or tides.

Half-hourly electricity prices are given on the Elexon website (Elexon, 2025). These could be incorporated into the generation model to optimise financial return. The prices can be downloaded as spreadsheet files. The average half hourly sell price from recent years is summarised in Table 5-13 as the average for each slot throughout the year, shown graphically in Figure 6-3.
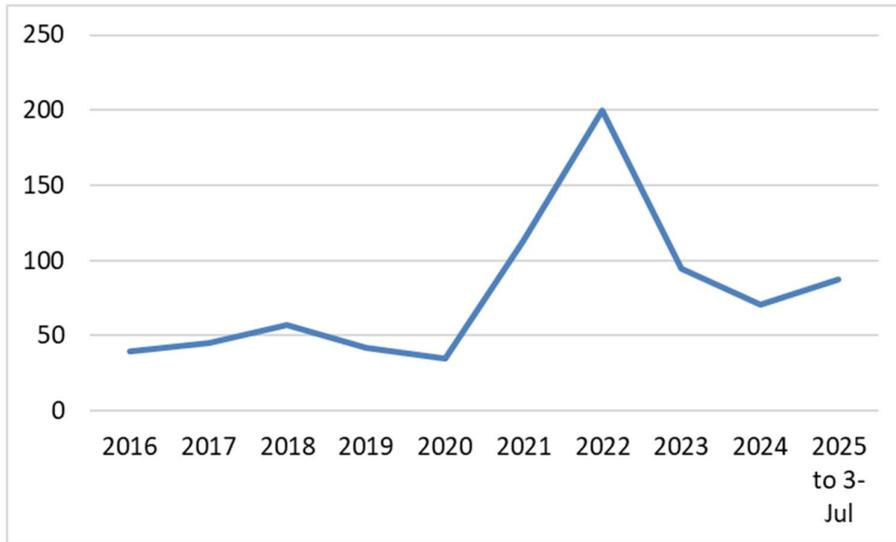
Figure 6-3 Annual mean price of electricity in £/MWh.

March 2020 was the start of the Covid-19 world pandemic, with the peak occurring in 2021, electricity demand reduced significantly as offices and manufacturing was shut down for many weeks. By 2022 there was a post Covid-19 recovery but also the outbreak of the Russian invasion into Ukraine, and the associated instability in the oil and gas markets. Although the electricity price has stabilised, it is still running at nearly triple the average price between 2016 and 2020. The average price since 2020 is currently £113/MWh and the maximum price so far for 2025 (£2,900/MWh) exceeds the figures for 2023 and 2024.

Figure 6-4 is produced from the Elexon data for 2018 and shows the average monthly prices for electricity for each month of the year over a 24-hour period. The orange line represents the average price during March 2018. During the day it is mostly within the range of £80-£100/MWh. This was the time of a severe cold period called "The Beast from the East". There was very little wind generation at a time and high demand. However, the peak price for a half hour slot was £1,000/MWh. There were also concerns that the availability of gas for generation was also becoming critical. Old coal fired power stations (including Aberthaw, near Cardiff) were called into service to maintain electricity supplies.
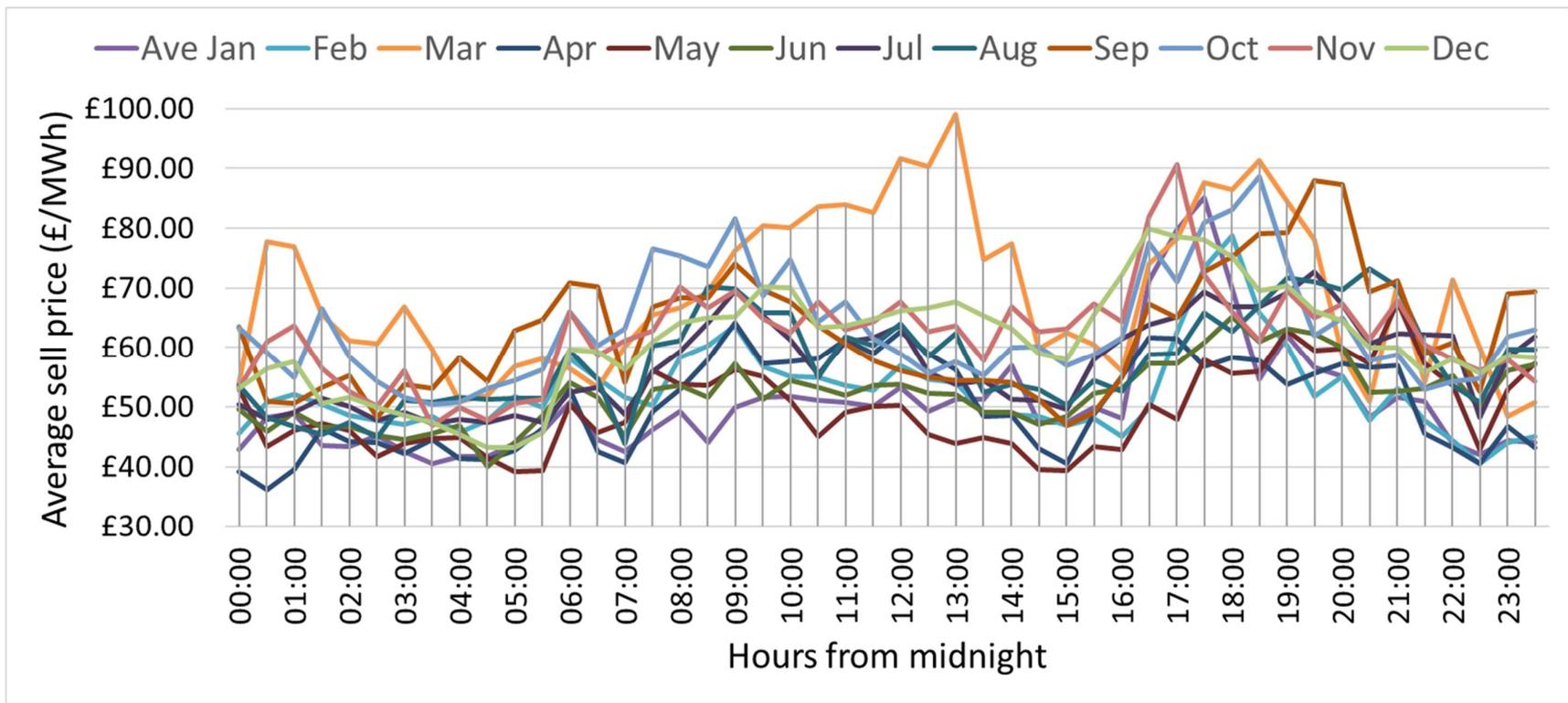
Figure 6-4 Average monthly sell price for 2018 in half-hour slots, data from (Elexon, 2025).

The price in recent years has been driven by the cost of fuel (coal and gas) and the availability of wind power. As the use of fossil fuels declines and wind generation and demand increase changes may be expected.

