

A Review on the Potential of Tidal Energy: Resources, Technology and Market Size

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Table of Contents

1	Executive Summary	2
2	Introduction	4
2.1	The Tides	4
3	Tidal Stream Energy Conversion Technology.....	8
3.1	Tidal stream energy conversion devices	8
3.2	Arrays.....	10
3.3	Foundations	12
4	Technology Readiness Level (TRL)	15
5	Tidal stream resource potential	17
5.1	UK resource potential	18
5.2	UK Tidal stream projects securing government support.....	20
5.3	Global resource potential.....	23
5.4	International Projects	26
5.5	Effects of Climate Change	30
6	Learning Rates.....	33
7	Factors affecting LCoE of Tidal Stream Energy	46
7.1	Tidal Stream Energy cost drivers	51
7.2	Example of a Tidal Project Timeline	59
8	Tidal Range Energy	60
8.1	Introduction	60
8.2	Tidal Range Projects – Active and Proposed.....	63
8.3	Costs of Tidal Range Energy Projects	75
8.4	Prospects for Tidal Range Energy.....	79
9	Conclusions.....	84

1 Executive Summary

Tidal energy is a renewable, free from weather influences and highly predictable energy resource and thus is attractive for use in a decarbonised electricity system, however, in terms of maturity it lags behind wind and solar energy. This lack of maturity means that the business case for investment is weak without substantial subsidies but learning rates are expected to apply that will reduce cost. As with all energy technologies, tidal energy has impacts on the environment and these are not fully explored. This report, as part of the Centre for Sectoral Economic Performance (CSEP) initiative, reviews the issues concerning tidal energy as a prelude to further investigations on specific issues. This report mainly addresses tidal stream energy, that is, turbines operating in open water generating from tidal flows. A brief section is included on tidal range energy, in which turbines embedded in dam walls generate energy from water held in barrages or lagoons.

There are many proposed devices for tidal stream generation and the industry has not converged on a consensus design but a 3-bladed horizontal-axis turbine of similar appearance to the consensus design of wind turbines is the most common device. UK currently has 10.4 MW operating capacity with another 122 MW of projects underway, to be operational between 2027 and 2029 having secured Contract for Difference (CfD) support. Although this is by far the largest deployment worldwide of tidal energy, it is small compared to wind and solar, each above 1,000 GW. The current cost of tidal stream electricity, as revealed by the CfD strike price in the recent UK Allocation Round 6 auction stands at £172/MWh and compares with £129/MWh for floating offshore wind and £58/MWh for bottom-fix offshore wind. That said, tidal energy is free of weather dependence, and will be present every day, brings some additional value to an electricity system but that value is yet to be established and assessment will be needed of how that value is rewarded beyond the simple energy market.

Tidal stream projects face technical, environmental, regulatory and financial issues which are investigated in this report. Projections of cost reductions via learning as these difficulties are addressed vary from 2% to 17% per doubling of installed capacity. Despite the similarities with established technologies such as offshore wind and offshore oil and gas installations, stark differences stand out such as submerged operation, operating with a high-density fluid and difficult access for support vessels in shallow waters in confined spaces typical of early tidal stream deployments. The cost of tidal electricity will depend on various factors including technological maturation in terms of turbine rotor size, strength of materials, plus improved site selection and improved operation and maintenance processes.

Tidal range schemes are large projects with capacities of hundreds or thousands of megawatt with lifetimes extending to 120 years or more and very high capital costs. Tidal range projects are heavily dependent on subsidy and the volume of subsidy for such large projects has proved an impediment with only two projects currently operating worldwide but many more stalled in planning for several years. The technology is mature, with key elements present in other areas such as hydropower.

The expectations are that tidal energy can see a growth on par with wind and solar industries but a major question remains over the total global resource, which is likely to be smaller than that for wind and solar. Resources vary due to geographical factors such as tide speeds, channel depth and site specific influences. The estimates of total worldwide resource vary considerably between sources and consensus has not yet been reached.

UK Marine Energy Council estimated that the UK has 50% of Europe's tidal stream energy resource¹. The UK's National Energy System Operator (NESO) sees tidal stream energy as a novel technology, and in their scenarios, it is small-scale and grows gradually after 2030². NESO sees tidal range as a well-established technology that can be deployed at scale but requires additional government support and therefore is deployed at large scale during the early 2040s in NESO pathways. NESO's Clean Power 2030 Report states that tidal generation would become feasible if the costs fall in future, highlighting again that the current deployment costs are high in comparison to wind and solar generation³.

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¹ [UK Marine energy Council](#) 2024

² [2024 Future Energy Scenarios: ESO pathways to net zero](#) 2024

³ [NESO Clean Power 2030](#) 2024

2 Introduction

The UK is seen as the global leader in the research, development and harnessing of tidal energy but even so despite 20 years of research and development in the UK, tidal energy is still at a very early stage of having only 10.4 MW of deployed tidal stream devices and 122 MW of live projects under development. This stands in contrast to the 25 GW of wind (onshore and offshore) that has been built in the UK. So, the question is whether we are now on the cusp of a major new industry being created or will this remain a niche activity.

The Energy System Operator's Future Energy Scenarios sets out different pathways the UK could take to meet its net zero targets and the strategic choices that need to be made. As part of that, tidal power (stream and range capacity) is forecast to reach a minimum of 3 GW to a maximum of 5 GW in delivering the UK's 2050 net zero target⁴. The UK has over 11 GW of predictable tidal stream energy potential, which when harnessed could provide over 11% of its electricity demand⁵. A report by the Grantham Institute⁶ in 2023 stated that tidal energy has the potential to contribute to four strategic objectives relevant to sustainable growth in the UK: (1) achieving a net zero energy system; (2) ensuring energy security; (3) capturing export opportunities and (4) securing regionally balanced growth. It has been forecast by the European Marine Energy Centre (EMEC) that the global ocean energy market could be worth \$165 billion by 2050⁷. The positive outlook found in reports such as these needs to be assessed critically so that one can determine if tidal energy can if tidal energy could become a driver for economic growth and employment through generating a high Gross Value Added (GVA). This report is the initial stage of what will become a deeper study, and it gathers publicly available data on tidal energy prospects.

2.1 The Tides

If the earth were a perfect sphere without large continents, all areas on the planet would experience two equally proportioned high and low tides every lunar day. The large continents or land portions on the planet block the westward passage of the tidal bulges as the earth rotates. Due to constriction of movement, these tides establish complex patterns within each ocean basin that often differ greatly from tidal patterns of adjacent ocean basins or other regions of the same ocean basin.

Three basic types of tidal patterns are observed along the earth's major shorelines.

- Diurnal tides as shown in Figure 1 experience only one high and one low tide each day, e.g. the Gulf of Mexico.
- Semidiurnal tides as shown in Figure 2 experience two high and two low tides of approximately equal size, e.g., east coast of North America, west coast of Europe, all of the UK and Africa.
- Mixed semidiurnal tides as shown in Figure 3 experience two high and two low tides of different size, e.g., the west coast of North America.

⁴ [NESO Future Energy Scenarios](#) 2024

⁵ [Unlocking UK's tidal power](#), Marine energy council UK 2024

⁶ [Seizing sustainable growth opportunities from tidal stream energy in the UK](#), Grantham Research Institute of Climate Change 2023

⁷ [EMEC](#) 2023

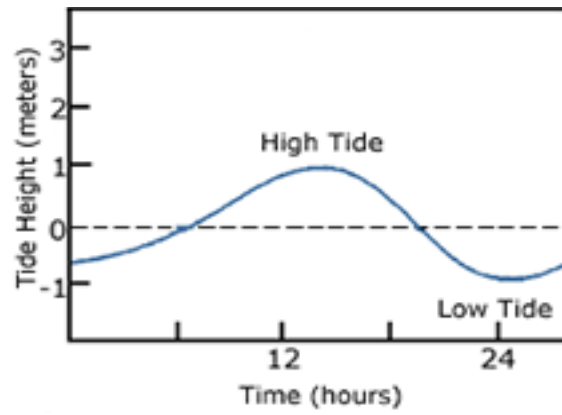


Figure 1 Diurnal cycle⁸

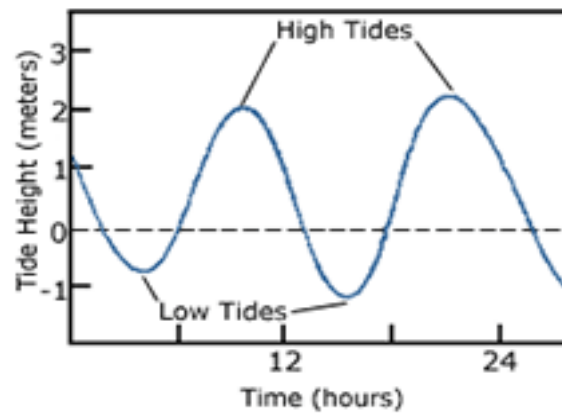


Figure 2 Semidiurnal cycle⁸

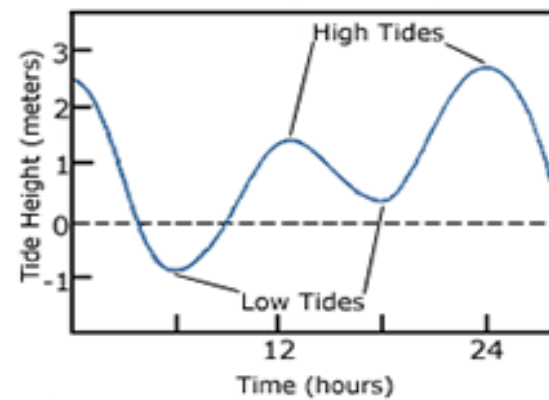


Figure 3 Mixed semidiurnal cycle⁸

Figure 4⁸ shows that most regions of the world have semidiurnal tides, that is two high-tides and two low-tides.

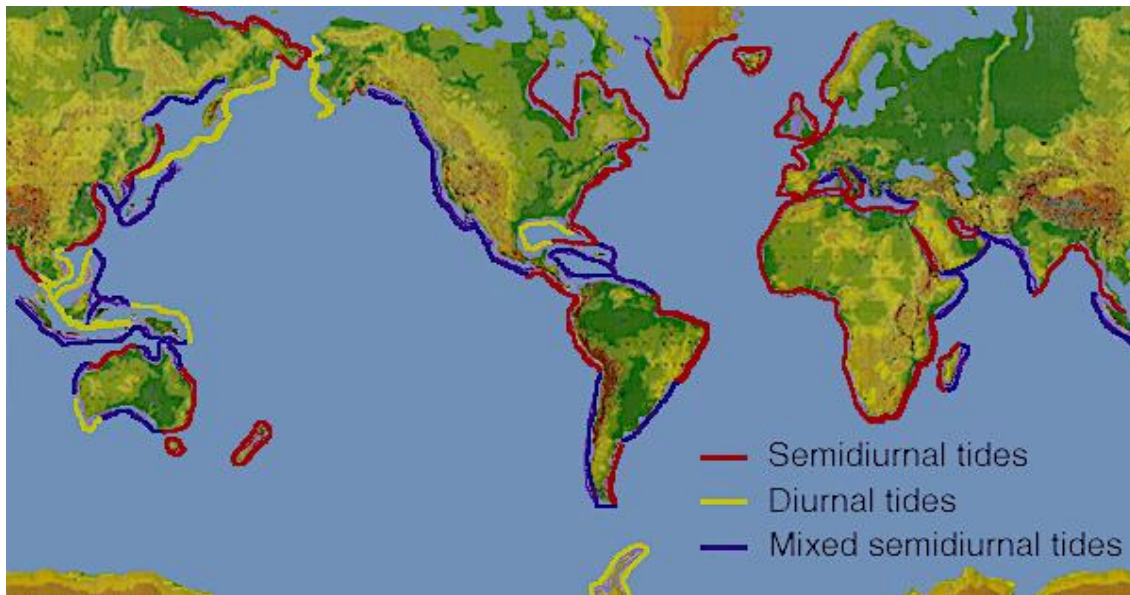


Figure 4. Tidal cycles and continental interference⁸

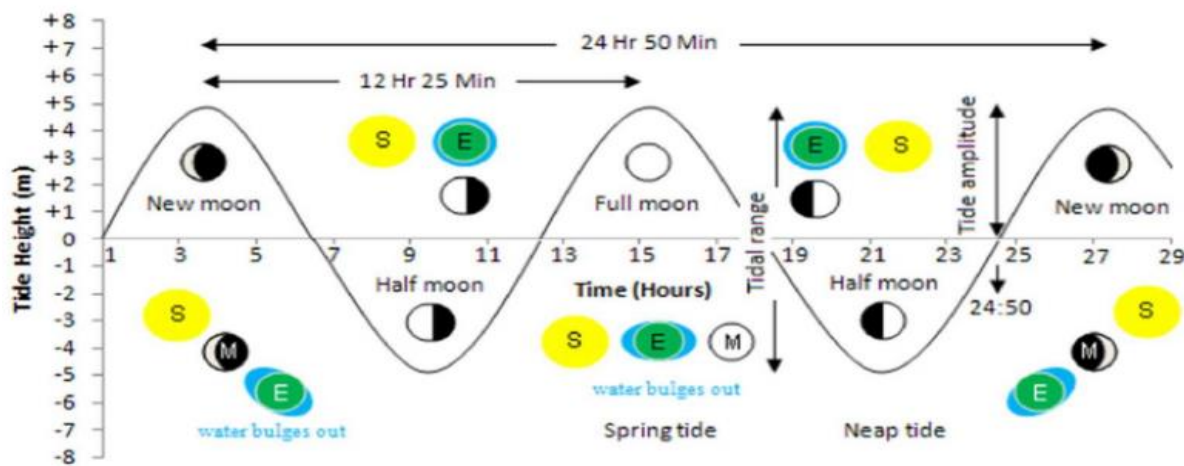


Figure 5 Tidal period and strength variation⁹

Of all the three tidal patterns, semidiurnal pattern produces the highest possible tidal currents leading to the highest energy availability⁸.

⁸ [Tides and water levels](#), National Ocean Service, US Gov website accessed March 2024

⁹ J W Burchell, [Advancement of direct drive generator systems for offshore renewable energy production](#), PhD thesis, University Edinburgh, 2018

Tidal streams are periodic and are the result of the gravitational pull acting on large bodies of water resulting in opposite wave like swellings of water which circle the globe following the passage of the moon and sun. The resulting forces created by the passage of the moon and sun are presented in Figure 5.

The sun, the moon and the earth are in alignment at the time of the new and the full moon and so the solar tide has an additive effect on the lunar tide, creating highest tidal ranges, popularly known as spring tides¹⁰. A week after new or full moon, the sun and moon are at right angles to each other and the solar tide partially cancels the lunar tide and produces lowest tidal ranges known as neap tides. During each lunar month, there will be two sets of spring tides and two sets of neap tides, as shown in Figure 5. A lunar month lasts 29 days and 10 minutes whereas a solar month 30 days and so is 50 minutes longer than lunar month.

Tidal period and strength as given by the alignment of the sun and moon combined with the centrifugal force of the Earth's rotation, the Coriolis effect, these swells introduce a potential energy to the water as it flows through a contained site producing tidal currents as water fill and empty from coastal regions⁹.

As tides rise and fall, differences in pressure between areas of sea causes water to move from areas of high pressure to areas of low pressure. Flood currents propagate landwards and ebb currents recede seawards. Kinetic energy from the tidal stream water movement can be used to generate electricity. The tidal stream resource is found in both shallow and deep water¹². Tidal velocities vary from zero at slack water to maximum in between these slack water periods. Tidal streams are driven by gravity alone however, tidal currents can be affected by meteorological forcing as well. Tides involve water moving up and down and currents involve the movement of water back and forth. The kinetic energy flux passing across a plane perpendicular to the flow is a key value. The available power within a tidal energy system is proportional to the cube of the water velocity and the power that can be captured by a turbine is related to that as expressed in equation 1.

$$\text{Turbine Power} = \frac{1}{2}\rho C_p A v^3 \quad (1)$$

where ρ is the density of sea water, C_p is the power efficiency of the turbine, A is the swept-area of the turbine blades and v is the water flow velocity.

A flow velocity of 1 m/s is generally seen as the minimum economically viable resource.. There are many regions around headlands and within channels, where the spring current velocities exceed 2.5 m/s. Regions of strong currents and high tidal speed are highly valued by tidal developers¹¹. These conditions are commonly observed at specific geographical locations where the flow is restricted such as narrow passages such as straits, channels, but also near islands and headlands. Tidal currents are accelerated when water is driven through narrow channels and around headlands. Fast or improved hydrodynamic mechanisms identify in three classes: resonant basin systems, hydraulic currents and tidal streaming. Very fast currents are encountered in resonant systems, such as the Bristol Channel, UK and the Bay of Fundy, Canada. Tidal power generation devices are usually located in shallow water, typically 10 – 40 m depth. The potential power output for a tidal turbine is also dependant on friction coefficients, these vary depending on the submerged topology and flora and fauna of the seabed, thus site-specific investigations are required to install devices in the best possible configurations.

¹⁰ [TIGER project website](#) 2024

¹¹ [The wave and tidal resource of Scotland](#), Renewable Energy 2017

Tidal range technologies exploit the potential energy, the difference in height between high and low tides by holding back water at high tide and releasing it through turbines at low tide. Tidal range resource is at its maximum in shallow waters¹². Both tidal barrages and tidal lagoons are tidal range schemes. Barrages span an estuary or embayment, whereas tidal lagoons enclose a discrete area of water in shallow coastal locations¹².

This study reviews the tidal stream resource potential (sections 2-6) in the UK and the assumptions underlying those calculations. Tidal range resource is discussed in section 7.