Figure 6-5 shows the dramatic average, minimum and maximum prices in 2021 which is mostly due to a doubling of gas prices. The maximum price can also be affected by lack or wind or light or equipment failure. Cost/benefit analysis requires an estimate of the price for the next 40-years or more and is normal for a power generation scheme. The actual variance can often be more than the variation in the cost of construction.
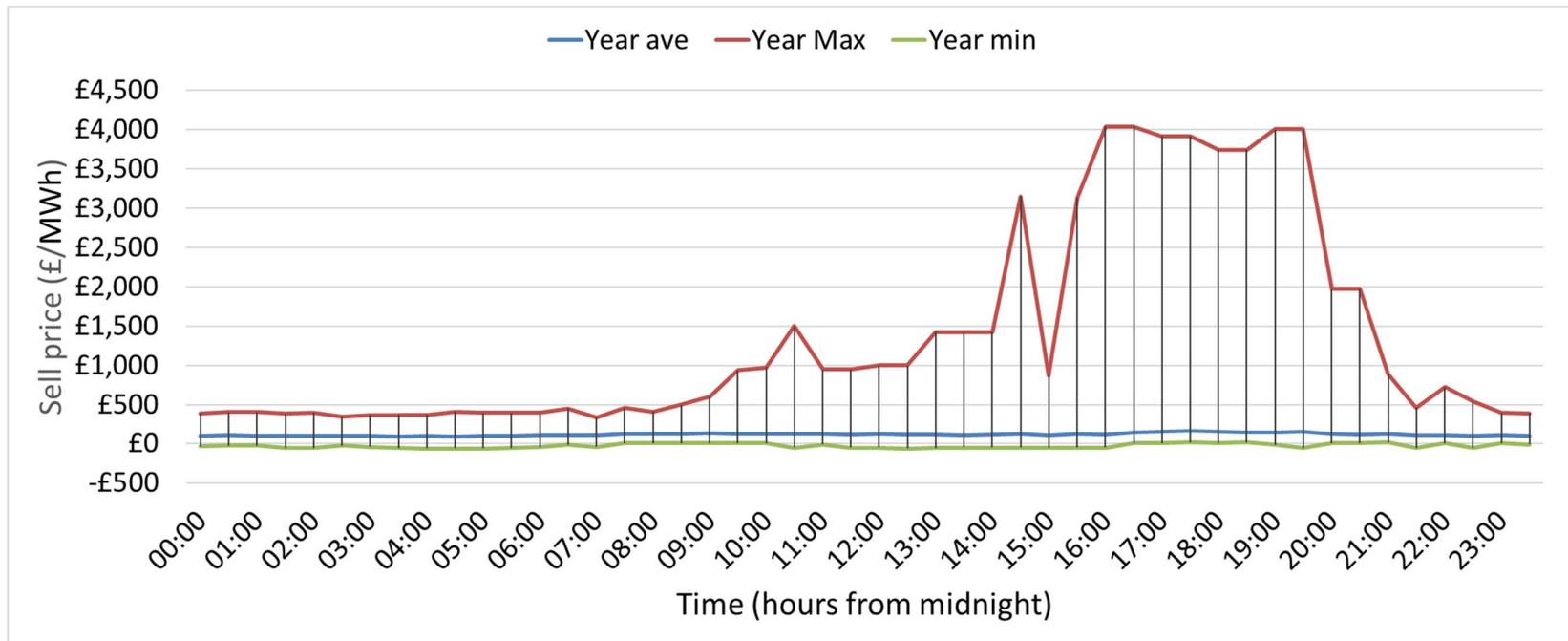
Figure 6-5 Maximum, average and minimum sell price for 2021 in half-hour slots.

Figure 6-6 shows the average monthly prices for 2022 which is the highest annual average price on record and was mostly due to the restrictions on the use of Russian gas and the high wholesale prices charged, see gas price in Figure 2-25.
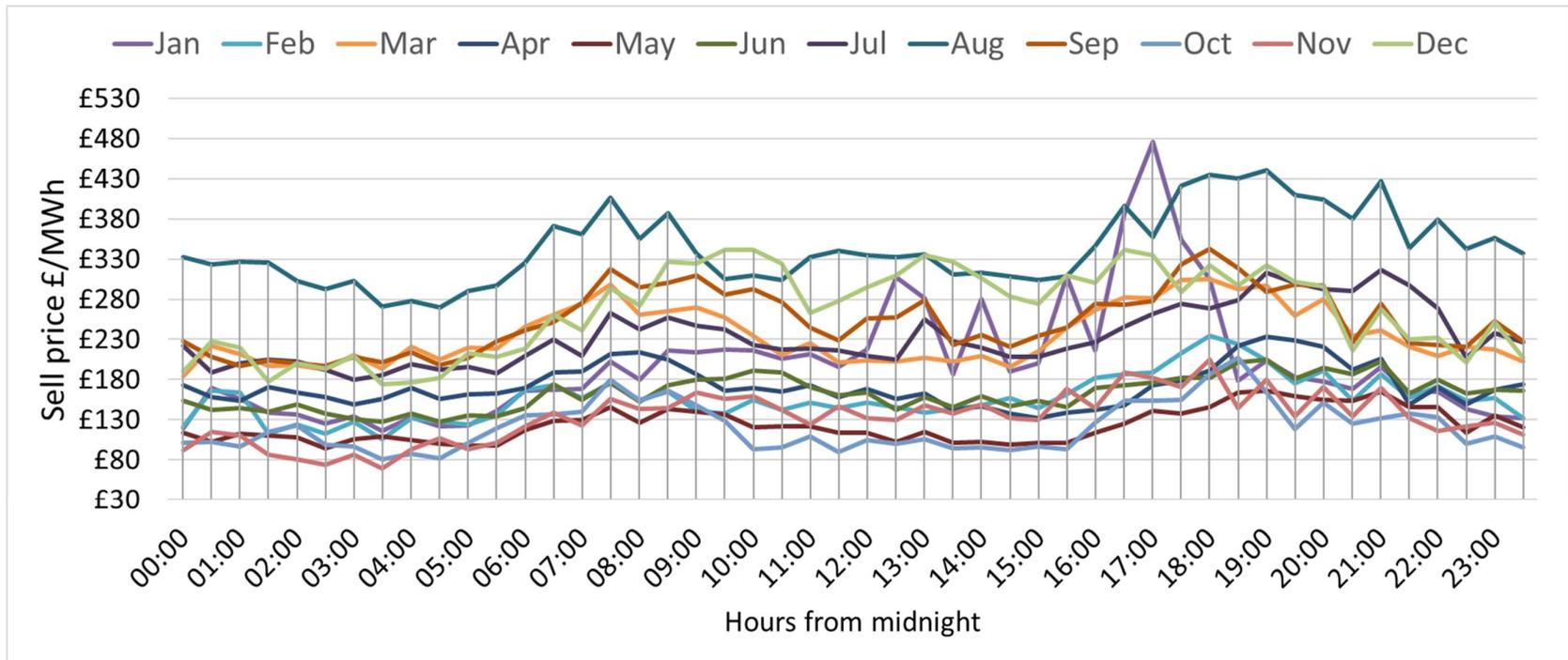
Figure 6-6 Average monthly sell price for 2022 in half-hour slots.

Whilst there is a lot of variation the higher prices tend to occur between 17:00 hours and 21:00 hours. There is a smaller high price period around 06:00 to 10:00 hours. Both these match domestic times for evening meals and breakfast. The winter period from December to February also has high demand due to shorter daylight hours and increased heating.

The year average, maximum and minimum price for 2022 is shown in Figure 6-7. The maximum price is going to be increasingly dependent on any shortages in renewable energy, mainly wind and solar, as the proportion of renewable generation increases. However unexpected short term high prices can be due to equipment failure or fires. Any estimates of generation income should not be based on peak prices. It is more reliable to use average prices but also consider the standard deviation of the average.
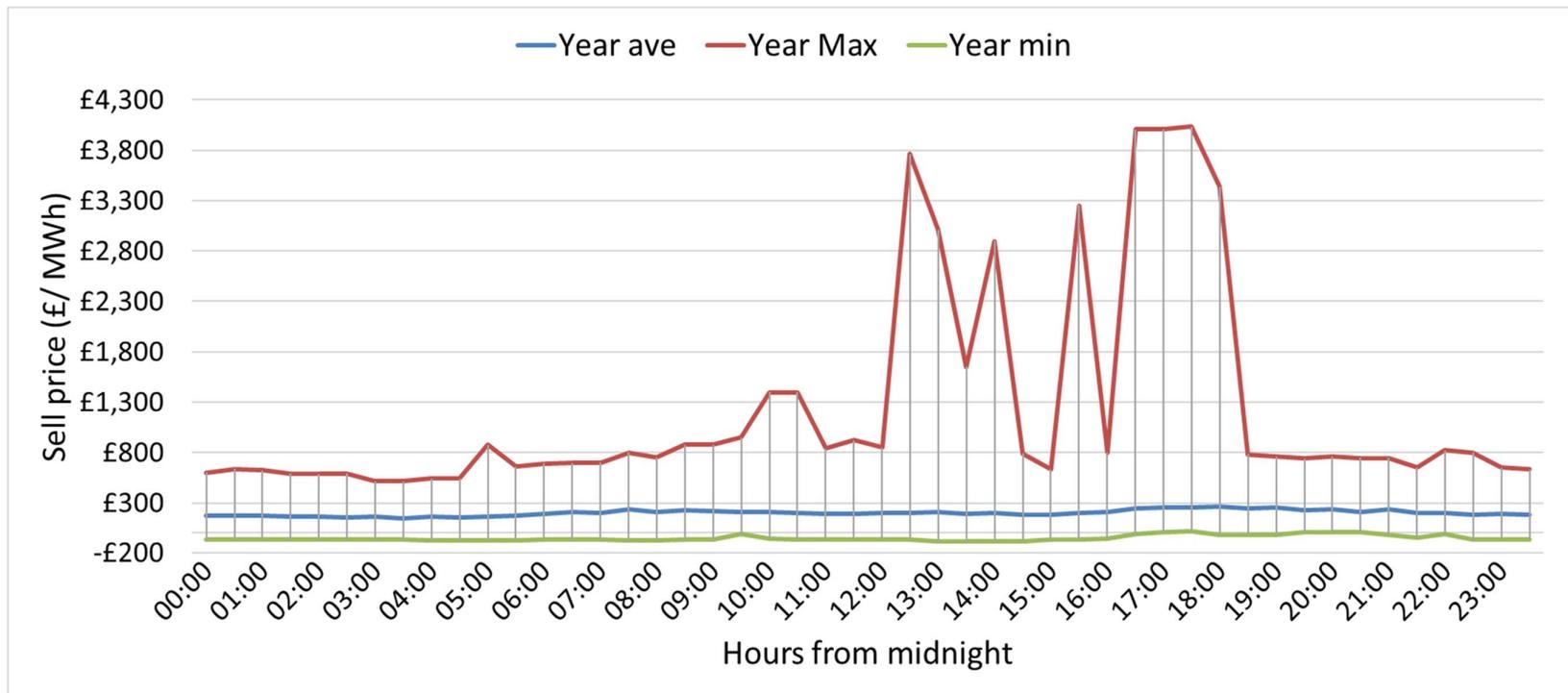
Figure 6-7 Maximum, average and minimum sell price for 2022 in half-hour slots.

Figure 6-8 shows the average monthly sell price for 2024 for each half-hour throughout the day. There is an obvious rise in October to December figures which reflects rising gas prices and the greater demand in the winter.
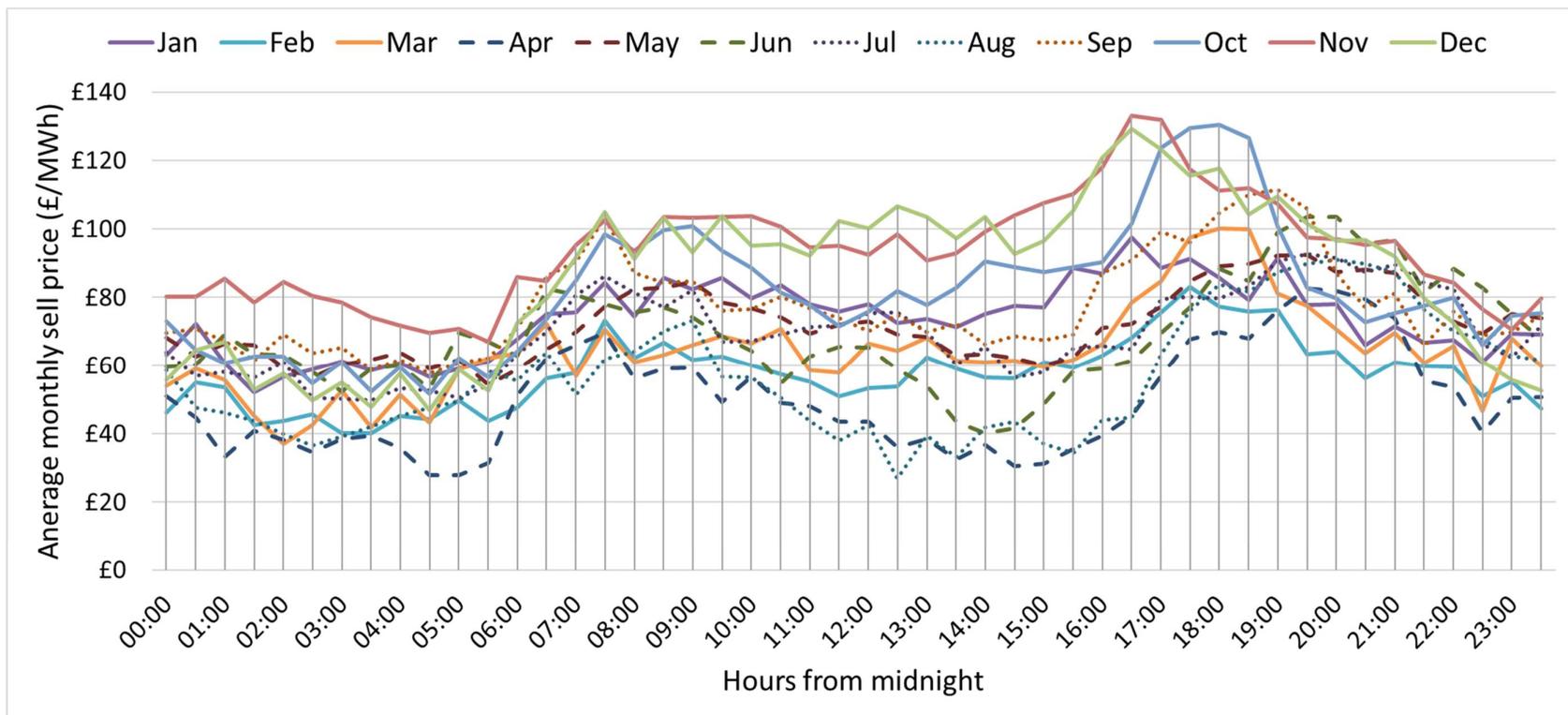
Figure 6-8 Average UK monthly sell price for MWh of electricity 2024 in half-hour slots, adapted from (Elexon, 2025).