3 Tidal Stream Energy Conversion Technology

The following information on the tidal stream energy conversion technology definitions is extracted from the European Marine Energy Council (EMEC) website¹³.

The tidal stream devices are broadly similar to submerged wind turbines and are used to exploit the kinetic energy in tidal currents. Higher density of water means the rotor blades can be smaller and operate at lower velocities yet delivering a significant amount of power. Concentrators (or shrouds) are often used to further increase the power output. A variety of energy systems are currently in use and new prototypes are being tested, however there is not a one single standard design that emerges as a clear winner yet.

3.1 Tidal stream energy conversion devices

The various types of these devices are shown in Figure 6.

3.1.1 Horizontal axis turbine

Horizontal axis turbines extract energy from moving water in much the same way as the most common form of wind turbine extracts energy from moving air. The tidal stream causes the rotors to rotate around the horizontal axis and generate power.

3.1.2 Vertical axis turbine

Vertical axis turbines extract energy from the tides in a similar manner to that above, however the turbine is mounted on a vertical axis. The tidal stream causes the rotors to rotate around the vertical axis and generate power.

3.1.3 Oscillating hydrofoil

A hydrofoil is attached to an oscillating arm. The tidal current flowing either side of a wing results in lift. This motion then drives fluid in a hydraulic system to be converted into electricity.

3.1.4 Enclosed tips/venturi

Venturi effect devices house the device in a duct which concentrates the tidal flow passing through the turbine. The funnel-like collecting device sits submerged in the tidal current. The flow of water can drive a turbine directly or the induced pressure differential in the system can drive an air-turbine.

¹² [An overview of Tidal Technologies](#), Sustainable Development Commission 2007

¹³ [EMEC website](#) accessed April 2024

3.1.5 Archimedes screw

The Archimedes Screw is a helical corkscrew-shaped device (a helical surface surrounding a central cylindrical shaft). The device draws power from the tidal stream as the water moves up/through the spiral turning the turbines.

3.1.6 Tidal kite

A tidal kite is tethered to the seabed, and 'flies' through the tidal stream with a turbine attached below its 'wing' to generate power from the motion. The kite swoops water in a figure-of-eight shape to increase the speed of the water flowing through the turbine. Tidal kites can be effective in areas with slower tidal flows.

These are the major devices currently found to be in operation worldwide and while newer technologies are being tried and tested, according to EMEC.

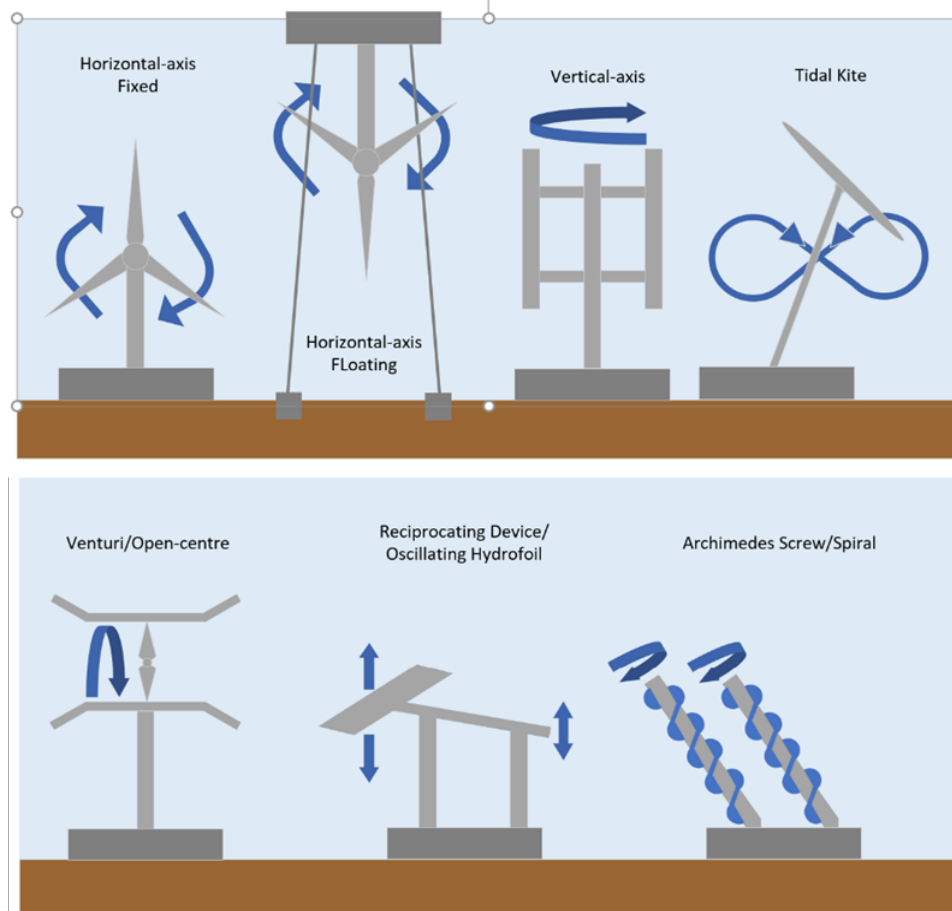


Figure 6 Tidal stream energy conversion devices¹³

3.2 Arrays

A larger array of turbines will naturally produce more energy. However, for tidal stream energy arrays, it is not a completely linear relationship between installed array capacity and energy output because, as the number of turbines increases within an array, global blockage effects increase leading to reduced net output per turbine¹⁴.

EnFAIT (Enabling Future Arrays in Tidal) is a EU Horizon 2020 flagship \$23m project to advance tidal stream energy, led by Nova Innovation¹⁵. The project programme ran in the UK, France, Germany and Belgium sites. As part of the project, Nova Innovation installed the world's first offshore tidal array at Bluemull Sound, Shetland in 2016¹⁶. It was originally an array of three turbines, a fourth turbine, Eunice was added in 2020. Now, with the installation of the 5th and 6th turbines, it became the array with the largest number turbines and has a total capacity of 600 kW¹⁷. It is claimed that Nova enhanced its technology and achieved a 40% reduction in the cost of tidal energy¹⁸. More details on how the cost savings has been achieved, is discussed in the section 7.1.2. In 2023, Nova Innovation obtained EU funding for a 4 MW, 16-turbine, tidal energy farm at the Fall of Warness tidal test site in Orkney, Scotland. This would be the largest number of tidal turbines anywhere in the world¹⁸. Nova Innovation is also installing a 1.5 MW array of 15 turbines in the Bay of Fundy, Nova Scotia¹⁹.

3.2.1 Blockage effects

Blockage is slowing of the resource speed as it approaches the first turbine leading to a reduced output compared to output on its own.

Research by Dirieh et al. indicates that the blockage effects need to be carefully considered during the calculation of annual energy production²⁰. There are two types of blockage effects, local scale and global scale. Local scale blockage is defined as ratio of the swept area of a turbine to the cross-sectional area of local passage. Global scale blockage is defined as the ratio of the combined swept area of all turbines to the cross-sectional area of the channel. The study by Dirieh et al. assessed local and global blockage effects at two hypothetical tidal farms with aligned and staggered arrangements. It confirms that the performance of an array is impacted, however, it can also be corrected by blockage corrections to some extent. On the environmental impact side, notably the change of velocities through the array, can lead to a side effect on the physical environment.

3.2.2 Wake Effects

Tidal arrays operate in a similar environment to the wind farm arrays. So, it is important to understand the resource dynamics through the array. Hence, windfarm array wake effects are felt relevant and are discussed in this section.

The wind flowing inside a farm (array) is disturbed by the layout of the turbines due to the complex interaction between turbines, their wakes and the ambient turbulent flow. This impact is commonly known as wake effect. The wind farm layout with respect to wind direction is a

¹⁴ [Review of technical assumptions and generation costs: Levelised Cost of Electricity from Tidal Stream Energy](#), Department for Energy Security and Net Zero, 2023

¹⁵ [Enfait Project](#) EU 2016

¹⁶ [Nova Innovation](#), Tidal energy arrays, accessed June 2024

¹⁷ [Nova Innovation](#), accessed in June 2024

¹⁸ [Nova Innovation News](#) 2023

¹⁹ Nova News, Bay of Fundy, 2023

²⁰ N.D. Dirieh, J. Thiébot, S. Guillou and N. Guillou, "[Blockage corrections for tidal turbines—application to an array of turbines in the Alderney Race](#)", Energies 2022

significant design factor to be considered as it impacts the performance and energy output of the array.

Wake effect, as shown in Figure 7, causes higher turbulence levels or lower incident velocities to certain turbines/rows in the array, therefore causing a reduction in the energy production of wind farm/array. It also leads to an increased turbulence on the dynamic mechanical loading on the wind turbines. These factors affect the capacity factor, hence the energy produced by the farm.

For example, Horns Rev wind farm experienced a reduction in energy generation capability because the downstream rows have produced 40% lower energy compared to the front row turbines²¹. It is important to analyse the mechanical loading on rotor blades to avoid its impact on the performance of tidal turbines.

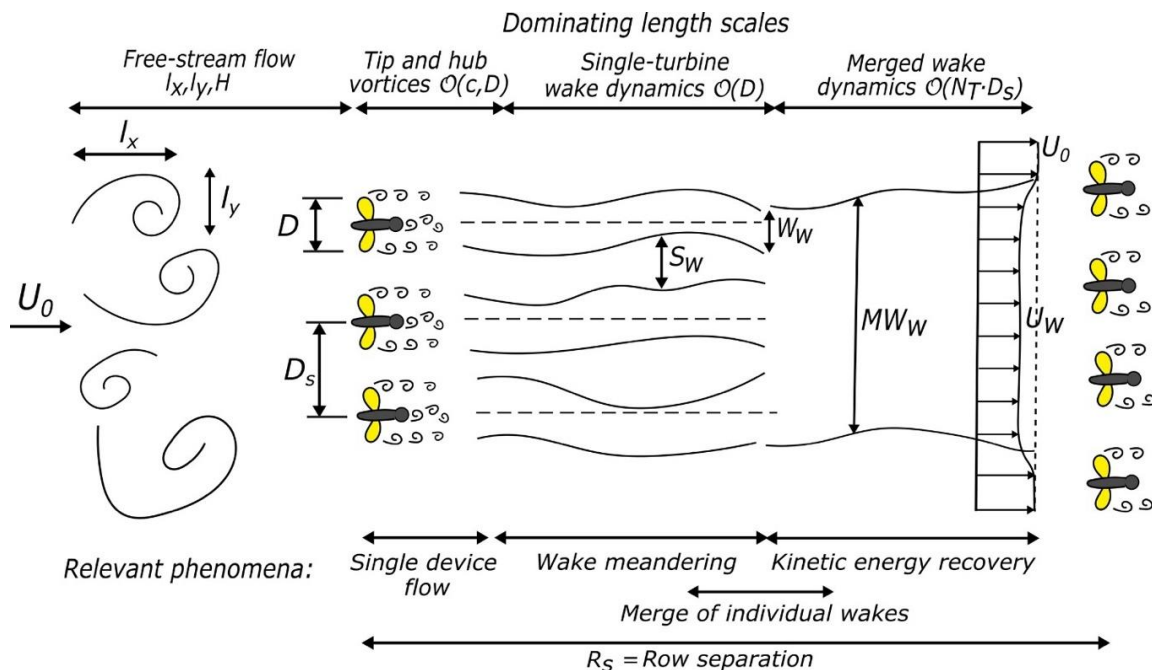


Figure 7 Wake effect²¹

A key issue is the prescription of how much energy can be effectively removed from hydro dynamic system, that can be ascribed to useful energy generation.

Another area that could benefit from further research is wake losses, the amount of energy that is lost due to wake propagation between rows of turbines.

Thus, wake effect is an important factor to be considered in the design and placement of turbine blades in order to maximize the tidal arrays' energy output. The detrimental mechanical effects can be avoided by prior support structure loading and fatigue damage analysis. It is essential to avoid the sudden failure or unscheduled maintenance.

²¹ P Ouro, L Ramírez and M Harrold, [Analysis of array spacing on tidal stream turbine farm performance using Large-Eddy Simulation](#), Journal of fluids and structures, 2019

3.3 Foundations

The cost of foundations for tidal stream turbines is a significant factor in the CapEx of a tidal project. The cost of the foundation and installation could account for around 32% of the total CapEx^{93, 94}. For example, offshore wind foundations typically contribute to 15 - 25% of the project cost²². Looking at an offshore wind project, foundation cost optimization is dependent on the selection of most suitable foundation type, combined with a progressive and integrated design process.

Geotechnical investigations, alongside environmental impact investigations must be carried out in the early stages of a tidal project to determine the soil type, depth leading to a decision on the type of suitable foundation. Currently, UK tidal projects²⁸ are using various types of foundations as shown in Figure 8.

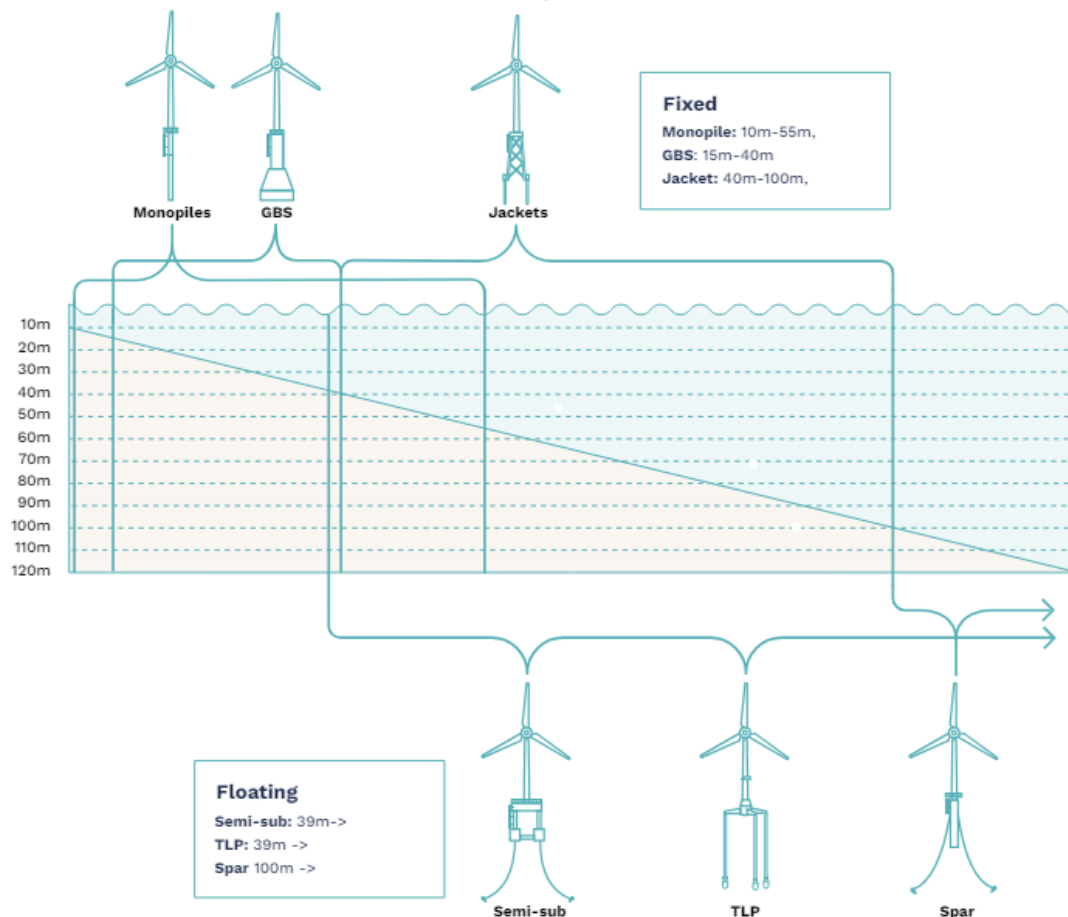


Figure 8 Offshore foundations⁹³

Tidal projects can benefit from the learnings gained by the existing offshore wind industry. With that in mind, the current offshore wind foundations have been reviewed. For water depths less than 50 m, existing offshore wind turbines commonly use fixed foundations, such as gravity base, monopile, tripod and jacket foundations, which are discussed in detail in the next section. At water depths greater than 50 m, floater options are seen as a better economic viable option

²² [GWEC prefeasibility study - offshore wind farm](#), 2015

for the resource exploitation²³. Same rule applies to tidal turbines as well²⁴. Alongside offshore wind turbine placement advancements, tidal turbines can also benefit from the advances in the floating oil and gas platforms such as tension leg platforms, semi-submersibles, and spars in the usage of mooring systems and anchor foundations²⁵.

Tidal turbines can be fixed to the seabed, or float nearer the surface with moorings attached to the seabed. Tidal energy systems commonly use one of these three fixed structures and three floating structures.