The red line in Figure 6-9 represents the maximum sell price for each half hour slot in 2024 and the three peaks of early morning, lunchtime and early evening are clearly visible. This is when demand is greatest but is likely to change in future by the development of smart pricing and nighttime charging of batteries.
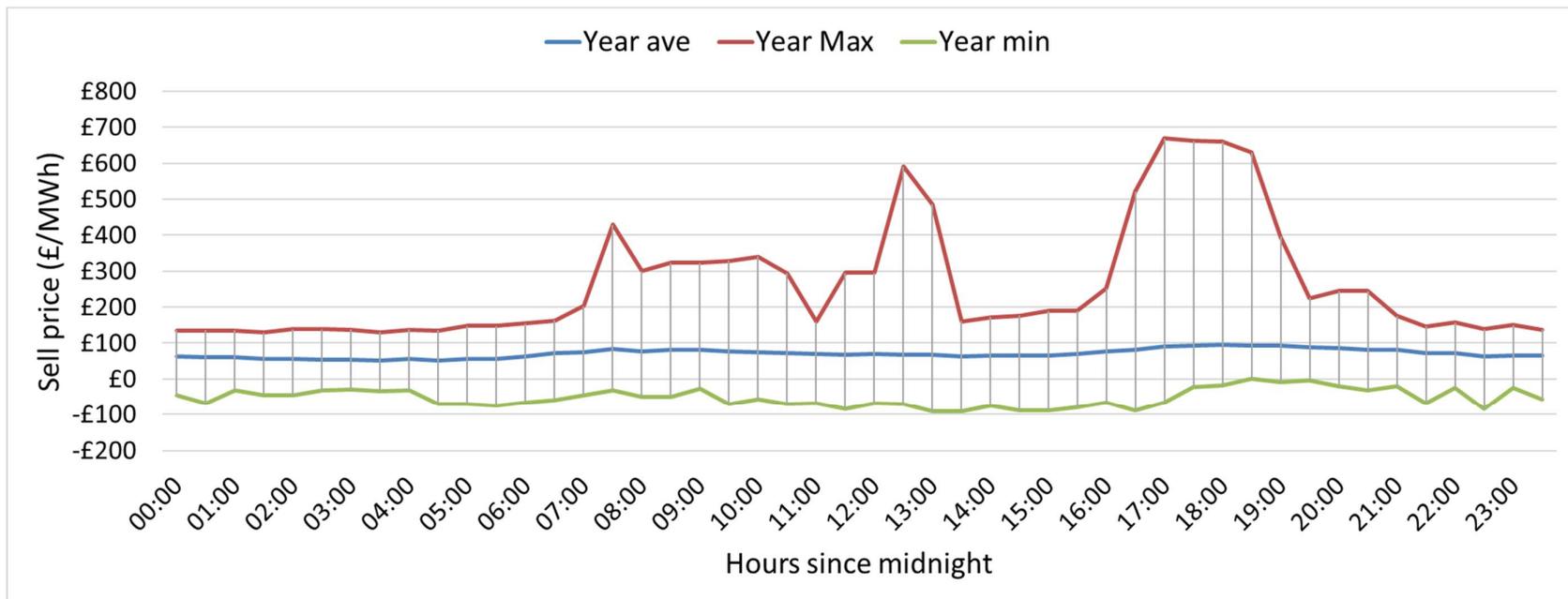
Figure 6-9 Maximum sell price for 2024 in half-hour slots.

The UK government's stated intention of phasing out natural gas is certainly not going to reduce electricity prices in the future.

6.4 Economic methods for comparing renewable energy schemes.

Another output from this study (DiLellio et al., 2025) investigated the levelised cost of energy (LCOE) which is being used to compare different generation technologies. It highlighted several problems when used to compare technologies with vastly different operating lives.
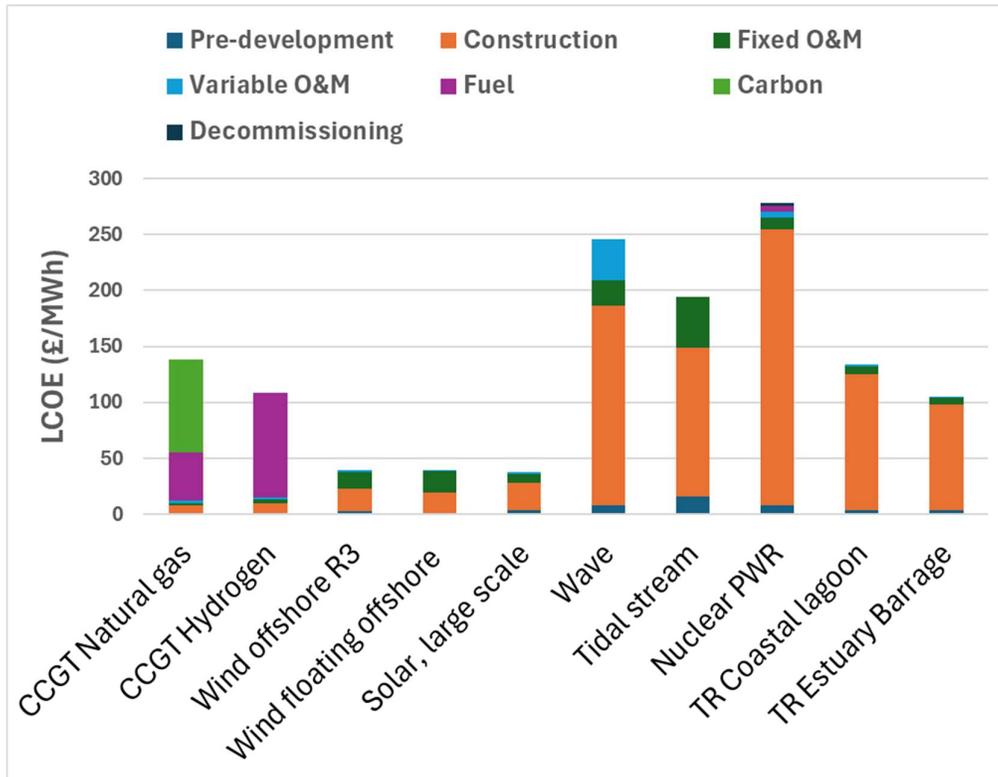
Figure 6-10 Levelised cost of energy (LCOE) for 10 clean technologies, ref (DiLellio et al., 2025).

An improved metric was proposed as a sustainable cost of energy (SCOE) (DiLellio et al., 2025) which used the same costs for continuous generation over 120 years. Thus, two consecutive nuclear stations with 60-year operational lives were compared with one tidal range scheme. Similarly costs for four consecutive CCGT stations with operational lives of 30 years were included. The results shown in Figure 6-11 show the lowest five technologies have virtually similar SCOE within the order of magnitude of the calculation.
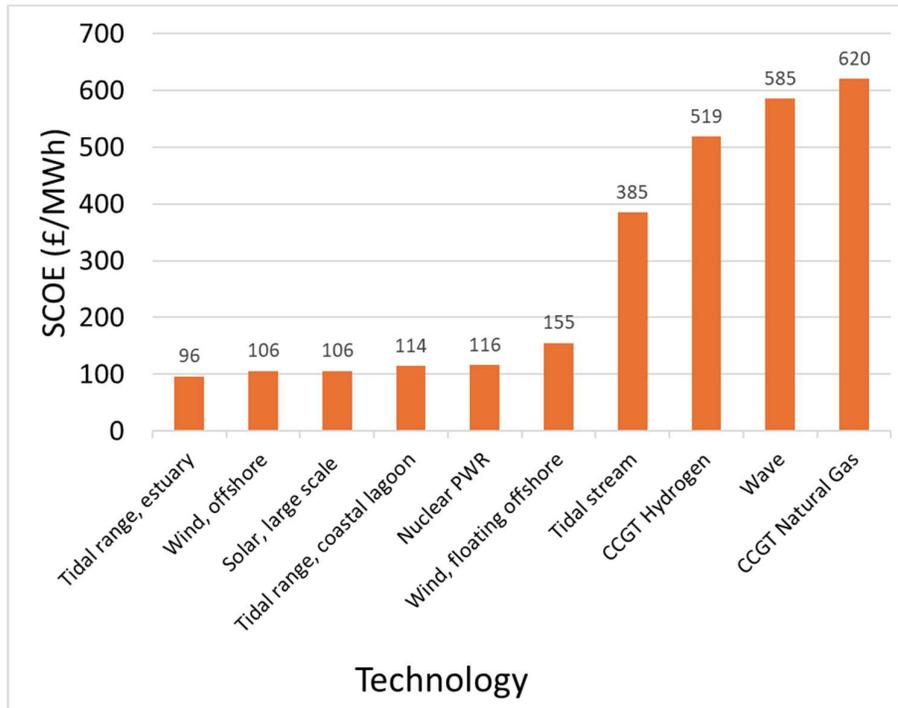
Figure 6-11 Sustained cost of energy (SCOE) for 10 clean technologies with 2% inflation (DiLellio et al., 2025).

6.4.1 Benefits of flood protection.

Tidal range schemes are frequently reported as providing flood protection to coastal and estuarine areas. However, to date this has been difficult to quantify. The UK National Oceanography Centre (NOC) has carried out several assessments of coastal flooding and the benefits of flood protection from coastal lagoons. In 2015 NOC considered a long length of coastline from North Wirral in England to Conwy in North Wales (NW) (Lyddon et al., 2015). The study area includes the NW lagoon, and the Morecambe Bay (MB) estuary is approximately 60 km north of the Wirral. The study produced flood projection maps and estimated costs of damage but did not estimate the annual damage cost (EAD). Also, in 2015 Prime investigated the economic impacts on sea level rise (SLR) for the town of Fleetwood at the mouth of the River Wyre (Prime et al., 2015), estimated the cost per hectare per inundation event. A later study (Prime et al., 2017) investigated the flood risk around the Mersey Estuary which estimated EAD ranging from £99m to £741m, with a mean of £249m for a sea level rise of 0.98m by 2100. The SLR compares with the Institution of Mechanical Engineers recommendation

"to design for 1.0m rise but plan for 3.0m by the end of the century" (Inst of Mech Engs (IMechE), 2019).

The Mersey estuary is a highly developed land and port area but the flood risk areas for both case study schemes are larger. To demonstrate the possible significant of the flood benefit we can apply half the Mersey figure (£125m/a) to both case studies. The benefit to the community, ratepayers and local municipalities can be included in the SCOE by subtracting the EAD from the annual fixed operating expenses; the benefit exceeds the operating cost. The SCOE for the coastal lagoon reduces from £114/MWh to -£16/MWh. For MB barrage the SCOE reduces from £96/MWh to £15/MWh when the annual flood benefit is included. The potential offset benefit makes tidal range cheaper than any other technology, see Figure 6-12. Site specific EADs should be calculated for both case study sites.
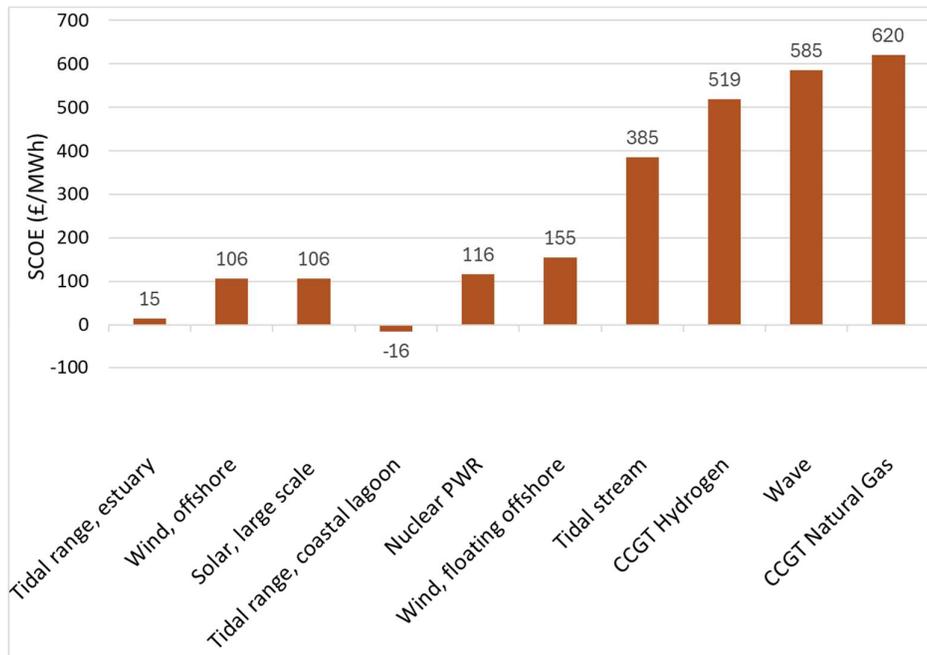
Figure 6-12 SCOE including annual flood benefit for tidal range schemes.

To put this into context the North Wales Lagoon includes about half the coastlines of Conwy and Denbighshire. Denbighshire County Council has just arranged a £92m loan for coastal defences

(National Wealth Fund (NWF), 2025). North West & North Wales Coastal Group produced a shoreline management plan which estimates £3.3bn damage between the Great Orm and the Point of Aye if there is no intervention (Halcrow for The North West & North Wales Coastal Group, 2025) which is almost entirely included in the North Wales lagoon.

6.5   Uncosted benefits

- The benefit of protecting estuarine mudflats is also significant as these are vital ecosystems and a sink for CO_2. If the mudflats are washed away by sea level rise, locked in CO_2 will be released into the atmosphere.

- Barrages across estuaries can incorporate roads to improve transport links. The additional costs for widening and raising the bund could be met by toll charges if required. Northern Tidal Power Gateways (NTPG) propose roads across Morecambe Bay and the Duddon. NTPG list benefits as:-

    o   estimate nine million crossings per year, reducing travel distance by 50% and journey time by 75% with fuel savings of 750,000 litres annually.

    o   Social benefits arise from increased mobility and healthcare across the bay

    o   Providing growth opportunities for vital industries through better transport links.

6.6   Future proofing

Tidal range schemes will be very long lasting with a minimum design life of 120-years. The 120-year life often quoted may be related to the design codes for bridges which are based on 120-year design life. Reinforced concrete can last much longer in a marine environment as evidenced by the abundance of harbours and coastal structures around the world. However, there are aspects for tidal range that will require consideration in the initial design:-

- Replacement or upgrading of turbines
- Raising the barrage to protect from future average sea level rise (SLR).

- The turbines acting in pump mode can probably maintain existing low tide levels up to a SLR of 0.5m, after this rise, stand-alone pumps will be required.

6.6.1 Turbine upgrades

The turbines and generators can be maintained by installing temporary stop-logs in the culverts, removing the culvert top cover inside the turbine hall and lifting the unit out with the hall crane and placing onto a laydown area.

The analysis in this thesis is based on eight-meter diameter turbines which are believed to be the largest low head bulb turbine currently capable of manufacture. During the development and manufacture of the first turbines for a new generation of tidal range schemes it should be possible to increase the diameter of the turbines. This would improve the efficiency and probably increase the economic return. The turbine culverts will be designed as a square cross section with internal dimensions of 15 x 15 m. The flow race or guide tube inside the culvert should be designed as replaceable. Material selection will need to allow for at least 50-years life, possibly steel, concrete or GRP. If concrete the transition from square to circular section can be done as precast tunnel sections, allowing the future installation of 9m diameter turbines although the intake and outfall size of the culverts would remain.

6.6.2 Barrage crest level

The initial crest level of the barrage will be designed for a SLR of 0.5m which is the expected rise in the first 40-years to reduce the initial capital expenditure (CAPEX) and the construction time. As the rate of SLR is better understood the crest can be raised as required in 40-, 80- or 120-years. The initial barrage design must consider these increases from the outset so that there is no problem extending in the future. The factors of safety for embankments generally increases with time and it may not be

necessary to widen the base of the embankment. If necessary, the stability can be increased by adding concrete slabs to the seaward face of the embankment.

6.6.3 Stand-alone pumps

As explained in chapter 4.6.3, it may be necessary to install additional submersible pumps at some time in the future to maintain existing low water levels. If so, they will be a separate installation and can be built without affecting the operation the barrage.

6.7 Summary

Other things being equal, an estuarine barrage is more likely to produce a higher return of investment than a coastal lagoon because the estuary scheme is likely to have a greater impounded area per km of barrage length than a coastal lagoon. Also, there is a funnelling effect in estuaries that usually results in a higher tidal range. However, there is still much concern that barrages across estuaries can cause significant environmental damage but now demonstrated to be false because barrages can protect intertidal areas from sea level rise (Vandercruyssen et al., 2023b).