- Piled foundations have the support columns are sunk into the seabed. Suitable for clay, sandy and hard soils. These are simple to install therefore, a popular choice as it is an established offshore foundation method for years. Potential issues include scour and erosion. On the other hand, these foundations use less steel compared to gravity foundations leading to reduced costs. These foundations are simple in design, take less space, allow the flexibility to optimise the micro sitting of turbines, lower cost and ease of adjustment, smaller ratio of supporting structure in comparison to the turbine rotor size.
- Monopile foundations, which are commonly used in offshore wind, are simple design and use less space. Monopile foundations have much smaller footprint compared to gravity-based foundations. These provide greater flexibility to optimise the micro-siting of turbines due to a much smaller footprint than gravity-based foundations, and are less expensive due to reduced steel requirement for the foundations by up to 90%¹⁴ leading to lower material cost per unit power¹⁴.
- Gravity based foundations rely on the weight of concrete and steel foundations that hold the modules in place. Highly suitable for hard seabeds and take a lot of space. Gravity based foundations do not need seabed drilling and post installation adjustments are easier, therefore optimisation of the array is easier. Hence these seem to be another popular choice for the tidal stream energy systems in the UK so far, even though these are heavier and expensive due to higher cost due to more concrete and steel usage.
- Semi-submersible is the most popular floater design in use. It consists of multiple columns, to provide stability and multiple pontoons to provide additional buoyancy. Catenary or taut spread mooring lines and drag anchors are used to hold the foundation in place. It is suitable for a wide range of water depths, from 40m.
- Tension-Leg Platform is a vertically moored platform consisting of columns and pontoons. Its unique feature is the mooring system, restraining the vertical heave motion, but laterally allows surge, sway and yaw. The three-leg platform offers good stability and can be used in a range of water depths, from 40 m. However, its construction and anchoring system costs are higher than other floater designs.
- Spar foundation offers great stability, however more suitable for around 100 m depth.

²³ [Deep Water](#), European Wind Energy Commission 2013

²⁴ X Wu, Y Hu, Y Li, J Yang, Lei Duan, T Wang, Thomas Adcock, Zh Jiang, Z Gao, Z Lin, A Borthwick and S Liao, Foundations of offshore wind turbines: A review, Renewable and sustainable energy reviews 2019

²⁵ M Barooni, T Ashuri, D V Sogut, S Wood, S G Taleghani, [Floating Offshore Wind Turbines: Current Status and Future Prospects](#), Energies 2023

The decision between the fixed and floating foundations is primarily made based on the water depth. Soil type influences this decision as well.

3.3.1 Fixed versus floating foundations

In recent decades, there has been a shift from fixed foundations to floating foundations. Floating offshore turbines can be categorized into three main concepts, spar buoy, three-leg platform, and semi-submersibles and the selection is dependent on how they achieve their stability²⁶.

Both Fixed and floating foundations have their merit and fit in selection criteria based on the depth. Floaters seem to be a popular choice when the depth increases further than 40m as can be noted from Figure 8⁹³.

- Bottom-fixed devices typically sit low enough in the water column to allow vessels to pass overhead, with minimum clearance requirements of 8m imposed, so they do not impact on local shipping activities.
- Bottom-fixed devices benefit from relative simplicity of design, learnings taken from the offshore wind industry and a smaller ratio of supporting infrastructure to rotor size which leads to lower material costs per unit power.
- Floating structures use anchors and flexible or rigid moorings to attach the structure to the seabed. Some of these designs hold the turbines in place on arms that can be levered up or down to allow easy access for maintenance of the turbines.
- Floating tidal stream devices can be towed to site for low-cost installation, flexible repositioning, and decommissioning.
- Floating platforms may also use a turret configuration to allow the device to passively align the turbines with the flow, without the need for a manual yawing system.

While the operation and maintenance costs of floating foundations are lower, the CapEx costs are still high. For example, the current Levelized Cost of Electricity (LCoE) for floating wind can be 2 to 3 times that of onshore wind as the CapEx costs for these structures are much higher⁹³. The facilities for the serial production of floating foundations are still being developed, hence there is scope for advancement in manufacturing, which can lead to cost reduction.

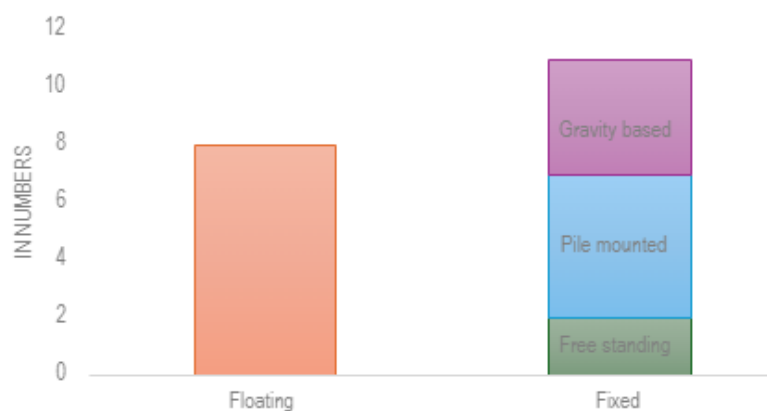


Figure 9 Tidal foundation types found in the UK

²⁶ N M Nasab, J Kilby and L Bakhtiaryfard, [Integration of wind and tidal turbines using spar buoy floating foundations](#), AIMS Energy 2022

Based on EMEC data²⁸ Figure 9 show the various foundation types currently in use in the UK deployments. A rise in floating foundations in comparison to the conventional pile mounted and gravity based projects can be observed. It is difficult to predict at this time, which foundation would finally be the popular one in terms of economics, however it is important to note that the site conditions also do dictate the type of foundation chosen.

4 Technology Readiness Level (TRL)

Technology readiness is instrumental in determining the development stage of that technology and its ability to enter the market, competing with others in the market. The development from conceptual idea to commercial stage is complicated. The energy system development process is envisaged to grow through five defined stages, each stage includes defined technology readiness levels as stated in Table 1²⁷.

Stage	Description	TRL
1	Tidal-stream energy conversion concept formulation	1 - 3
2	Testing of intermediate-scale subsystems, engineering studies.	4
3	Testing of large-scale subsystems	5 - 6
4	Full-scale prototype tested at sea	7 - 8
5	Commercial demonstrator tested at sea for extended period	9

Table 1 TRL system stages²⁷

Each subsystem/component will have different levels of opportunities for innovation and different levels of knowledge transfer from other existing established generating sectors as shown in Table 2. As can be noted, various turbine design developments are at different levels. Overall, the TRL of tidal stream is to be in the range of 8 to 9, so technically ready for the next step of commercialization¹⁴.

Design	TRL
Horizontal Axis - Fixed	8
Horizontal Axis - Floating	7
Vertical Axis	5
Tidal Kite	6
Venturi/Open centre	7
Reciprocating Device/Oscillating Hydrofoil	5
Archimedes Screw/Spiral	6

Table 2 Turbine design category and TRL¹⁴

²⁷ [EMEC](#), accessed in May 2024

Various Tidal turbine designs have been proposed, tested and in use, in the extraction of tidal stream energy. Based on EMEC data²⁸, various device types currently in use across the world and the UK are plotted in Figure 10 and Figure 11 respectively. The Horizontal axis tidal turbine is clearly the most popular one in use, followed by vertical axis turbine followed by others, indicating a good number of new technologies are being explored.

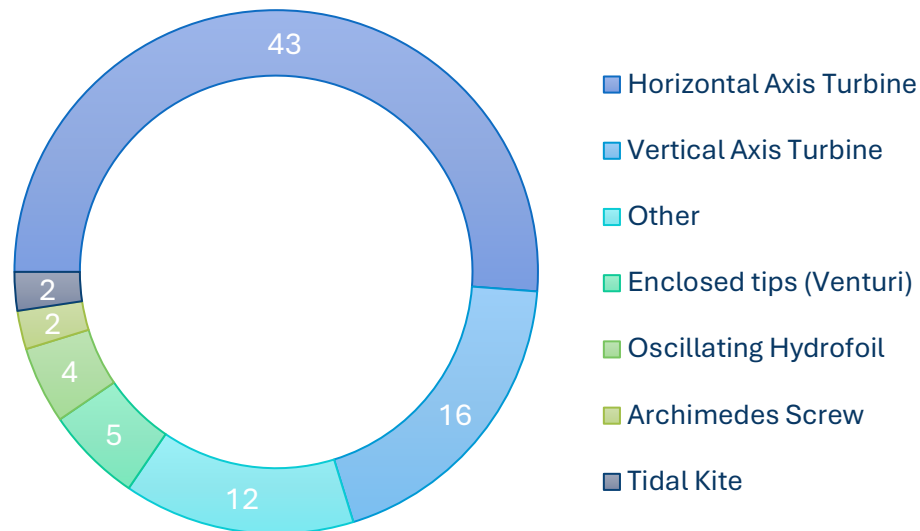


Figure 10 Numbers of each type of tidal device worldwide

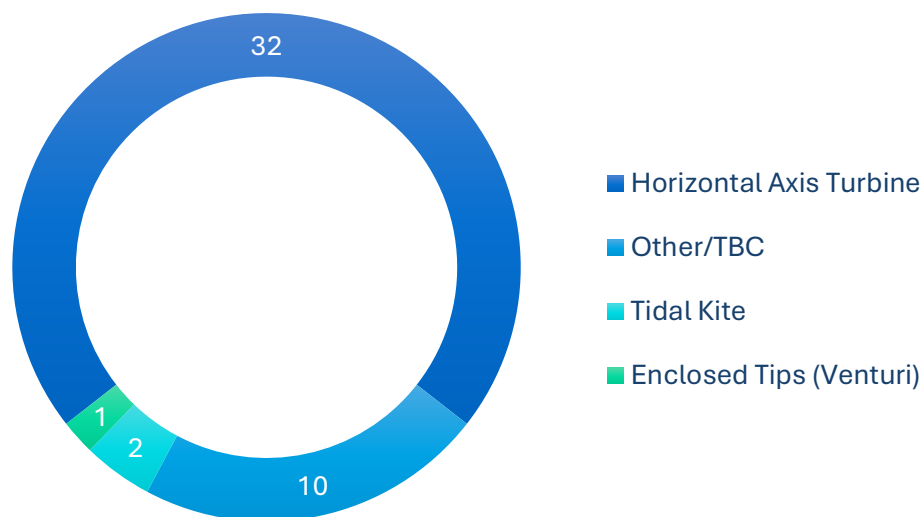


Figure 11 Numbers of each type of tidal device in the UK

From EMEC data²⁸, it is clear that the conventional Horizontal Axis Tidal Turbine (HATT) is a well-established turbine type taking up 43 out of 84 total installations worldwide as shown in

²⁸ EMEC Tidal projects, website accessed in April 2024

Figure 10. As these take up 51% installations, vertical axis turbines are the next most popular category with 19% installations. Figure 11 represents the turbine installations in the UK, with horizontal axis turbine being the most popular design, with 71% of the installations, taking up 32 out of 45 installations. Currently, HATT is a well-established and more evolved technology in comparison to the rest in operation. The other technologies are still emerging and being tested, hence it is difficult to predict which turbine would be the most suitable considering the site specific nature.

Within the horizontal axis category, the turbines modules are held in place by either bottom-fixed or floating structures. The support structure selection is heavily dependent on numerous factors including the position of the module, the water depth, the sea-bed environment, and construction limitations. Fixed structures use piled or gravity-based foundations. HATT is the one category where a converged technical solution has been reached.

UK renewable energy road map²⁹ identified,

- managing the risks and costs of research, development and demonstration;
- securing the investment required for commercial deployment;
- developing supply chain infrastructure and planning & securing consents;

as major roadblocks for the successful deployment of tidal stream energy.

Overall, the tidal range technologies are considered largely proven. However, their deployment is yet to see a commercial-scale success. While developers are currently evaluating many specific technologies and at larger capacities, but these are unlikely to be operational soon given the high costs and lead times for construction²⁹.

5 Tidal stream resource potential

A study³⁰ by the Crown Estates has estimated the theoretical resources of the tidal energy resources available in the geographic areas around the UK. The study defines

- the total resource is the ‘total energy that exists within a defined tidal system;
- the theoretical resource is the maximum energy that can be harvested from tidal currents in the region of interest without consideration of technical, economic or environmental constraints;
- the technical resource is the energy that can be harvested from tidal currents using envisaged technology options and restrictions (including project economics) without undue impact on the underlying tidal hydrodynamic environment;
- the practical resource accounts for key external restrictions (e.g. shipping, fishing, Ministry of defence etc.) The practical resource therefore refers to a proportion of the technical resource.

²⁹ [UK renewable energy roadmap](#) UK Government 2011

³⁰ [UK Wave and tidal key resource areas project – Summary report](#), Crown Estates Report., October 2012

5.1 UK resource potential

Total theoretical UK tidal stream resource is estimated to be around 32 GW according to a report by the Crown Estates. Table 3 outlines the geographical spread of tidal stream resource across the UK regions.

Country	Annual Energy TWh	Capacity GW
England	34	11.0
Wales	28	9.5
Scotland	32	11.0
Northern Ireland	1	0.5
Total	95	32.0

Table 3 Theoretical tidal resource in the countries of the UK³⁰

It is interesting to note that error bands for the tidal stream resource results were estimated to be between -30% and +45%. This highlights the emerging nature of the technology and the uncertainty in the assumed figures. The resource distribution study was carried out by Black and Veatch³.

UK tidal stream potential is estimated as 32 GW. However, approximately only 21% of this total is considered extractable, at 6.88 GW. Practical resource meant it included the site-specific external constraints⁴⁵.

The assessed results were obtained by imagining generation devices are deployed across large areas of seabed, and estimating how much electricity the devices would generate. This estimate did not take into account of existing sea uses for other generation or usage or environmental sensitivity factors. While technology is emerging, it is difficult to quantify these, while these factors were identified to impact the predicted capacity values. Additionally, any existing rights for offshore wind projects in any area take precedence over speculative interest in tidal projects in the same area.

Offshore Renewable Energy (ORE) Catapult report³¹ published in 2019 stated that “Tidal energy could deliver up to 15 GW of capacity on the UK grid, providing a valuable low-carbon, reliable power source to replace fossil fuels in the capacity market”. Renewables UK report³² estimated that wave & tidal stream energy combined has the potential to deliver around 20 per cent of the UK’s current electricity needs which equates to an installed capacity of around 30 – 50 GW. The Dutch marine energy centre estimated the UK tidal potential to be around 10 GW⁴⁶. Table 4 details a selection of various published estimates on the UK tidal potential. Some estimates were not clear enough to decipher whether tidal energy in that context included both tidal stream and tidal range estimates.

³¹ [Parliament evidence paper](#), 2020

³² [Renewables UK report](#), 2023

Source	Year	Estimated Tidal Resource (GW)	Resource
ORE Catapult report ³³	2019	15	Tidal Stream
Renewables UK report ³²	2023	30 - 50	Wave and Tidal
Dutch Marine Energy Centre ⁴⁶	2016	10	Tidal Stream and Range
Atlantis Resources ⁴⁵	2015	32	Tidal Stream (theoretical)

Table 4 Tidal resource estimates-UK

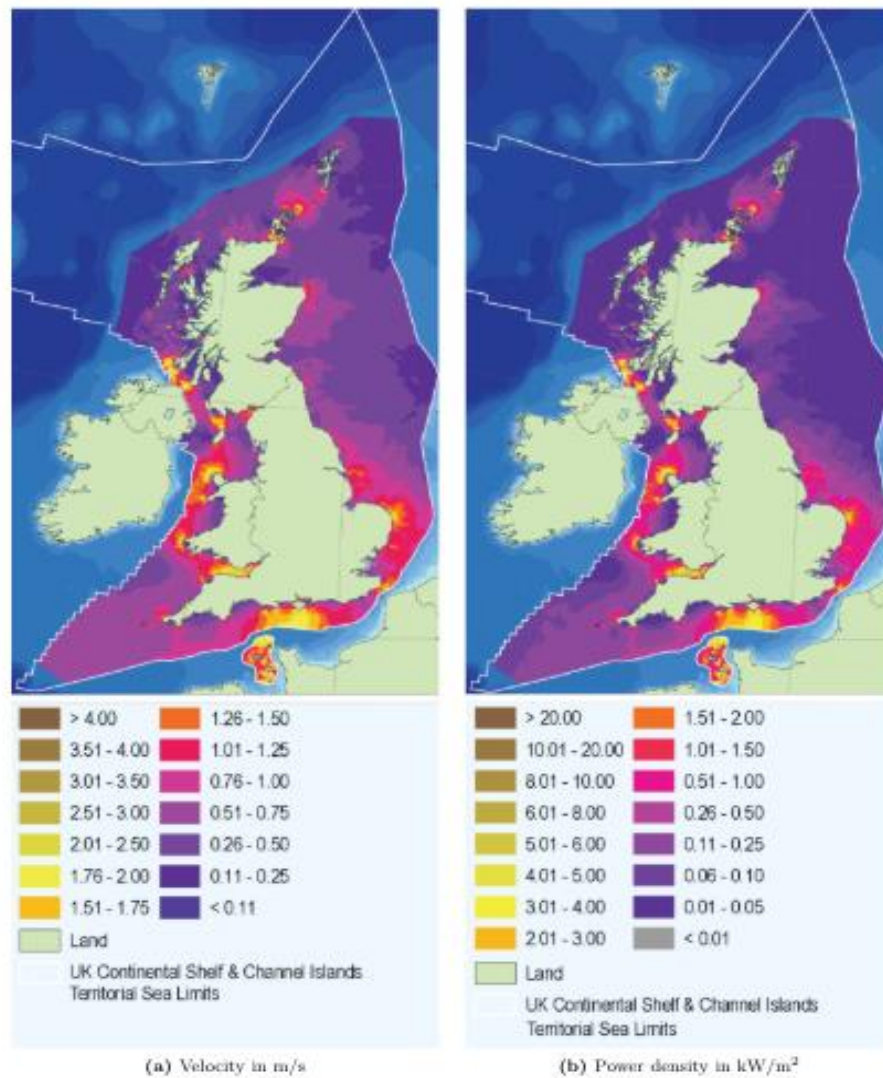


Figure 12 Tidal stream resource map for the UK³⁴

³³ [Tidal stream: opportunities for collaborative action](#), ORE Catapult Report 2019

Figure 12 gives a pictorial view on the UK tidal stream resource, by peak velocity and by power density³⁴. UK is amongst the countries with the highest available resource levels both in Europe, and worldwide³⁵.