It has been demonstrated that the levelised cost of energy is a poor metric for comparing different forms of renewable generation, particularly where the scheme operating lives are significantly different. The sustained cost of energy metric and internal rate of return should be used when considering the ranking of the different forms.

Electricity demand in the UK is greatest during the winter months (November until February) but is dependent on average temperatures which are gradually rising. Demand could increase fivefold arising from the UK government's drive to reduce the use of fossil fuels for transport and heating (Amble, 2023). The UK government are seeking to use offshore wind and nuclear to fulfil demand, but offshore sites are becoming further away and more expensive than inshore sites.

The price of electricity will become less dependent of the price of gas as the UK moves towards renewable energy. However, as most forms of renew energy are intermittent (excepting geothermal and biomass), the price will be focused on the gap between demand and renewable supply. Energy storage facilities and open cycle power stations will need to be built and paid for to be used when needed.

7   CONCLUSIONS & RECOMMENDATIONS

The conclusions are summarised below for each chapter of this thesis.

7.1   Literature review

CO_2 levels and global average temperatures are increasing exponentially. The UK is trying to reach net zero emissions by 2050. However, as the UK is only responsible for 1% of the world's CO_2 emissions it requires all nations to reduce their emissions. This is very unlikely to occur due to population growth and 3rd world development.

There are currently only two grid scale tidal range (TR) power plants, La Rance in France has been operating since 1966 and Lake Sihwa in South Korea since 2011. There are however more than a dozen TR schemes proposed around the coast of Great Britian (GB), most are concentrated along the west coast which has the second highest tidal range in the world. None of the proposed GB schemes are currently actively progressing, the main impediments to investment are:-

- The economic viability

- Perceived damage to the environment

- Lack of government support

To a lesser extent, the intermittency of generation is a concern although common to most mainstream renewable sources but is at least predictable for TR. Thus, energy storage is becoming an urgent need as the UK switches to renewable energy. The most efficient form of storage is pumped hydro (PHS) and there are proposals to develop more of these, mainly in Scotland as suitable sites are limited.

The UK demand for electricity has decreased since 2006 possibly due to economic slump, Covid and the war in Ukraine. Generation from coal and nuclear is falling whilst from gas, renewables and imports are increasing. World trends are clear that the demand for electricity and the use of fossil fuels (coal and gas) is still increasing at an alarming rate.

7.2 Lancaster 0-D model

0-D models are ideal for the initial development of schemes by rapid calculations for different combinations of turbine diameters, generator ratings and sluice ratios. For any chosen site, they require only two site specific inputs which are the bathymetry between high and low tides and sea level data in the area. Past and future sea level data is readily available. The bathymetry may be estimated from admiralty charts or LIDAR information until site specific surveys have been carried out.

Appling a simple cost model (Vandercruyssen et al., 2022a) allows the optimisation of components and the ranking of schemes by financial return (Vandercruyssen et al., 2023a). Once funds are available for feasibility studies site investigations will provide the data required for 2-D and 3-D models to estimate the effects on the environment and refine the arrangement of schemes.

Pumping is usually applied after the sluice phase of the generation cycle using the turbines as pumps (TaPs). The idea is that pumping at low heads helps to meet the natural tide limits and provide a greater head for the next generation cycle. Investigations have shown that standalone submersible pumps may be needed in 40-years' time to help maintain existing low water levels in the face of sea level rise (Vandercruyssen et al., 2023b). This appears to have little effect on the cost of generating electricity but may be a significant benefit to maintaining existing mudflats and ecosystems.

7.3 Simplified and demand led 0-D models

The simplified 0-D model shows promise for evaluating a full year of tide date and can be used to give maximum generation or income where the price is fairly constant over a generation cycle. Development of the Matlab code started and should be completed.

The reason why the simplified model coding was stopped was because it became clear that in some cases where the price fluctuated significantly the simplified model would generate at negative income.

A demand/price led model has been developed as a spreadsheet analysis over 22-days shows; showing that controlling the flow of water relative to demand helps to stabilise the grid and increase revenue at the same time. The algorithm for the analysis would be very complicated and beyond the time allowed for this study but is hoped to develop later.

7.4   Economics

The electricity demand in the UK is likely to increase dramatically in the next decade if government net zero targets are to be met: principally due to the drive for electric cars and the need for heat pumps to replace gas boilers. Some authors have estimated that the UK demand will increase by a factor of two, four or even five times (Amble, 2023) from present levels.

Prices in previous years were driven by the cost of fuels such as oil, coal and gas. Coal and most oil have now been phased out from the UK and gas is intended to be reduced, fitted with carbon capture equipment or converted to run on hydrogen or biofuel. As the supply of renewable energy increases the UK will be less dependent on foreign fuel prices. Initially there is the capital cost required to build renewable energy schemes but thereafter fuel for renewable energy is free. Subsidies for the development and construction of renewable energy schemes are recovered through consumer bills.

7.5 Contribution to knowledge.

This research has contributed to the development of knowledge of tidal range generation as follows:-

- Explaining and demonstrating how 0-D modelling can be used to optimise the components of tidal range schemes.

- development of a cost model for tidal range schemes base on five elements.

- investigated the implications of sea level rise over the 120-year operational life of tidal range schemes to understand what would be required to protect existing low-level ecosystems and provide flood protection to coastal communities.

- development of a simplified 0-D generation model and a demand/price-based model which would increase income and help to stabilise the grid at the same time.

- A proposed a new design for precast concrete caisson units for the barrage which can be built on shore and floated out in shallow water and ballasted with dredged sand and gravel.

- investigation of the financial methods used to compare costs for various renewable energy schemes with different operational lives and found that tidal range produced electricity at similar costs to solar, wind and nuclear. If the annual benefit of flood protection is included, it shows that tidal range is the cheapest of all current technologies.

7.6   Recommendations for further work.

7.6.1   Possible changes to the existing Lancaster 0-D model

- Modify the input to read the tidal constituents, tabular tide levels and bathymetry by selecting input file names, making the program general for any location.

- Half hourly prices can be included in the tabular tide levels so that price optimisation can be carried out, allowing estimated future pricing to predict operation a day ahead of time.

- The effects of storm surges can be modelled by altering the tide levels by +/- 2m in the 0-D program.

- Include efficiency reduction for reverse flow of bulb turbines.

- Extend the program so that other hill charts can be included as compiled subroutines, e.g., black box.

7.6.2   Vertical Archimedes screw

Archimedes screws are ancient devices for moving water as pumps and later used for electricity generation. They are reported to have high efficiency at low heads (Waters and Aggidis, 2016). Figure 2-17 shows the efficiency of Archimedes screw above 70% with a maximum around 86%, depending on flow. The screw has minimal impact on fish, and some have been installed as fish ladders to promote migration.

During this research an idea for a vertical screw has occurred which potentially would save significant sums on civil engineering installation and ongoing maintenance. The screw operates at ambient air pressure and so does not require the deep installation of the bulb turbine. Also, the generator would be above sea level for easy maintenance or swapping out. The basic idea requires a cylindrical tube around the screw which has slots to control the water flow. The cylinder will rotate slowly by 180° for each half-tide cycle, i.e. 6-hours see Figure 7-1.
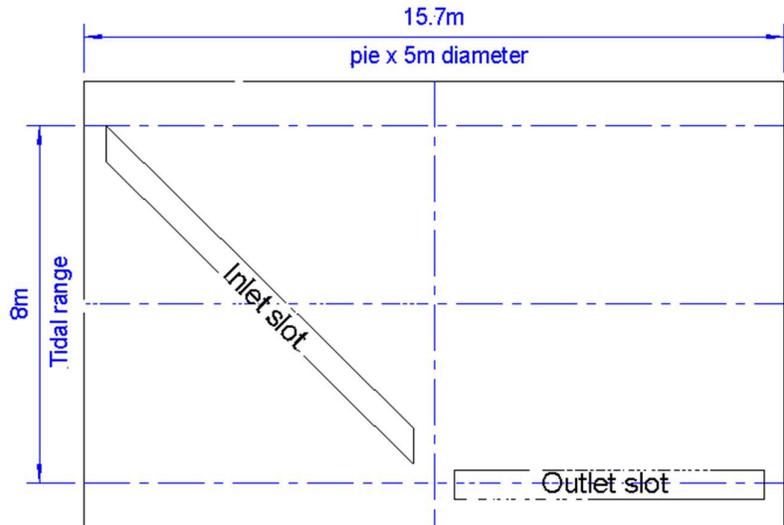
Figure 7-1 developed elevation of screw caisson.