5.2 UK Tidal stream projects securing government support

The UK government's main mechanism for supporting early-stage renewable electricity generation technologies is a Contracts for Difference (CfD). A 'reference price' is defined which is a measure of the average market price for electricity in the GB market³⁶. Generators holding a CfD are paid the difference between reference market price and the CfD strike price if the market price is lower but repay if the market price is higher. The counter party for the CfD is a government owned body, the Low Carbon Contracts Company.

Renewable energy technologies face high capital costs in the early stages of development. The CfD mechanism supports these developers by providing protection from volatile wholesale prices and a secure revenue stream for the duration of the contract. CfDs are auctioned in a number of allocation rounds (AR), with sperate auctions for a variety of technologies. The expectation is that as a particular technology develops and its costs reduce and its strike prices in the allocation rounds reduce toward the average market price. For 2024 allocation round 6, tidal stream generation costs were aligned based on the projections made in the published 2023 electricity generation costs report by Frazer-Nash consultancy¹⁴³⁷.

A list of tidal projects,^{38, 39, 42} that have been supported under allocation rounds 4, 5 and 6 are given in Table 5.

Tidal stream energy capacity of 10.4 MW was operating in the UK before 2022, and these projects were supported by the Renewable Obligation Certificates (ROC) scheme⁴⁰. The new CfD mechanism replaced the ROC scheme, from 2014, in a phased manner⁴¹.

Across the CfD allocation rounds the following volumes have been supported

- AR4 in 2022 supported a total of 40.82 MW tidal projects at a strike price of £178/MWh
- AR5 in 2023 supported 53 MW at a strike price of £198/MWh
- AR6 in 2024 supported 28 MW at a strike price of £172/MWh.

It seems as positive development as the final strike price achieved is £172/MWh as against the announced £261/MWh, meaning a 34% reduction in the sixth allocation round⁴², other technologies in this round have achieved a saving of around 20%. Overall, from round 5 to round 6, the strike price reduced from £198 to £172 which is a 15% reduction in prices. Overall, allocation rounds 4,5 and 6 will further add a capacity of 122 MW to the current operating 10.4 MW by the end of 2029.

³⁴ C Hachmann, [Power Generation from large-scale Tidal Stream Turbine Arrays](#), PhD Thesis, 2019

³⁵ [Wave and Tidal Energy in the UK: Conquering Challenges, Generating Growth](#), Renewables UK 2013 London

³⁶ [Contracts for Difference](#), UK Gov website 2024

³⁷ [Contracts for difference: methodology for Allocation Round 6](#) 2024

³⁸ Round 4, [UK Gov Website](#), Department for energy Security and Net Zero, accessed in May 2024

³⁹ Round 5, [UK Gov Website](#), Department for energy Security and Net Zero, accessed in May 2024

⁴⁰ [Archives from the department of energy and climate change](#), accessed December 2024

⁴¹ [Renewable Obligation guidance for generators](#), Ofgem 2017

⁴² Round 6, [UK Gov website](#), Department for Energy Security and Net Zero, accessed in Sep 2024

AR4 and AR5 would mean a doubling of capacity, three times by 2028, may double fourth time by 2030 if allocation round 6 and 7 go ahead with similar support from the government. If a 1 GW capacity has to be reached, it would mean the capacity doubling has to happen 7 times.

Tidal stream energy were able to compete for CfD grants alongside other renewables since the first allocation round in 2014. However, tidal alongside offshore wind and wave technologies were not able to secure funding under the first three allocation rounds of the CfD, held between 2014 and 2019. Following government consultations, in 2021, a ringfenced grant of £20 million per year was set aside, to help the marine technologies to be able to get the CfD awards⁴³. This clearly point to how reliant tidal energy is on support from government policies. The government then cut down the ringfence amount to half, £10 million. In March 2024, the ring-fenced amount was reset to £10 million, only to be increased to £15 million in August for the allocation round 6 renewable auction⁴⁴.

Allocation Round 4, 2022
Strike Price £178.54 / MWh

Project Name	Country	Tidal Developer	Capacity (MW)	Delivery
Orbital Marine Eday 2	Scotland	Orbital Projects 4	4.8	26/27
Morlais Magallanes GR3	Wales	Magallanes Tidal Energy	5.6	25/26
Orbital Marine Eday 1	Scotland	Orbital Projects 3	2.4	26/27
MeyGen Phase 2	Scotland	MeyGen	28.0	26/27
Total			40.8	

⁴³ [Government support for marine renewables](#), UK Parliament 2022

⁴⁴ [Marine energy Wales News](#) 2024

Allocation Round 5, 2023
Strike Price £198 / MWh

Project Name	Country	Tidal Developer	Capacity (MW)	Delivery
MeyGen AR51	Scotland	MeyGen	11.8	27/28
Ynni'r Lleuad	Wales	Hydrowing Tidal Projects	10.0	27/28
MeyGenAR52	Scotland	Meygen	5.6	27/28
Morlais VerdantIsles BL3	Wales	Verdantisles	4.9	27/28
Orbital Marine Eday 4	Scotland	Orbital Projects9	4.8	27/28
Morlais Mor Energy Zone GO3	Wales	Morenergy	4.5	26/27
Morlais Magallanes GR3 Extension	Wales	Magallanes Tidal Energy	3.0	27/28
MeyGenAR53	Scotland	MeyGen	2.9	27/28
Orbital Marine Eday3	Scotland	Orbital Projects 8	2.4	27/28
MeyGen AR54	Scotland	MeyGen	1.6	27/28
EMEC Magallanes Berth 1	Scotland	Magallanes Tidal Energy	1.5	27/28
Total			53.0	

Allocation Round 6, 2024
Strike Price £172 / MWh

Project name	Country	Tidal Developer	Capacity (MW)	Delivery
Seastar 1	Scotland	Sea Star Tidal	4.0	28/29
Ynni'r Lleuad 2	Wales	Hydrowing Tidal Project	10.0	27/28
Magallanes Berth 1 Extension	Scotland	Magallanes Tidal energy	3.0	28/29
Oceanstar 1	Scotland	Ocean Star Tidal	1.5	28/29
Oceanstar 5	Scotland	Ocean Star Tidal	0.5	28/29
MeyGen AR62	Scotland	MeyGen	9.0	28/29
Total Capacity			28.0	

Table 5 Tidal stream projects supported in the UK in recent allocation rounds through contracts for difference

5.3 Global resource potential

It is currently difficult to predict an accurate picture of available global potential, due to lack of high-quality hydraulic data on tidal resource. Recent studies have arrived at some tentative estimates of the tidal resource. Atlantis resources have estimated that the global potential of tidal stream energy could exceed 120 GW, with specific global estimates⁴⁵.

Various estimates on the global tidal potential vary widely as summarised in Table 7. For example, Atlantis resources (Atlantis Resources Limited is no longer in business. A related business, SIMEC Atlantis Energy Limited, still exists and trades as SAE Renewables and is the parent company of MeyGen. The world resources map is no longer available as a primary resource but has been preserved in secondary documents, Page 7, PhD thesis⁴⁵) estimated the global tidal potential to be well above 23 GW of realisable /technical resource, as indicated in Figure 13. Tidal stream resource split by country can also be observed from here, which are further plotted for a better country level presentation in Figure 15.

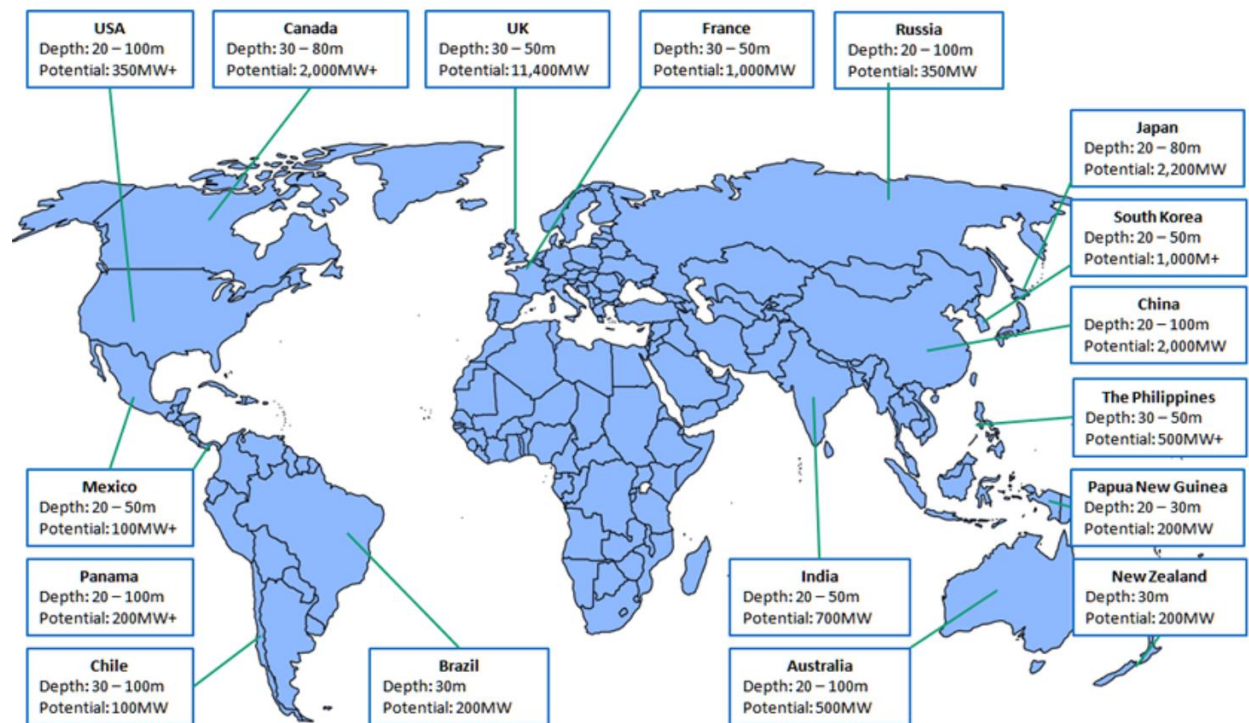


Figure 13 Global tidal stream resources (Atlantis)⁴⁵

⁴⁵ P Evans, [Hydrodynamic Characteristics of Macrotidal Straits and Implications for Tidal Stream Turbine Deployment](#), PhD thesis, Cardiff University 2015

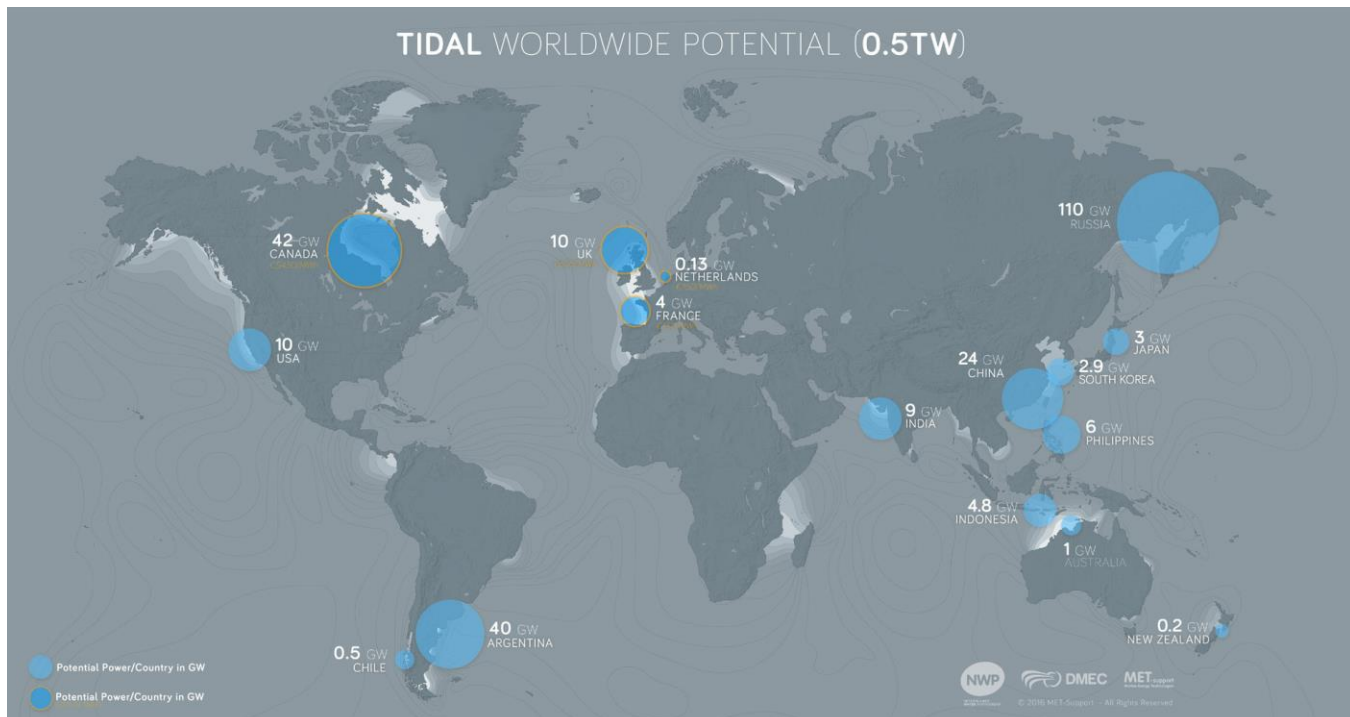


Figure 14 Global tidal resources (DMEC)⁴⁶

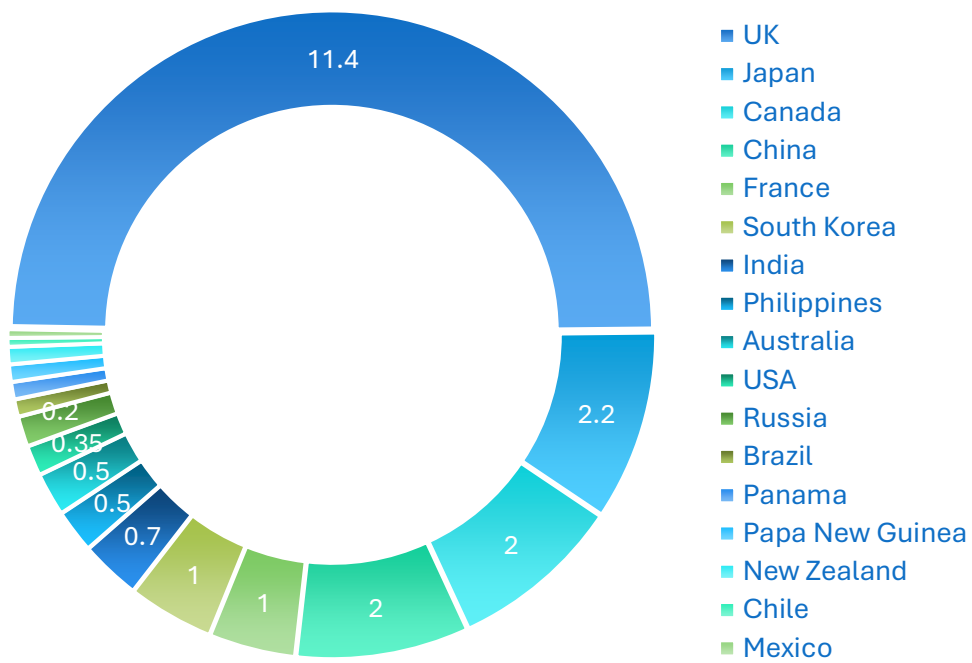


Figure 15 Tidal stream resource by country⁴⁵

Country	Estimate by Atlantis⁴⁵ (GW)	Estimate by DMEC⁴⁶ (GW)
UK	11.4	10.0
Japan	2.2	3.0
Canada	2.0	42.0
China	2.0	24.0
France	1.0	4.0
South Korea	1.0	2.9
India	0.7	9.0
Philippines	0.5	6.0
Australia	0.5	1.0
USA	0.4	10.0
Russia	0.4	110.0
Brazil	0.2	-
Panama	0.2	-
Papa New Guinea	0.2	-
New Zealand	0.2	0.2
Chile	0.1	0.5
Mexico	0.1	-
Argentina	-	40.0
Netherlands	-	0.1
Indonesia	-	4.8
Total	23.0	267.0

Table 6 Global estimates of tidal stream resource - comparison

An alternative global estimate by the Dutch Marine Energy Center (DMEC) is shown in in Figure 14⁴⁶. It varies significantly from the Atlantis estimate and states that the global tidal resource is as high as 500 GW. Russia has the highest capacity at 110 GW which is many times greater than the Atlantis estimate. The Russian resource is situated in East Siberia, an area stated to be uninhabited. Other large differences are seen in estimates for Canada and China, and a large resource of 40 GW in Argentina for which no estimate was given by Atlantis. There is, broad agreement on the figure for the UK with 11.4 GW stated by Atlantis and 10 GW by DMEC.

It is not clear from the information if it is theoretical resource, which would then mean, once it is subjected to practical constraints such as technology options, site specific restrictions, internal and external restrictions, the actual realisable potential would be far less. The global estimates from Atlantis resources and DMEC widely vary at 23 GW and 500 GW respectively. It is possible that the DMEC estimate is taking into account of both tidal range and tidal stream potential. The country-based estimates from these sources are put together in Table 6 to see how much they differ. While the estimates on the UK and Japan are do not vary widely, countries like Canada, China, India, USA and Russia vary significantly.

⁴⁶ [Dutch Marine Energy Centre, 2016](#)

A study by Ocean Energy council⁴⁷ estimated the global tidal potential to be 64 GW. Another estimate in the European renewable energy road map states the global ocean energy target, that includes wave and tidal stream energy, is set at 748 GW⁴⁸.

Based on Atlantis resources, a Canadian news article reports that the estimates of potential of tidal stream generation capacity could exceed 120 GW globally⁴⁹. Theoretically, it would mean a potential total global market size of up to 90 GW of generating capacity.

Source	Year	Potential Power	Resource
Dutch Marine energy Centre ⁴⁶	2016	500 GW	All Tidal
Ocean energy council ⁴⁷	2018	64 GW	All tidal
Atlantis resources ⁴⁵	2015	120 GW	Tidal stream

Table 7 Estimates of global tidal resource

The future global market for tidal stream energy will be dictated by feasible exploitable natural resource. Grantham institute⁵⁰ indicates that “Despite some differences in estimates, there is reasonable agreement that the global tidal stream energy resource is equivalent to more than 100 GW of generating capacity”. This is not an ignorable level of capacity coming from renewables. The tidal streams are predictable and well ahead, this gives them a good opportunity to replace energy at peak times. Tidal energy can potentially replace other renewable energies as well as natural gas for power generation.

5.4 International Projects

This section reviews the state of tidal stream energy projects in a selection of countries where tidal energy has gained interest.

Over a period of time, a number of tidal stream projects have been planned in the UK, many have hit various hurdles, the main one being financial constraints because of their dependency on public funding. Some are delayed during their development stage.

Perpetuus Tidal Energy Centre (PTEC) is currently working to develop a 30 MW tidal array project in the English Channel at Isle of Wight⁵¹. The 5km² development site will be segregated into a number of berths, with each berth having a defined area, leased to a developer in which they will demonstrate their tidal technologies. Berth capacities may vary between 1 MW and 10 MW and tidal device capacities may vary from 100 kW to 6 MW. According to a signed agreement in 2021 with Orbital marine power ltd, the world’s most powerful tidal turbine, the Orbital O2, will be installed at the site. The initial target is to deploy up to 15 MW by the end of 2025. In January 2023, PTEC transitioned to a Build-Own-Operate model and private offtake with large energy users. Scottish-based Orbital already operates the world’s most powerful tidal turbine, the O2, and is currently progressing with a portfolio of commercial projects in the UK market⁵².

⁴⁷ [Ocean Energy Council website last updated 2018, accessed in April 2024](#)

⁴⁸ [European Offshore Renewable Energy Roadmap](#), Ocean Energy Council 2011

⁴⁹ [Tidal energy today news](#), Energy BC 2017

⁵⁰ [Grantham Research Institute on climate change and environment, website accessed May 2024](#)

⁵¹ [Perpetuus Tidal energy Centre website](#), accessed June 2024

⁵² [Orbital Marine](#) 2024

A 30 MW capacity project is being developed at Portland Bill, England with devices of 1 MW capacity²⁸.

A tidal stream research project in Ramsey Sound, Pembrokeshire, UK undertaken by Delta Stream was initiated with funding of £18m but stopped generating electricity after just three months because of a fault⁵³. The reasons for the project closure were claimed to be an intermittent fault with an active sonar device, followed by a mechanical failure in the 400 kW turbine. Soon after, Delta Stream went into administration.

The Ynys Enlli tidal energy project planned to transform Bardsey Island in Wales, into world's first blue energy island⁵⁴. Nova Innovation received a £1.2 million grant to progress environmental consenting and the technical design of the project. The funding provided by the Welsh government, through the European Regional Development Fund (ERDF). The plan was to install five 100 kW turbines on the seabed with a view to installing more turbines in the future. However, the development hit severe problems in 2023, due to a range of site-specific factors, revenue support limitations and grid and cable routing constraints⁵⁵.

The Netherlands, which was predominantly looking into wind and solar panels, has now extending its support to tidal energy exploration. Dutch Government has invested \$5 million into tidal energy exploration in the Wadden sea region⁵⁶. The fund is being invested into turbine development including a tidal kite. The European companies, in general, are currently responsible for 70% of the global ocean energy capacity.

The Canadian federal and provincial governments have invested approximately \$200 million in the tidal industry, engaging over 500 companies⁵⁷. A regulatory task force was set up to investigate staged approach of authorizing tidal projects in order to increase the pace of the projects approval process while ensuring risk assessments have taken place.

The US Department of Energy allocated a five phase \$35 million funding to advance tidal and river current energy systems⁵⁸. Fund will be spent on innovation, research, development, demonstration, easing the complexity of installing devices and navigating permitting processes, local grid connection. A proposed legislation, marine energy technologies acceleration act, to invest \$1 billion to propel marine energy toward full-scale commercialization, has been introduced to the U.S. House of Representatives in August 2024⁵⁹. The United States have some pilot projects operating and in various stages of development. These are Roosevelt Island Tidal Energy (RITE) project pilot in the east river of New York, Western passage tidal energy project in Maine and Cobscook Bay tidal energy project in Maine⁶⁰. There are no commercially operating tidal power plants apart from the demonstration projects.

France's first tidal farm at North Brittany has been operational in 2016⁶¹. It is a 4 MW tidal energy plant costing \$49 million⁶². In 2023, France ministry of energy transition has announced at least \$71 million of funding, plus dedicated revenue support, for the pioneering 17.5 MW tidal energy pilot farm

⁵³ [BBC News](#), 2016

⁵⁴ [Bardsey island](#), Marine Energy Wales 2020

⁵⁵ [ReNews](#) 2023

⁵⁶ [Euro News](#), 2024

⁵⁷ [Govt. Canada, Department of Fisheries and Oceans](#), 2023

⁵⁸ [U.S Department of Energy](#), 2024

⁵⁹ [Offshore news on marine legislation](#), 2024

⁶⁰ [U.S. Energy Information Administration](#), 2024

⁶¹ [Power Technology News](#), 2017

⁶² [Recharge News](#) 2016

project FloWatt⁶³. It will be located at Raz-Blanchard in the English Channel. This pilot project will be made up of seven turbines, each with a capacity of 2.5MW is expected to become operational in 2026.

Tidal Stream Industry Energiser Project (TIGER), launched in 2019 funded by the Interreg France (Channel) England Programme, with \$55 million invested to drive collaboration and cost reduction through tidal turbine installations in the UK and France. The France tidal power market size is expected to grow from 242.56 MW in 2023 to 302.85 MW by 2028⁶⁴. After the UK, France is the second country to deliver strong support and market visibility to boost tidal development.

Philippines has allocated \$187 million, leveraged from the public and private sectors to invest into tidal stream sector with hybrid systems. Proposed projects will install 64 MW of tidal stream energy hybrid systems, and around 100 MWh battery storage in off-grid islands in the Philippines during the lifespan of the project⁶⁵. South east Asia's first tidal power plant at 1 MW capacity in the Capul island is being built by UK Inyanga marine energy group.

Indonesia has one of the biggest tidal stream energy potential in the world, with more than 13,000 islands. Companies such as UK's Nova innovation, Hydrowing and France's Sabella are contracted to provide the necessary tidal infrastructure. Innovate UK has awarded £200k to Nova's Feasibility of Larantuka and Indonesian Tidal Energy (FLITE) project that will deliver a feasibility study for a 7 MW tidal array in Larantuka Strait⁶⁶. Tidal power plant Larantuka is a 30 MW project, with an estimated budget of \$220 million is under development.

Taiwan, is undertaking site development to establish the first tidal energy arrays with Minesto's technology in Asia⁶⁷. This will be a demonstration project, aimed to supply baseload generation from the continuously flowing Kuroshio currents.

Faroe islands, Denmark is in the process installing the first tidal energy kite array using Minesto's technology. In April 2022, Minesto announced a detailed plan for large-scale buildout of tidal energy arrays. It set out a stepwise installation plan for tidal kite arrays, each with 20-40 MW installed capacity, at four verified locations. As a start, using DG100 tidal kite model, two 100 kW turbines at Vestmannaund, exported electricity to the grid, first time in the world. Hestfjord is chosen to install a tidal array of about 30 MW, including twenty-four kite systems at 1.2 MW each. Minesto was also awarded a \$3 million grant from the European Commission's SME Instrument programme. This funding supported the installation of Minesto's technology in the Faroe Islands together with Faroese utility company SEV through a project named 'Deep Green Island Mode' (DGIM)⁶⁸.

⁶³ [Offshore news on Flowatt project](#), 2023

⁶⁴ [France tidal power market forecast](#), 2024

⁶⁵ [Mitigation Action Facility](#), Philippines 2023

⁶⁶ [Innovate UK Larantuka project](#) Indonesia 2021

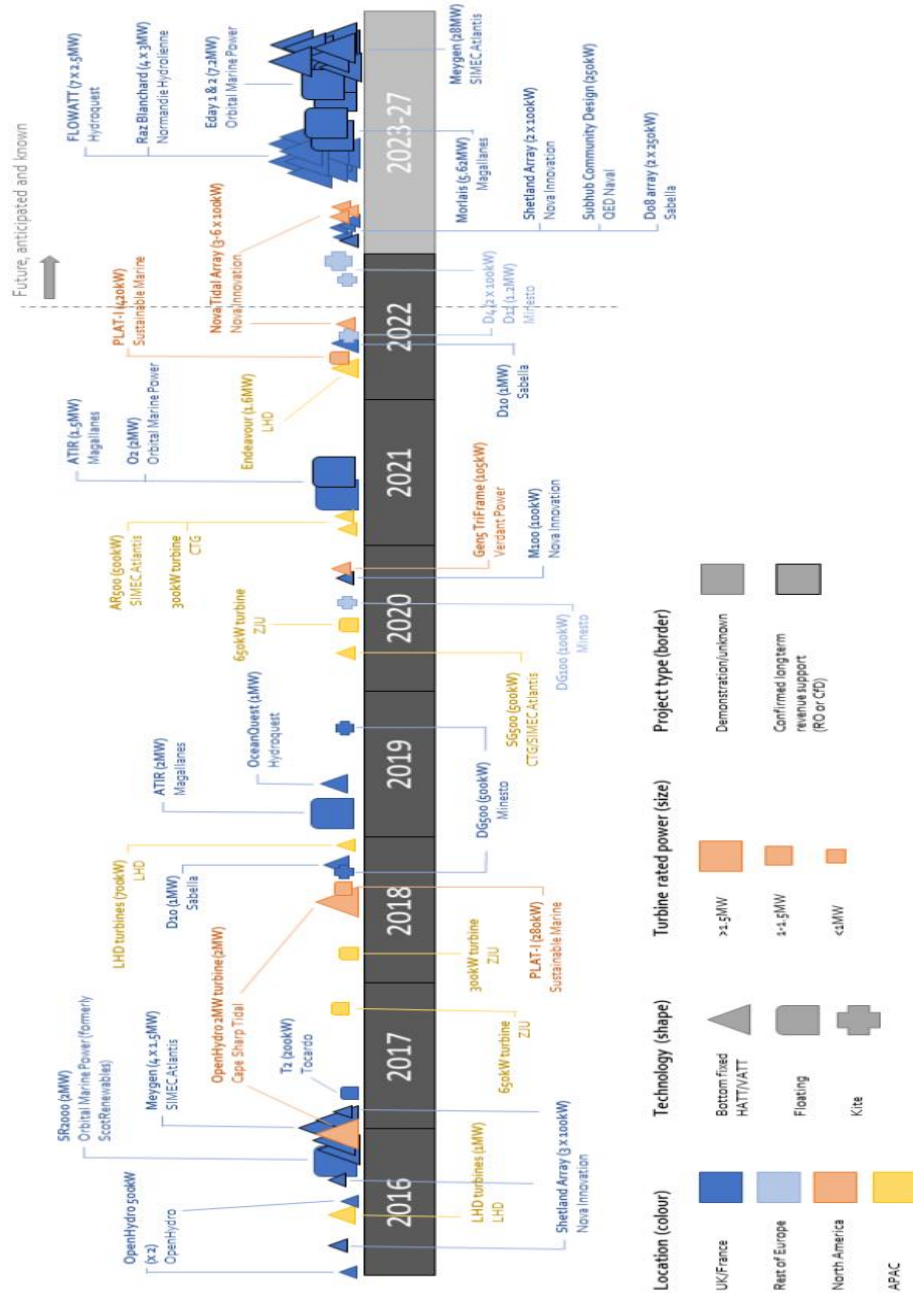
⁶⁷ [Minesto in Taiwan](#) 2024



Figure 16 Faroe Islands deep green island project⁶⁸

Figure 17 represents the timeline showing the global tidal stream turbine deployments, including anticipated deployments from 2016 to 2027. The timeline also shows anticipated turbine deployments out to 2027⁸⁹.

⁶⁸ [Minesto in Faroe Island](#) 2019

Figure 17 Tidal stream deployments worldwide⁸⁹

5.5 Effects of Climate Change

Tidal energy projects can help achieve Government's climate change policy objectives leading to reduced greenhouse gas emissions. However, if climate change is not controlled, it can lead to long term shift in global temperatures. This causes ocean warming and rise in sea levels. This happening can potentially alter the tidal energy resource.

Tidal Stream Energy is site specific. It mainly depends on external driving forces such as tides, wind, river inflows, etc., boundary conditions such as bed/bank roughness, intrinsic fluid properties such as density, and estuarine geometry like, shape, length, depth, bed slope etc. Any potential adjustments in estuarine geomorphology due to changes in sea levels can directly influence further changes in the stream velocity and power. The United Nation's Intergovernmental Panel on Climate Change (IPCC) estimated a sea level rise between 0.28 m and 1.02 m by 2100, whereas some recent studies suggest a rise of 2 m by 2100⁶⁹.

A study was conducted on the effect of sea level rise on the available tidal energy from estuaries and hotspot locations⁷⁰. It is found that sea level has an impact on the spatial and temporal distribution of tidal stream power and location of the best-suited sites. It means that the currently worth exploring optimal tidal sites may be eliminated and displaced due to geomorphic adjustments and the shift in the spatial energy patterns within an estuary. So as sea levels rise, the existing tidal power may cease to exist.

Hence rising sea levels due to climate change potentially pose a potential challenge to the tidal energy development and production. It is important to understand the precise level of impact on tidal energy, but there is very little research available on this at this time.

5.5.1 Similarities and dissimilarities between Wind and Tidal stream

Bringing together two marine renewable technologies with considerable synergies, the combined harnessing of offshore energies presents an excellent potential for development.

Tidal stream generators draw energy from water currents in much the same way as wind turbines draw energy from air currents. Tidal generators can also benefit from the substations, subsea cables technology which is already established with offshore wind. The vessels and maintenance schedules vary, due to smaller sized tidal turbines. In terms of operation and maintenance, tidal energy systems can benefit from the fact that the turbines are smaller in size, the distance to shore is lot less, so easier transportation and smaller sized vessels will suffice. It is preferred that the maintenance parts are carried to offshore for repair and service especially due to the submerged nature of the components which makes it difficult to carry out onsite maintenance.

The tidal energy and the longer-established wind energy exhibit similarities in terms of their energy conversion system. However, several key technological differences also exist.

The main difference between the wind and tidal is the turbine operational environment, tidal turbine is operating in high density of the seawater, which is 840 times denser than air. The positive consequence is that the energy available in water is much higher since the kinetic energy flux per unit area will be significantly larger. In other words, a smaller diameter tidal turbine is required for the same energy. The negative consequence is that turbine core materials must withstand higher forces as well as a harsher operating environment, particularly in terms of corrosion by seawater.

⁶⁹ [Climate change in the critical decade, a summary of the IPCC 6th assessment report and its implications for the UK](#), The Royal Society 2022

⁷⁰ D Khojasteh, S Chen, S Felder, W Glamore, M R Hashemi and G Iglesias, [Sea level rise changes estuarine tidal stream energy](#), Energy 2022

Turbine blades of tidal and wind appear visually similar. They are both made of glass or carbon fibre composites but there are significant differences between the structures. The tidal turbine blades experience different environmental conditions including pressure, salinity and marine debris. The blades are expected to withstand variation in loading due to pressure changes with increasing depth during rotation. The blade design has less focus on being light weight and instead a focus on strength. The European Composites Industry Association has been contributing its expertise on life cycle assessment (LCA) of composites¹⁰⁰. A study that reviewed 58 tidal stream energy deployments between 2003 and 2020 for failure modes, concluded that majority of the deployments, 54%, performed well, 14% generated less power than planned, 18% failed and 14% were withdrawn from service⁷¹. The dominant cause of failure was blade failure, followed by generator and monitoring failures. Ducted devices and devices in high velocity locations were more likely to fail, indicating the importance of withstanding the difficult conditions imposed by high flow velocity. Blade failures were attributed to underestimation of loads during design. Floating tidal turbines deployments were found to be less likely to fail than bottom-fix deployments, but they were more likely to be curtailed by dynamic motion under strong currents. There was no difference in failure rate between off-grid and grid-connected deployments.

Tidal energy devices, depending on their scale, are affected by both a static bottom boundary (the seabed) and a dynamic surface boundary (the water surface), while a wind-power device is only subject to a bottom boundary. These boundaries limit the freedom in increasing the tidal turbine rotor diameter.

The largest onshore wind turbine is as big as 5 MW, while offshore wind turbines can be as large as 12 - 15 MW turbines⁷², so increase in turbine rating may not be seen applicable to tidal systems to the same degree⁵⁰. The current highest building tidal turbines are rated up to 2 MW, but the scope for going larger is limited by environmental factors including shallow water depth operation, which limits blade length.

Tidal energy systems use squirrel cage induction machines and permanent magnet synchronous machine generators. Most turbine manufactures use an air gap generator, which is the same as in use for wind and hydro energy systems. However, the generator needs to be encased in a watertight nacelle, which makes it vulnerable to water ingress due to wear or leakage through the seals due to harsh operating conditions. Oil and gas industry ships and submarines have a system using a bilge pump and dehumidifiers, where this leakage water is drained periodically. Bilge pump does add to the capital cost. However, it improves reliability at extra cost.