Compare the typical cross sections of a bulb turbine installation (Figure 7-2) with a vertical screw turbine (Figure 7-3).
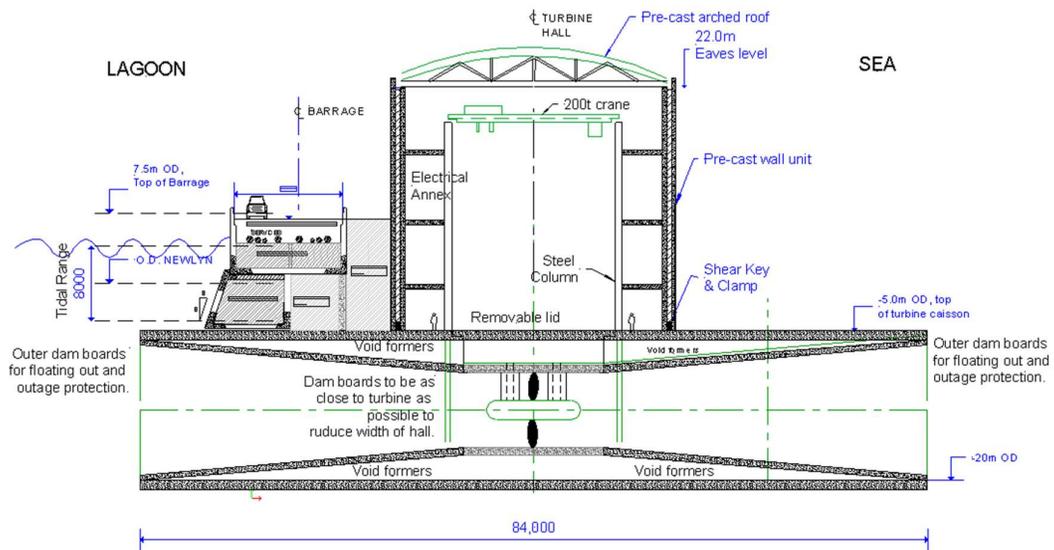
Figure 7-2 Typical cross section of bulb turbine installed in barrage.
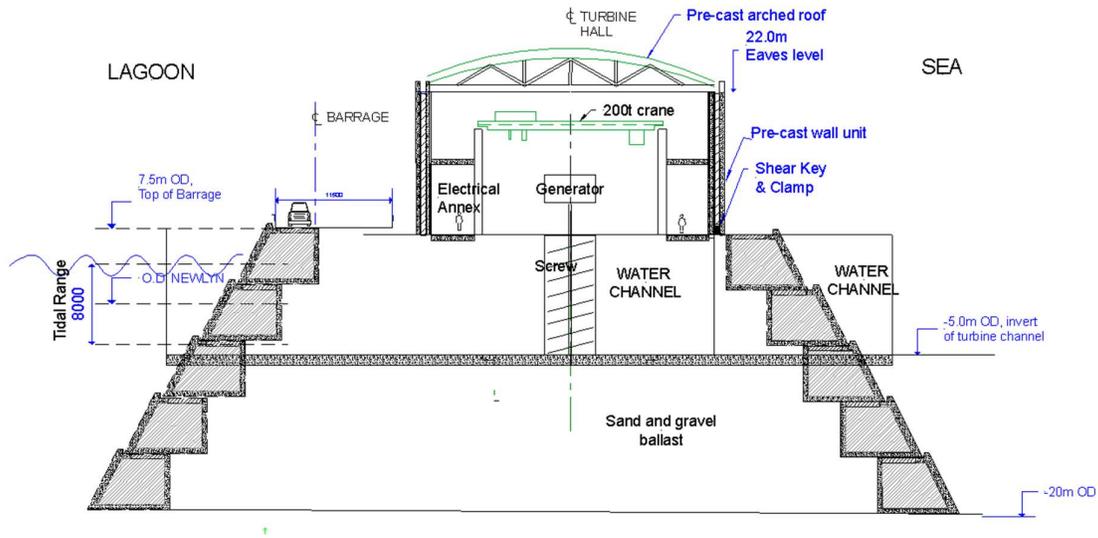
Figure 7-3 Cross section of vertical screw installed in barrage.

To develop the idea further a small-scale test model would be required, say 300 mm diameter screw. A full-size turbine would be as large as the blade technology would allow, say 5m diameter for a prototype. The screw could be manufactured in GRP to the same standard as the offshore wind technology. Any loss of efficiency could be outweighed by the significant reduction in installation and maintenance costs.

Alternatively, an inclined screw could be installing if this increased the efficiency, to do so would need high level input channels on each side of the screw so that it will rotate in the same direction with each tide.

7.6.3 Wave testing for longitudinal precast concrete caissons.

The barrage design and construction paper (Vandercruyssen et al., 2024) used the theory of wave forces on vertical walls. Forces on inclined walls needs to be investigated and models tested in a wave tank. The horizontal loads and factors of safety are likely to improve.

7.7 Proposed future papers

- Complete the publication of the paper on the River Wyre barrage at Fleetwood.

- Develop chapter 5 of into a technical paper describing the simplified and demand led tidal energy models, to demonstrate the flexibility of tidal range to demand using examples of North Wales lagoon, Morecambe Bay, Solway Firth and R Wyre barrages.

- Look at phasing two tidal range schemes and consider a longer timescale for the delivery of turbines with options for increasing the size of turbines and generators. Considering the two current case study schemes and staggering the construction by two or three years. Manufacturing 260 turbines in 10-years is likely to be a stretch, so what happens if the barrage is built to hold the full complement of machines with the empty turbine draught tubes used as sluices. Limited generation can start after six years. What are the implications on generation and cash flow if the remaining machines are installed over a ten-year period. What options can be considered for larger turbines or efficiency improvements.

- Use decision tree analysis to investigate possible phasing in of turbine installation and the effects on cash flow. The turbogenerators account for about 70% of the total CAPEX and we know that producing 120 turbogenerators in seven years would be a stretch for any scheme. Normally for infrastructure projects the best returns arise for the shortest possible construction phase and earliest operation to derive revenue. However, given the unknown turbine performance, possible developments and future price of electricity it may be worth considering option engineering to reduce risks and enhance financial returns. We consider construction of the bund and turbine halls with say an initial 50 turbines. The remaining enhanced turbines could be added later when the returns justify the costs.

- Investigate the cost benefit of flood protection for specific schemes and include in the SCOE calculations.

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APPENDICES.

Background data and all spreadsheets are included here or can be downloaded from the following dropbox link. The data will also be posted on the Lancaster University website when my PhD has been completed. Alternatively the data is available on the following dropbox link.

https://www.dropbox.com/scl/fo/fza0ebp02jbq7xpcttpjr/AOaSjyMwNubOO2j58OqCSQk?rlkey=tjafkhdxgb0ocr12iglzdr0r0&st=o68ortwf&dl=0

A.1.   Outputs

A.1.1. Presentations attended or viewed

- Marine Energy Wales (MEW) annual conference 4-Apr-19, presentation by North Wales Tidal Energy.
- IMechE online presentation on tidal range by Prof Aggidis on 20-Oct-20.
- IMechE online presentation on Morecambe Bay tidal range by Prof Aggidis on 24-May-22.
- IMechE online presentation on tidal range by Prof Aggidis on 8-Nov-22.
- Jacobs presentation on LCOE to Tidal Range Alliance on 12-Dec-23.
- Presentation by Tidal Lagoon Power on 12-June-24.
- Presentation on the value of real options by Prof DiLellio at Hull University on 23-May-24.

A.2. Chapter 5 Simplified & demand led models

Simplified model
calculation, NW 202

Demand-Price
based calculation, N

A.2.1. Spreadsheet construction

The rows 1 and 2 give the column titles to column W Income.

Rows 3 and 4 give basic data for the installation or column totals. The cells highlighted in yellow are

input data used in the sheet as follows:-

- T3 is the maximum net power in MW, the text goes red if it exceeds the installed capacity E4.
- U3 is the total net energy in MWh from ebb tides.
- W3 is the total net energy in MWh from flood tides.
- A4 is the number of turbines, 125 in the case study.
- B4 is the diameter of the turbine blades, 8 m in the case study.
- C4 is the generator rating, 15 MW in the case study.
- D4 is the availability, 95% in the case study.
- E4 is the maximum installed capacity, calculated as A4 x C4 x D4.
- F&G4 is the sluice ratio, 2 times area of turbine runner in the case study.
- I4 is the minimum generating head, 1.5m in the example.
- J4 is the low tide target, set to 0.75m above low tide to allow pumps to match low tide level.
- K4 is the high tide target, set to 0.5m below high tide to allow pumps to match high tide level.
- L4 is the total area of sluices, calculated as F4 x M4.
- M4 is the total area of turbine runners, based on A4 (No.) & B4 (dia.).
- P4 is the maximum Q11 flow, the text goes red if it exceeds 4.75 m3/s.
- R4 is the efficiency reduction in reverse flow, set to 20% but can be changed. The reduction is deducted from the turbine efficiency equation for flood tides only.
- T4 is the maximum net power in MW which should not exceed the installed capacity.
- X4 is the sluice discharge coefficient, Cd = 0.85
- Y4 is the sluice discharge coefficient, Cd = 1.10, based on the diameter of the blades.

Rows 5 onwards are the data and calculations at 10-minute intervals, with columns as:-

- Col A is the date and time from *Tide Plotter* (Belfield Software Ltd, 2025).
- Col B is the sea level from *Tide Plotter*.
- Col C is the wholesale half hourly system sell price from *Elexon* (Elexon, 2025).

- Col D is the change in sea level over the 10-minute time slot, calculated as Bn – B(n-1).
- Col E is the state of tide, ie high, low, maximum gradient or target level.
- Cols F and G indicate the generation cycle, ie hold, generate, sluice or pump. The sluicing can be coincident with generation or pumping.
- Col H is the weighted level change (WLC),
    - During the *hold* phase is zero.
    - During *generation* is set to a value between zero and maximum change to control the flow.
    - During *sluicing* is calculated as the combined flow through the sluices and turbines divided by the surface area, but not less than the change in sea level, calculated as:-

$$Hn = (Ln + Mn) * 600 / Kn / 1,000,000$$

Where H   is column H in the spreadsheet.

L   is column L in the spreadsheet.

M   is column M in the spreadsheet.

K   is column K in the spreadsheet.

n   is the row number

But check Hn is not more/less than the change in sea level for the first cycle, with:-

$$Hn = MIN (Dn, ((Ln + Mn) * 600 / Kn / 1,000,000)$$

Where H   is column H in the spreadsheet.

D   is column D in the spreadsheet.

L   is column L in the spreadsheet.

M   is column M in the spreadsheet.

K   is column K in the spreadsheet.

n   is the row number

600   is the number of seconds in 10-minutes

10^6 converts the surface area from km^2 to m^2.

- During the pumping this is set to the difference in lagoon level:-

$$H_n = I_n - I_{n-1}$$

- Col I is the lagoon or impoundment level,
    - During the *hold* phase is copied down from the level at the start of the hold.
    - During *generation* and *sluice* is set to the sum of the previous change in lagoon level and the lagoon level

$$I_n = I_{n-1} + H_{n-1}$$

    - During *pumping* is calculated as:-

$$I_n = -(L_{(n-1)} + M_{(n-1)}))/K_{(n-1)}*600/1{,}000{,}000$$

- Col J is the head between sea and impoundment levels, calculated as:-

$$J_n = I_n - B_n$$

- Col K is the surface area of the impoundment at the current level with linear interpolation from the bathymetry data at 1m intervals.
- Col L is the *sluicing* free flow through all sluices Qs in m³/s, calculated as:-

$$L_n = \$L\$4 * \$X\$4 *(2 * 9.81 * ABS(J_n))\;{}^{\wedge}0.5$$

Where L4 is the fixed cell for total area of sluices.

X4 is the fixed cell Cd for sluices.

- Col M is the flow through all turbines Qt in m³/s,
    - During generation based on the change in lagoon level times the average surface area and must be less than Nn:-

$$M_n = ABS(\,(K_n + K_{(n-1)}\,)\,/2\,/600 * H_n * 1{,}000{,}000)$$

    - During sluicing it is the free flow through all turbines,

$$M_n = \$M\$4 * \$Y\$4 * (2*9.81 * ABS(J234))\;{}^{\wedge}0.5$$

- During *pumping* it is based on the turbines as pumps running at 7.5 MW.

$$M_n = -380 * (2.2 - ABS(J_{n-1})) / 2.2 * \$A\$4$$

- Col N is the maximum flow through the turbines Qt based on the current head, calculated as:
  -

$$N_n = \$M\$4 * \$Y\$4 * (2 * 9.81 * ABS(J_n))\wedge 0.5$$

  Where $\$M\$4$ is the total area of turbines and $\$Y\$4$ is the Cd for turbines.

- Col O is the flow through a single turbine Q_1 in m^3/s, calculated as: -

$$O_n = M_n / \$A\$4$$

  Where $\$A\$4$ is the number of turbines.

- Col P is the model flow through Q_{11} in m^3/s, calculated as: -

$$P_n = O_n / \$B\$4^2 / ABS(J_n)^{0.5}$$

  Where $\$B\$4$ is the diameter of the turbine blades and has to be within the range of 1.6 m^3/s to 4.75 m^3/s. If the calculated flow is less than 1.6 m^3/s then generation should not start. If the calculated flow is 4.75 m^3/s then sluices should be opened to keep the turbine flow within limit.

- Col Q is the model speed n11, rpm, which is 188 rpm below Q11 = 3.6 m^3/s, and increases linearly to 255 rpm at Q11 = 4.75 m^3/s.

$$Q_n = IF (P_n <= 3.6, 185, 185+(P_n-3.6)/1.15*70)$$

- Col R is the model turbine efficiency % from Figure 5-1

$$R_n = IF (P_n < 3.6, 0.92-02*(P_n-1.6), 0.88-0.096*(P_n-3.6))$$

  For reverse flow this is reduced by the figure in $\$R\$4$, set at 20% in the example.

Col S is the full-size turbine speed from the affinity laws,

Equation 3-5

$$Nt = Q_n * ABS(J_n)^{0.5}/\$B\$4$$

- Col T is the net power in MW,
  - For generation this is

$$P_n = 1025 * 9.81 * ABS(J_n) * M_n * R_n /1,000,000$$

    Where 1,025 is the density of sea water, J is the head, M is flow and R is the efficiency.

  - For pumping the power is assumed to be 7.5 MW per turbine, where $\$A\$4$ is the number of turbines.

$$Power = -7.5 * \$A\$4$$

- Cols U and V are the net energy generated in MWh for ebb and flood tides respectively, i.e.. generated energy less pumping energy.

$$Energy = \$T216/6$$

- Col W is the net income for each time slot, being total generated minus the pumping costs.

$$\text{Income}_n = (U_n + V_n) * C_n$$

A.3. Chapter 6 Economics

LCOE.xlsx

SCOE+IRR.xlsx