A hybrid spar buoy floating structure providing foundation co locating both tidal and wind turbines on the same platform is a novel concept being investigated²⁶. It defines a method of foundation design of integrated wind and tidal structures in deep waters, which is expected to reduce the CapEx costs and operation and maintenance costs thus leading to reduced cost of electricity per unit.

The pitch control systems used in wind turbines are not suitable for tidal turbines, making this a new key area, open for development³³. The resource characteristics at a site and the difference in loading challenges coming from turbulence intensity in tide as opposed to wind, means that the control strategies will vary from those used to date on wind turbines.

⁷¹ S Walker, P R Thies, [A review of component and system reliability in tidal turbine deployments](#), Renewable and Sustainable energy reviews 2021

⁷² [Future of Wind](#), International Renewable Energy Agency (IRENA) 2019

6 Learning Rates

Technological change is a function of experience. The price of technology declines when more of that technology is produced, is a classic case of learning by doing. Increasing production gives the engineers an opportunity to improve the process and innovate. This section primarily reviews the learning rates of long established, wind and solar industries, the factors that affect the rate and finally looking at the projected tidal learning rates.

Estimating the future costs of emerging power generation technologies can help inform investments and power sector planning. However, it is challenging to project these costs accurately as the technological progress depends on innovation which is often unpredictable. From past experience can help projections through the concept of learning curves of technology development. Learning rates have been observed to hold true over large increase in installed capacity. A learning rate is defined as the change in cost for a doubling of cumulative market volume⁷³. Learning rates are seen to hold approximately constant, although subject to external disturbance (such a global supply chain shortages) and can be applied to deployment projections to estimate future costs. While learning rate is one of the most efficient ways of assessing future costs of generation, in the process of simplification it ignores the technology advancement related to operational costs, thus underestimating cost of electricity⁷⁴. It is important to note that learning rates apply to the capital cost of a technology and there are other important elements to the levelized cost of energy such as operation and maintenance costs.

The experience can be expressed as part of cumulative production or cumulative installed capacity as shown in equations 2 and 3⁷⁵.

$$P_t = P_0 Y_t^{-E} \quad (2)$$

where

P_t is the price of unit output at a time t . This could be a proxy cost.

P_0 is the price of the first unit, and

Y_t is cumulative output at t .

E captures the experience parameter.

A logarithmic estimate of E is captured as

$$\log(P_t) = \log(P_0) - E \log(Y_t) + e_t \quad (3)$$

where, e_t defined as error term.

Learning rate gives the percentage of change in cost corresponding to a doubling of experience as defined in equation 4⁷⁵.

$$\text{Learning Rate} = 1 - 2^{-E} \quad (4)$$

Equation 5 denotes the formula for the learning curve⁷⁶

$$y = ax^{-b} \quad (5)$$

where

⁷³ [Moore's law](#), Intel 1965

⁷⁴ M Bolinger, R Wiser and E O'Shaughness, [Levelized cost-based learning analysis of utility-scale wind and solar in the United States](#), Iscience 2022

⁷⁵ [Predicting the costs of photovoltaic solar modules in 2020 using experience curve models](#), Energy 2013

⁷⁶ [Learning curve](#), Oxford reference 2024

y is the cumulative average time per unit of production,
 a is the time taken to produce the first unit,
 x is the cumulative number of units manufactured to date, and
 b is the learning coefficient.

When the rate at which the technology's cost declines or stays roughly constant, that technology is said to be following Wright's law⁷⁷. Moore's observation on integrated circuit technology can be considered as a special case of Wright's law. This effect creates a virtuous cycle of increasing demand and falling prices. More of that technology gets deployed to satisfy increasing demand, leading to falling prices. At those lower prices, the technology becomes cost-effective in new applications, which in turn means that demand increases. In this positive feedback loop, these technologies power themselves forward to lower prices.

Technology cost reduction is popularly quantified through use of experience curves. Compared to learning curves, experience curves additionally include value-added costs such as administration, marketing, distribution, and manufacturing costs. Single-factor experience curves are most widely used, in which the learning rate quantifies the percentage cost reduction for each doubling of capacity. Learning rate predictions include an assumption on several drivers of cost reduction as detailed below⁷⁹.

- Learning by doing, by means of volume and deployment experience.
- Learning by research, by means of innovative research and development.
- Learning by adaption, by means of knowledge and experience transfer from other sectors.
- Learning by interaction, by means of collaborations and knowledge exchange platforms.
- Economies of scale, by means of increasing scale of individual devices.

Tidal stream energy technologies research has estimated a varied set of learning of rates from various sources and a selection of these sources and their learning rates are detailed in Table 8.

Organisation	Learning Rate	Year
ORE Catapult ⁷⁸	10-15%	2022
Carpower Ocean ⁷⁹	5-15%	2022
Carbon Trust ⁷⁹	2-18%	2011
EnFait Report ⁸⁰	16%	2019
Astariz and Iglesias ⁸¹	10-14%	2015
Frazer Nash ¹⁴	9-17%	2023
Black and Veatch ¹⁰⁴	8-16%	2011

⁷⁷ [Wright's law](#), Forbes article 2013

⁷⁸ [Quantifying the benefits of tidal stream energy to the wider UK energy system](#), ORE Catapult 2022

⁷⁹ S Pennock, A Garcia-Teruel, D R Noble, O Roberts, A Andres, C Cochrane and H Jeffrey, [Deriving current cost requirements from future targets: case studies for emerging offshore renewable energy technologies](#), Energies 2022

⁸⁰ [Enabling future arrays in Tidal energy](#), EnFAIT report 2019

⁸¹ S Astariz and G. Iglesias, [Wave energy vs. other energy sources, a reassessment of the economics](#), International journal of green energy 2016

Table 8 Tidal learning rates

The Enfait report has taken into consideration of similar technologies to estimate the learning rate of tidal technologies. These technologies include

- Offshore wind (17%),
- Aerospace (15%),
- Shipbuilding (15% - 20%),
- Machine Tools (15% - 25%),
- Electronics (5% - 10%), Electrical Wiring (15% - 25%),
- Machining (5% - 10%),
- Manual Assembly (10% - 20%),
- Welding (10%)

and their average learning rate stands at 13.7%. Their LCoE model has assumed a learning rate of 10% and 7% for CapEx and OpEx respectively.

Maturity Level	Learning Rate (%)	Sensitivity (%)
Low	15	±5
Medium	10	±5
High	5	±5

Table 9 Learning rate vs maturity

The diversity in specifications and in interpretation the data has resulted into a wide range of learning rates in the literature as can be observed from Table 7 Table 8 and their sensitivity to maturity levels in Table 9. This variation creates challenges for practical application.

Learning rate of a given technology is dependent and inversely proportional to its maturity level. A technology that is less matured, has more scope for learning, leading to higher cost reductions, thus its potential to learn is higher. Similarly, a highly matured/established technology has relatively limited scope for learning, leading to lower cost reductions. The exact learning rate for a given technology differs slightly across studies, mostly due to differences in the chosen data source, the chosen proxy measure for 'experience', the geographic location or the considered timespan.

It is clear from both Figure 18 and Figure 19 that renewable energy learning curves are steeper than fossil fuel generation⁸². Understandably, renewables are less mature than thermal generation, do not have fuel costs and therefore relatively smaller O&M costs, so reductions in capital costs are expect to be larger and feature more prominently in total cost. It is important to note the role energy production plays in the Levelised Cost of Energy. First, the improvements in load factor of offshore wind turbines as diameters and tower heights have increased also helps to improve the LCoE. Second, load factors of both wind and solar, and one should expect of tidal also, depend on location because of dependencies on, variously, the latitude, wind

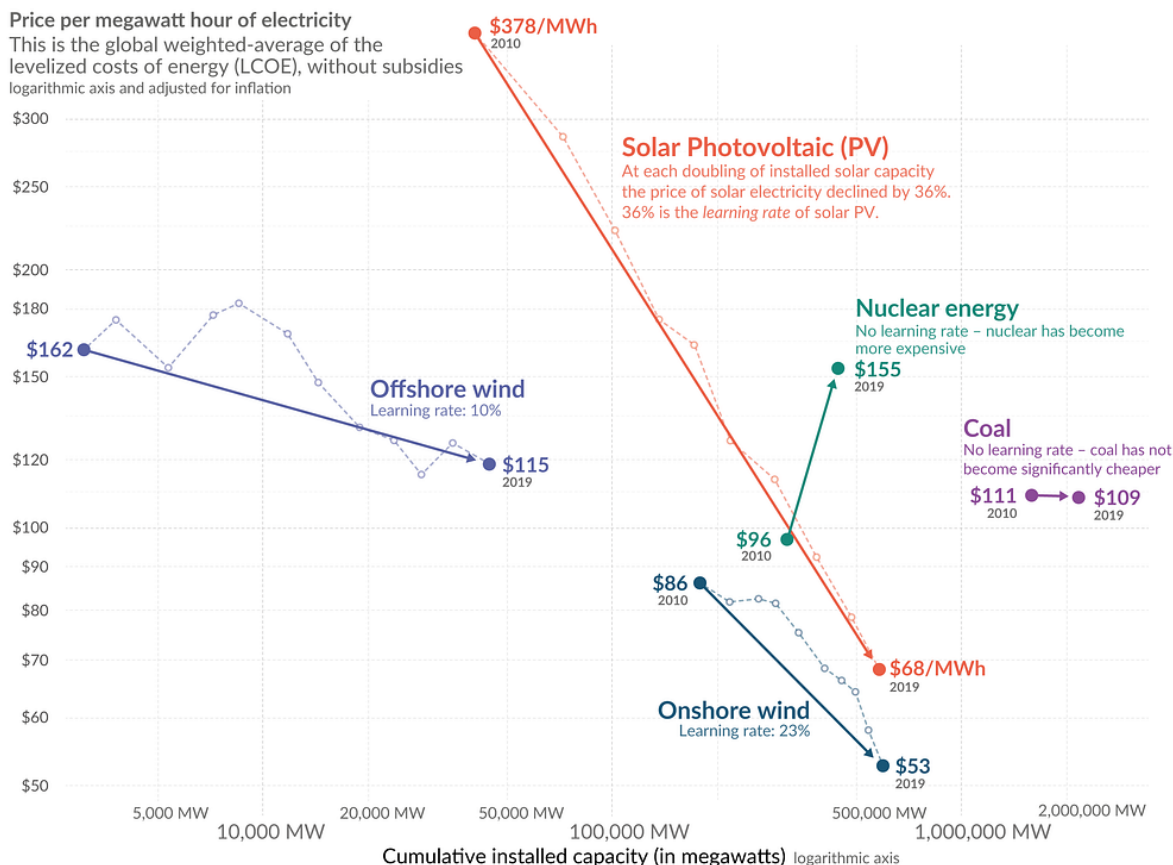
⁸² [Our world in Data](#) news article accessed May 2024

speed, cloud cover and tide conditions of the site. Thus, an LCoE quoted for wind in one region can not be expected to automatically apply in another region.

For reason of differences in cost data and region of study, significant differences are seen in published cost reduction curves over the same time period.

Electricity from renewables became cheaper as we increased capacity – electricity from nuclear and coal did not

Our World
in Data



Source: IRENA 2020 for all data on renewable sources; Lazard for the price of electricity from nuclear and coal – IAEA for nuclear capacity and Global Energy Monitor for coal capacity. Gas is not shown because the price between gas peaker and combined cycles differs significantly, and global data on the capacity of each of these sources is not available. The price of electricity from gas has fallen over this decade, but over the longer run it is not following a learning curve.

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Figure 18 LCoE electricity generation technologies⁸²

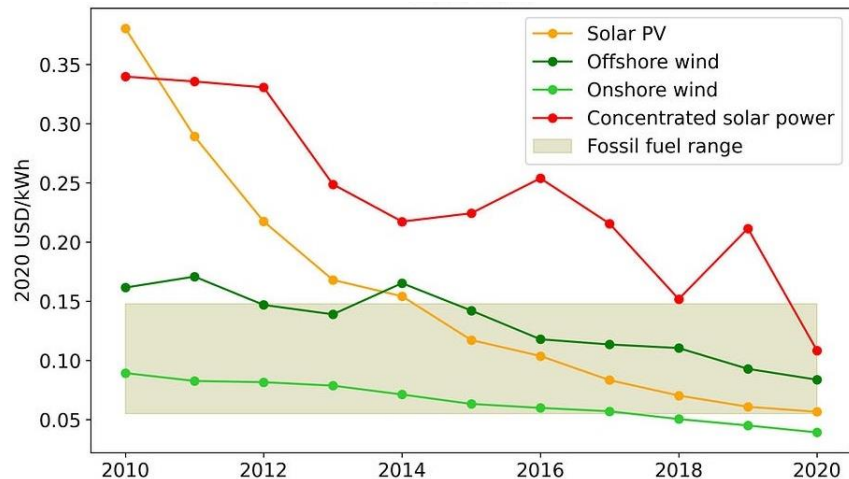


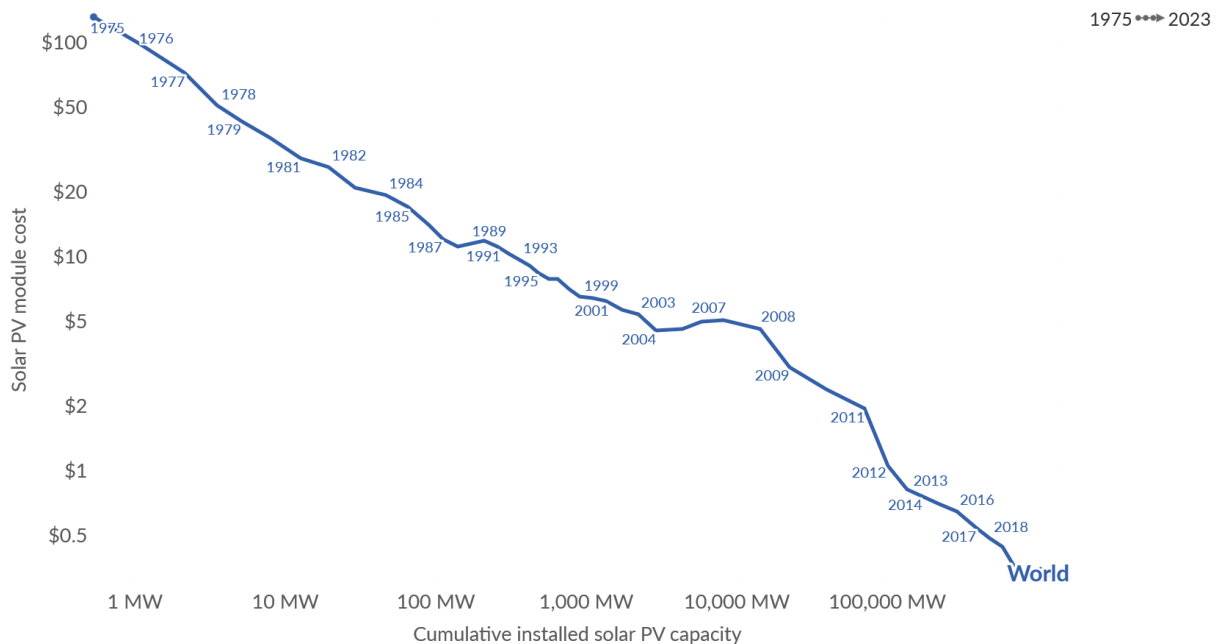
Figure 19 Weighted average LCoE by technology 2010 -2020⁸³

It is interesting to observe in Figure 19, how wind and solar technologies LCoE have varied between 2010 to 2020⁸³. These renewable technologies have started at significantly higher prices in comparison to fossil fuels, however their learning over time has contributed to massive reductions bringing those lower than the fossil fuel costs.

Solar (photovoltaic) panel prices vs. cumulative capacity

Our World
in Data

Learning curve for solar panels. This data is expressed in US dollars per watt, adjusted for inflation. Cumulative installed solar capacity is measured in megawatts.



Data source: IRENA (2024); Nemet (2009); Farmer and Lafond (2016)

Note: Data is expressed in constant 2023 US\$ per watt.

OurWorldinData.org/energy | CC BY

⁸³ [Learning curve effect on the global variable renewable energy](#), Medium article 2022

Figure 20 Solar modules price per watt⁸⁴ against cumulative installed power

It can be observed from Figure 20, that the price of solar modules have reduced by 99% from 1976 to now⁸⁴. Engineers managed to make progress alongside production savings, as the production increased from 1 MW to 100 GW. Both metrics are plotted on logarithmic axis, hence the exponentially declining cost of energy appears as a straight line. Here, the price of solar modules is not only a function of time, but also the resultant experience during that period. Economies of scale have led to a roughly constant learning rate.

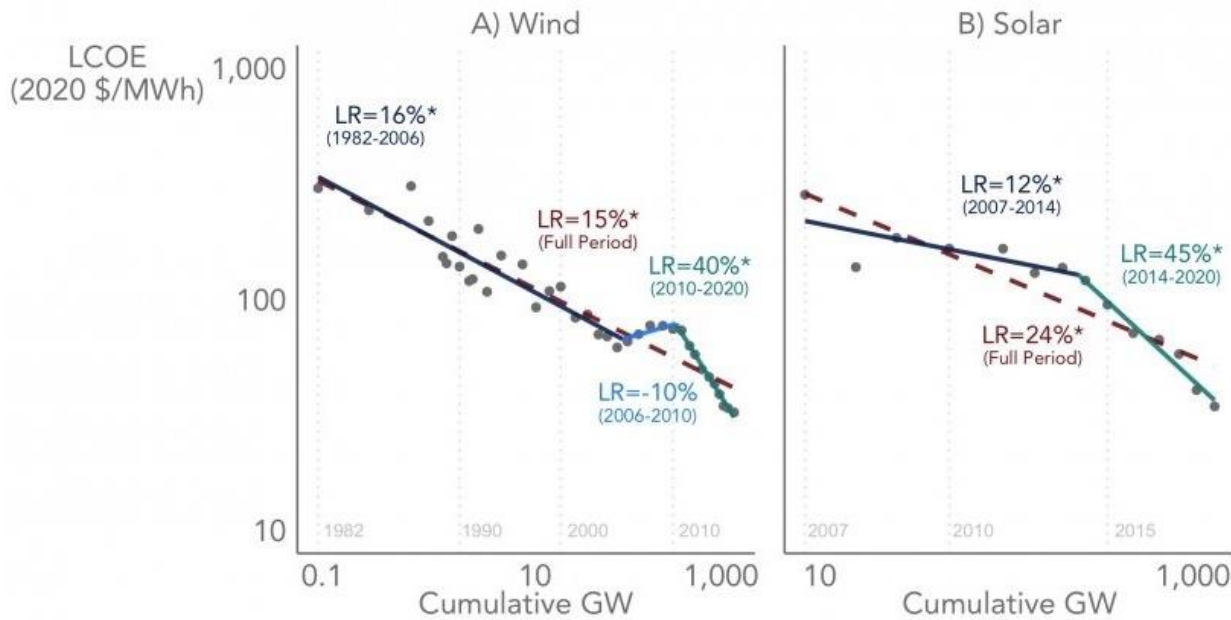


Figure 21 LCoE (\$/MWh) of wind and solar against cumulative installed capacity with learning rate annotation (2020 \$)⁷⁴

A full period learning rates of 14% for wind and 24% for Solar technologies can be observed from the graphs shown in Figure 21. There are tools other than learning curves for predicting future cost reductions. However, learning curves have proven to offer a practical and superior method of estimating LCoE reductions. Learning is not a fixed process, it is a noteworthy observation that it can appear accelerated or decelerated for certain time periods as in Figure 21. Interestingly, utility scale wind and solar LCoE learning has accelerated in the later years, as can be observed⁷⁴ in Figure 21. The study claims that the learning rate need not necessarily mature as the technology matures. These graphs are plotted in logarithmic scale as it is easier to visualize cumulative capacity on logarithmic axes. The study claims there is evidence that common energy-sector planning and integrated assessment models have not kept pace with the

⁸⁴ IRENA database, [Our world in Data](#)

recent declines in wind and solar costs, thus understating the deployment potential for these technologies.

The study by Bolinger, Wiser and O'Shaughnessy⁷⁴ claims that the data is normalized for geographical variations. Non-normalized factors are expected show higher learning rates in comparison to normalized factors but also be limited to analysed geographical locations. The geographical focus of this analysis was limited to the United States. However, the effect of US specific variables like tax credits, import tariffs, exchange rate effects, country specific costs or other specific incentives, were said to be excluded through normalization so that results close to global LCoE than domestic. The study also points out that the supply chain for both wind and solar is more global than domestic. Table 10 lists the normalization variables applied in their analysis. Normalization was not applied to OpEx. However, applying this methodology to other countries data can be interesting and might bring out the actual differences, if any.

Component of LCoE	Normalization Factor
CapEx	Regional variation in construction and labor costs Changes in materials prices (steel for wind and solar, silicon for solar only) The impact of exchange rate movements on imported equipment costs Import tariffs (solar only)
Capital Recovery Factor	Macroeconomic changes to the Weighted Average Cost of Capital (WACC)
Tax Factor	Legislative changes in federal corporate income tax rates
AEP	Regional variation in the wind and solar resource

Table 10 LCoE normalization⁷⁴

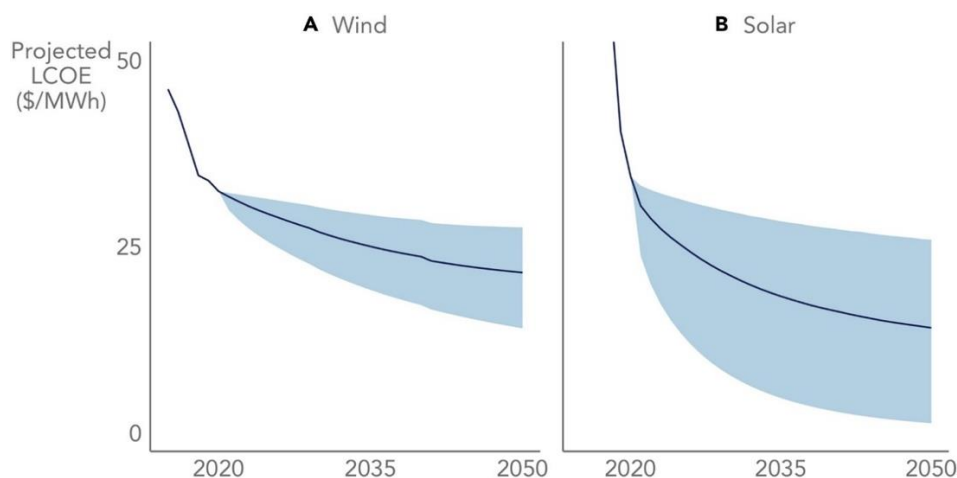


Figure 22 LCoE based on LR projections⁷⁴

The LCoE future projections in Figure 22 are said to be based on full period learning rates and central estimates of future deployment based on various estimates, including data from International Energy Agency (IEA), Energy Information Administration (EIA), Bloomberg, Det Norske Veritas (DNV), International Renewable Energy Agency (IRENA)⁷⁴. The lines represent point estimates and the bands represent 95% confidence intervals based on forecasting methods.

In the case of wind, the 15% full-period learning rate suggests that LCoE will decline by around 23% by 2035, or as much as 41% based on the lower bound of the 95% confidence interval. In the case of solar, the 24% full-period learning rate suggests a 47% LCoE reduction by 2035, or as much as 86% based on the lower bound of the 95% confidence interval⁷⁴.

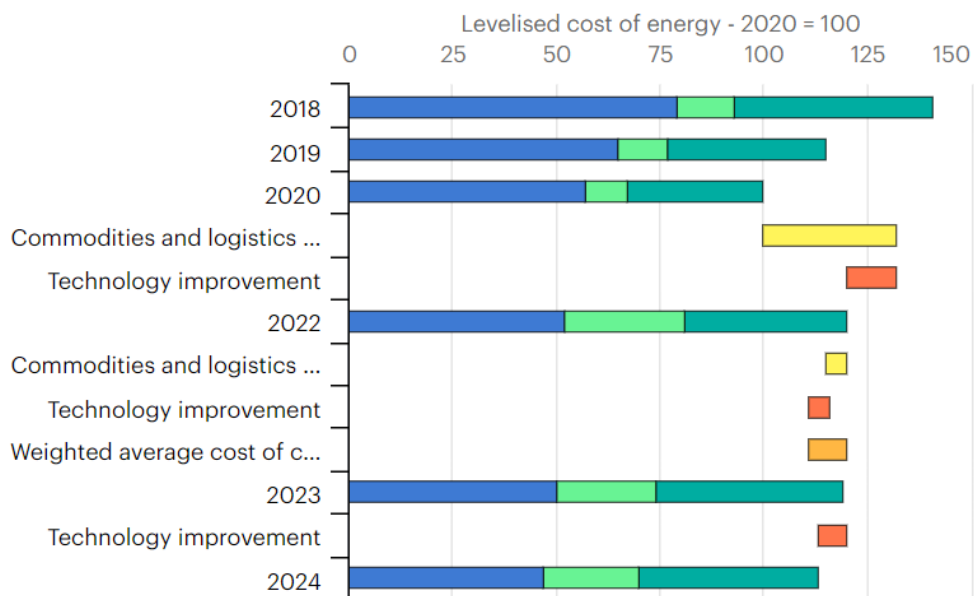
This study has compared LCoE projections in Figure 22 against NREL's 2021 Annual Technology Base (ATB) and found that ATB projections were well below the estimates of Figure 22. This highlights the high degree of uncertainty involved in the projections based on several assumptions.

According to IEA renewable energy market outlook report released for 2023 and 2024, the global average LCoEs for solar PV and onshore wind in 2024 are expected to remain 10-15% higher than 2020 levels⁸⁵. This is due to increased interest rates for financing and market conditions post Covid.

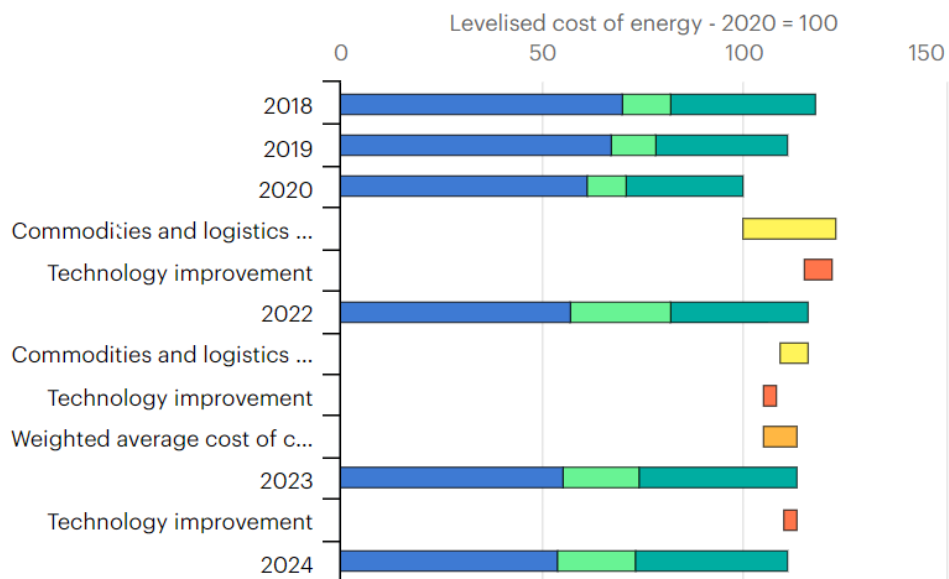
In late 2020, material costs and freight costs have increased, in 2022 again, the prices of crucial materials such as crystalline silicon and steel increased many folds and so followed freight rates. By 2022, the share of commodities and freight rates have increased double and to 30-35% of CapEx. This leads to a 15-20% increase in the LCoE. Although commodities and freight prices reduced slightly by 2024, the elevated prices still remain. This information is depicted in Figure 23⁸⁶.

⁸⁵ [Renewable energy market update](#), IEA 2023

⁸⁶ [Solar and wind costs in 2023-2024](#), IEA 2023



Solar



Wind

Figure 23 LCoEs for Solar PV and Wind 2018-2024 (IEA Licence CC-BY)
Blue: Other; Green: Commodities & Logistics; Turquoise green: Financing

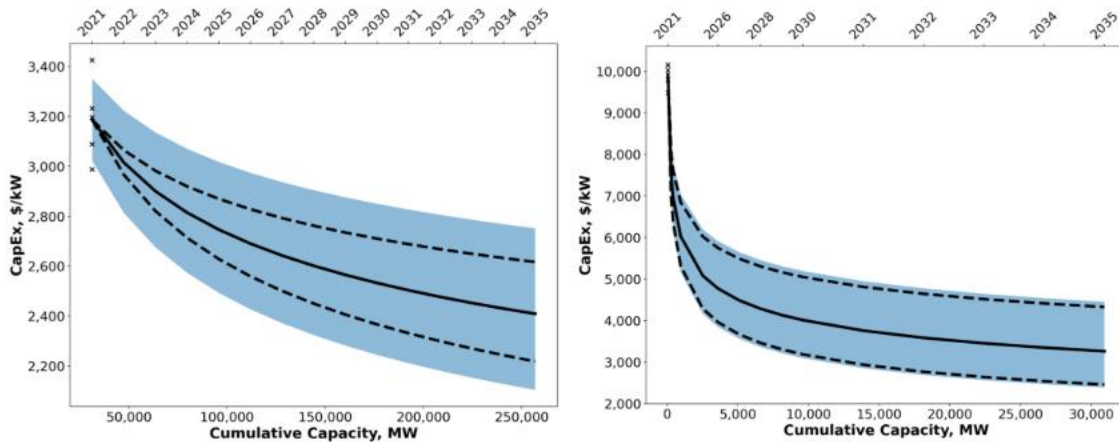


Figure 24 LCoE offshore wind, fixed and floating platforms CapEx⁸⁷

The CapEx uncertainties involved in the fixed and floating forecasts for offshore wind are shown in bands in Figure 24⁸⁷. The band variation is due to the differences in aggressive and conventional learning rates. The fixed bottom platform uncertainties are mainly driven by the site-specific factors and this accounts for a 62% uncertainty in the capital expenditure. The floating platform forecasts have a 90% uncertainty in the capital costs owing to the variation in aggressive and conventional rates.

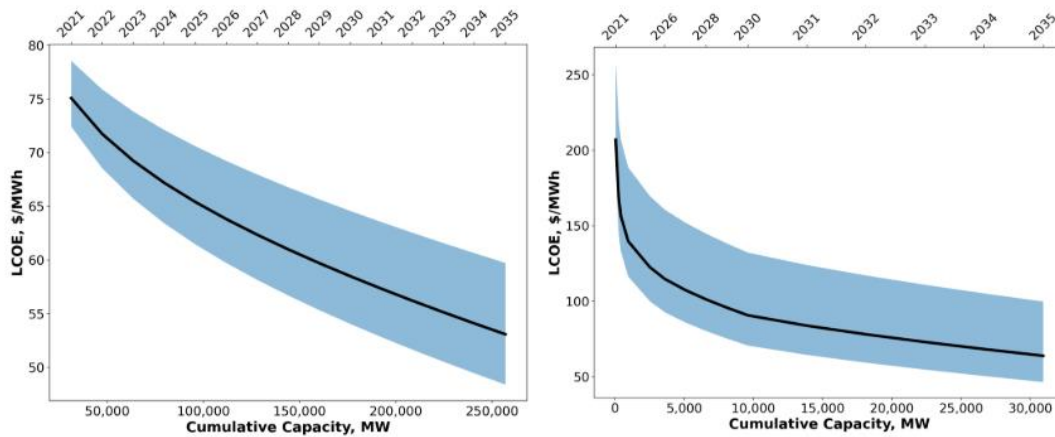


Figure 25 LCoE offshore wind, Fixed and floating platforms – OpEx⁸⁷

The NREL report⁸⁷ identifies the significant impact the technology type has on the learning rate variation as shown in Figure 25. The uncertainty bounds incorporate the effects of site-specific cost drivers as well as uncertainty involved in the estimated learning rate. The report identifies that the seemingly linear decrease in LCoE will not continue beyond 2035 and the linearity is only due to the assumption of linear reduction of OpEx in this analysis. The study expects that the offshore wind has the potential to achieve significant reductions in LCoE as supply chains,

⁸⁷ [NREL report](#), 2022

technology providers, and practitioners continue to mature. This can lead to higher efficiencies with deployment through 2035.

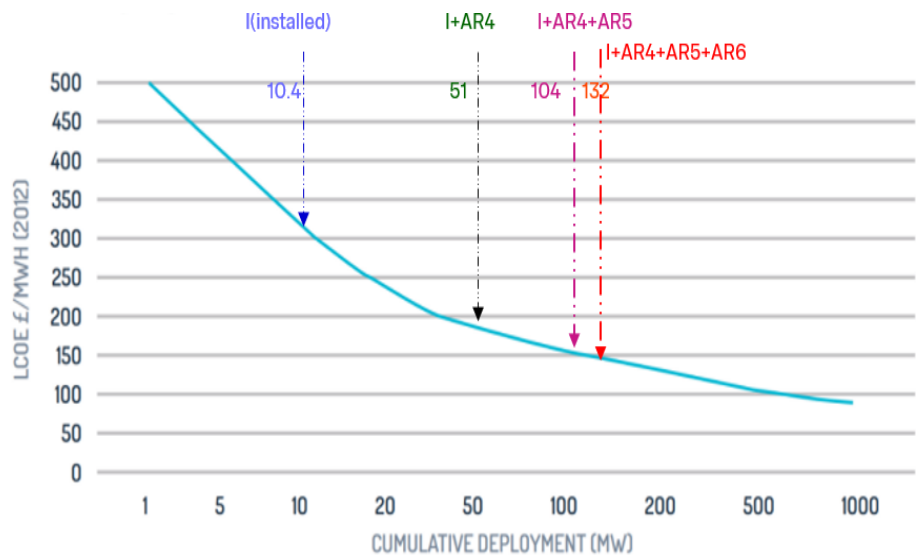


Figure 26 Projected LCoE of tidal stream versus capacity⁸⁹ annotated with CfD Allocation Round outcomes

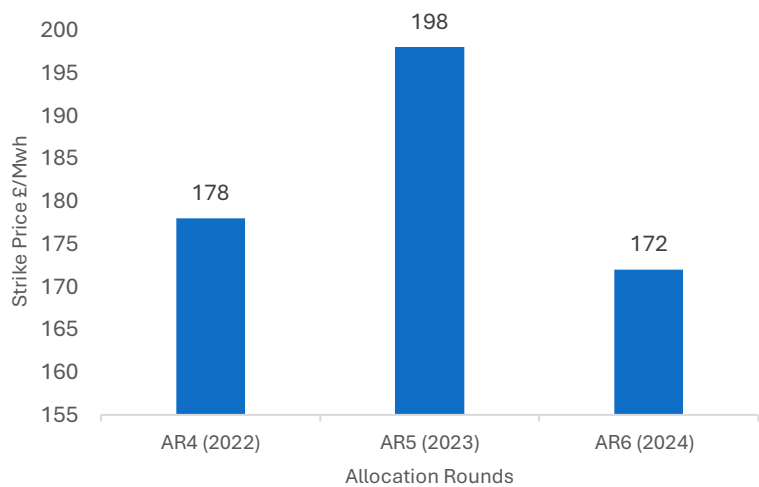


Figure 27 Tidal stream CfD strike prices for the three allocation rounds in the UK

As the technology advances, cost will continue to fall with incremental innovation and continual learning. With some modest deployment in supply chain, developers can commit with confidence. Supply chain includes device, electrical infrastructure, foundations and moorings, installations and O&M processes. TIGER project LCoE projections⁸⁹ indicate that tidal stream has potential to reach LCoE of 150 £/MWh by 100 MW installed, reducing to 90 £/MWh by 1 GW and 80 £/MWh by 2 GW according ORE catapult report⁸⁸, the predicted LCoE trajectory.

⁸⁸ [Tidal stream and wave energy cost reduction and industrial benefit](#), ORE Catapult report 2018

Currently, at the announcement of allocation round 6 results, UK will have tidal stream capacity of 132 MW by 2029, and the strike price secured is 172 £/MWh. However, there is marked difference to catch up between the anticipated curve and its actual price in 2024, that can be observed from Figure 26⁸⁹.

TIGER project has applied an overall learning rate, on both CapEx and OpEx of 15%, this has led to a prediction that it will lead to LCoE of 80 £/MWh by 1 GW. It is further noted that there is also potential for Weighted Average Cost of Capital (WACC) to reduce further, closer to the reductions implied by offshore wind auction bids and achieving a 5% cost of capital would also result in 1 GW LCoE of 80 £/MWh. Offshore Renewable Energy Catapult report⁷⁸ claims that the breakeven LCoE of tidal stream in 2050 will be 49-55 £/MWh. TIGER project forecasts that representative LCoEs in 2030 and 2035 will be 116±38 £/MWh and 78±25 £/MWh respectively⁸⁹. This is based on the assumption that global deployment of 730 MW by 2030 and 2.6 GW will reach by 2035. Given the current development rate, there appear to be slim chances of reaching that level of capacity so soon.

A review by UK Royal Society highlights that an estimated installation of the 124 MW, from different developers would help the learning thus leading to reduction in the levelized cost of energy from its 2021 level of around 240 £/MWh to below 150 £/MWh, based on a mid-range technology learning rate of 17%⁹⁰. In this view, at year 2024, with 132 MW capacity from CfD rounds is expected to be operating by 2029, the anticipated learning might be well underway.

Figure 26 shows the trajectory points as we pass through each of the CfD allocation rounds. There is a sudden hike in allocation round 5, with prices increasing to 198 £/MWh. Otherwise, the price trend seems largely in line with the TIGER project expectations. However, if we look at the prices at the time when the round 5 and round 6 are fully developed and operational by 2028/29, the prices may well have reduced. Figure 27 represents the strike price at which tidal stream projects have been awarded grant in allocation rounds 4, 5 and 6. It is difficult yet to conclude the significant price downturn from these three rounds, but it is a positive trend to see that the round 6 prices have fallen by about 13%.

Figure 28 shows the learning rates of wind and solar industries, from Figure 21. These are super imposed with tidal projections from TIGER project. It highlights the vast difference between the global potential estimates. Tidal at the current strike price of 172 £/MWh has a long way to go to reach the potential estimates comparable to wind and solar industries. Two learning rates at 17% and 12% are applied to the current price. It can be observed that even at 1000 GW the tidal price could be well above wind and solar achieved prices, unless much higher learning rate is experienced along the capacity build up.

⁸⁹ [Cost reduction pathway of tidal stream energy in the UK and France](#), TIGER, Sabella 2023

⁹⁰ [A review of the UK and British Channel Islands practical tidal stream energy resource](#), Royal Society publication 2021

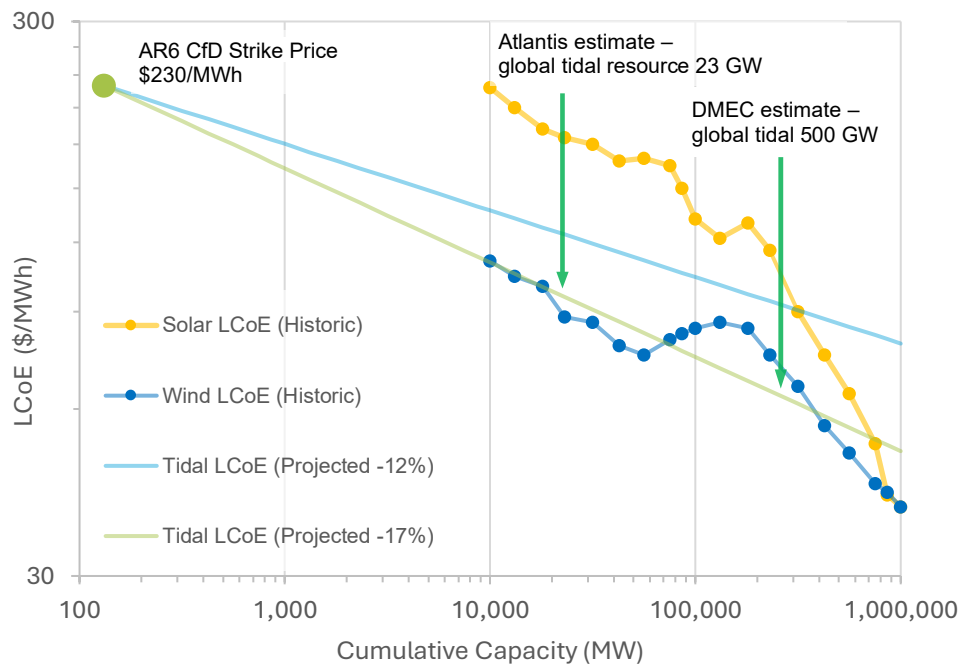


Figure 28 Comparison of learning rates of Wind, Solar and Tidal

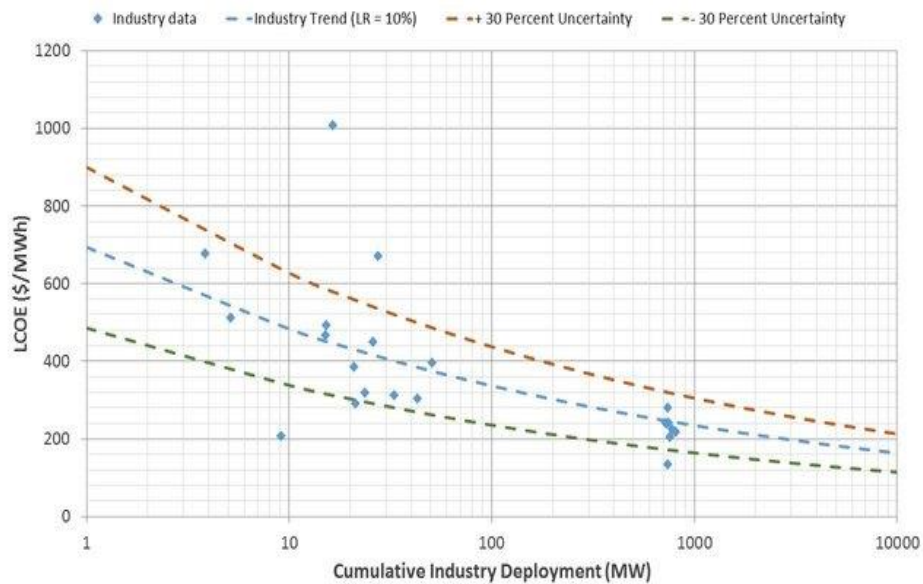


Figure 29 Tidal stream LCoE versus cumulative deployment ⁹¹

Figure 29 depicts the possible learning rates for the emerging tidal technologies⁹¹. These learning rate projections are based on hypothetical deployment scenario. The cumulative deployment is expected to drive cost competitiveness, on par with the current offshore wind costs.

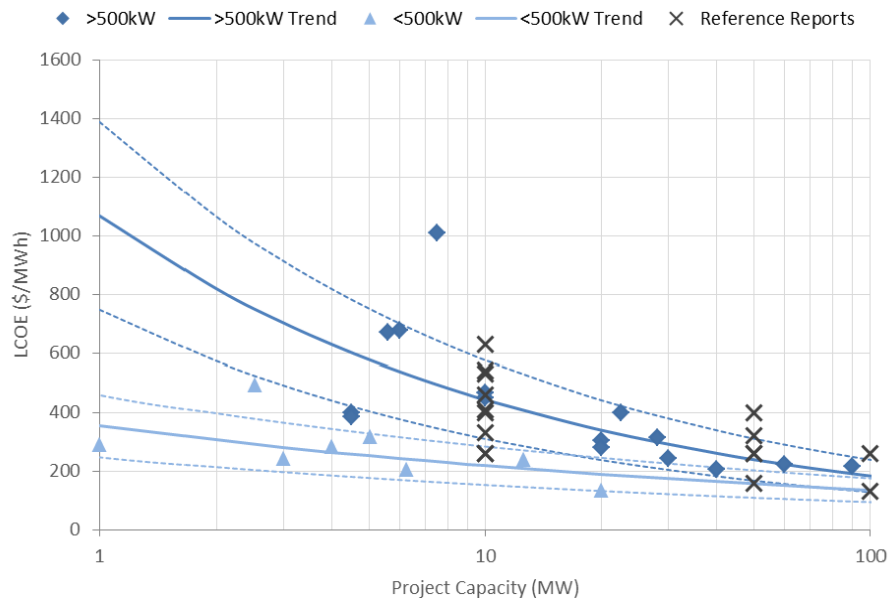


Figure 30 LCoE variation with capacity ⁹¹

Figure 30 depicts how the learning rate in turn, the cost of energy, depends on the array device size of the tidal array⁹¹. While the cumulative capacity does reduce the cost of energy overall, the actual reduction in cost is dictated by the capacity of tidal device. Large scale array (>500 kW) devices appear to achieve higher reduction in LCoE, than small scale array devices (<500 kW).

Historically, LCoE has been the core optimization variable in the wind and solar sectors, so it is justifiable we should measure technological progress in terms of LCoE-based learning. This can help us account for the various technology advancements and improvements that can improve LCoE for tidal stream energy.

7 Factors affecting LCoE of Tidal Stream Energy

The Levelized Cost of Electricity (LCoE) represents the costs associated with converting different forms of energy into electrical power. These generation costs include capital, fixed and variable operational expenses, as well as the desired capital interest over the operational period. Average LCoE enables comparison across various power plants with differing generation and cost structures. It helps evaluate the profitability of generation technology.

LCoE is seen as the lifetime cost of the project, per unit of energy generated, £/MWh. It is defined as the sum of discounted lifetime generation costs (£) divided by the sum of discounted lifetime electricity output (MWh). Generation costs include all capital, operating, and decommissioning costs incurred by the generator/developer over the lifetime of the project, including transmission costs. It does not necessarily correspond to the level of revenue (or 'strike price') that would be required to support the project. It is an expression of cost rather than revenue. The discount rate is the WACC over the lifetime of the project, as determined by the

⁹¹ M Previsic and J Chozas, [International levelised cost of energy for ocean energy technologies](#), IEA 2015

capital structure and financing costs⁹². This section examines tidal energy cost drivers against offshore wind and solar energy data, where it is clearly stated.

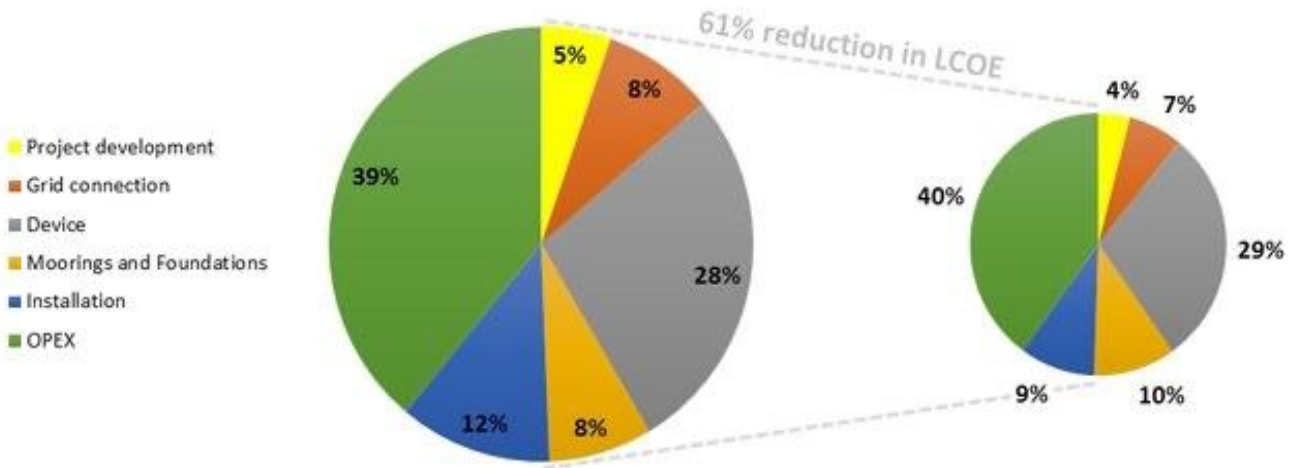


Figure 31 Tidal LCoE cost breakdown⁹¹

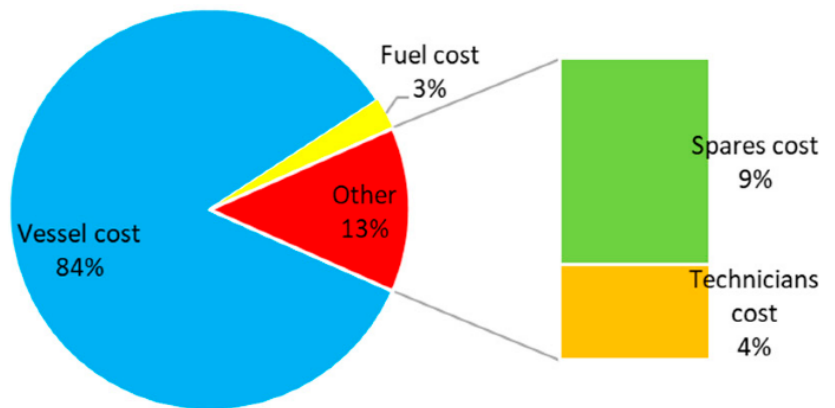


Figure 32 Tidal O&M cost breakdown⁹⁴

Tidal LCoE percentage breakdown as can be observed from Figure 31, based on data obtained by industry developers. The left circle represents the cost values of current stage deployment and the right circle, the expected commercial target⁹¹. The percentage breakdown represents an average across the tidal energy industry, rather than one particular tidal technology. The higher operational costs are estimated due to increased operational and maintenance associated with commercial arrays and offshore maintenance windows during which energy produced is hampered. Typical O&M costs of a tidal turbine breakdown is as shown in Figure 32. Clearly, at 84%, vessel cost is the predominant cost component, however it can be brought down using corrective planned maintenance strategy⁹⁴. Despite the fact that tidal projects need much

⁹² [Offshore wind cost reduction pathways study](#), The Crown Estate 2012

smaller vessels in comparison to wind, yet the costs are higher due to offshore maintenance and more maintenance intervals to ensure operation in harsh operating conditions.

If we observe the trend in offshore wind sector, currently about two thirds of an overall offshore windfarm budget is allocated to CapEx and 30% to OpEx, which is significant for operations⁹³. Another study indicates that the OpEx costs of a wind farm can be around 28%⁹⁴, which is also supported by the OpEx cost range of 20-30%, shown in Figure 33. Whereas a tidal farm data considered in Figure 31 indicates that the O&M costs could be very high, as much as 40%. Although both wind and tidal are offshore generation technologies, the significant difference in O&M costs are down to the way the maintenance is carried out. The key difference between offshore wind and tidal systems is that the tidal turbines operation is carried out onshore, unlike wind turbines whose maintenance operations are carried out offshore. Onshore maintenance means the tidal turbines are out of operation for longer periods, affecting the annual energy produced. On the other hand, a tidal turbine is smaller and lighter in comparison to wind turbine, meaning a less complex vessel would suffice for maintenance activities. The O&M cost of a tidal farm depends on the selection of maintenance vessels, deployment location and a suitable maintenance strategy. Tidal farm location factors such as distance to the port, vessel availability and the availability of suitable weather windows for access impact the maintenance cost. Optimising the maintenance strategies is also helpful.

It is common that many developers tend to focus on the cost reduction at the CapEx stage such as reducing the weight of the foundation, their designs etc. However, this largely inhibits real design innovation that can be done later which could lead to greater reduction on OpEx, which is more important given higher tidal stream OpEx. A holistic approach of technical innovation taking into account of both CapEx and OpEx elements will help reduce the over costs of production.

Phase	Development & Consenting	Component Manufacture		Installation	Operations / Maintenance	Decommissioning
		Turbine Manufacture			Support services	
Time	4 - 5 years	1 - 2 years		1.5 - 2.5 years	20+ years	1 - 2 years
Stage	CapEx 70–80%				OpEx 20 - 30%	
Costs	5 - 10% CapEx	Components & structure 20 - 30% CapEx	Turbine 20 - 30% CapEx	10 – 15% CapEx	Vessel & equipment 20-30% OpEx	0-5% OpEx
Risks	Regulatory uncertainty; costly surveys; risk bias on developers	Multiple contracting; lack of standardisation	Lack of risk sharing; insufficient capacity	Constrained vessel supply; lack of bespoke vessels; inefficient logistics; grid connection queue	Heavy dependence on subsidies; reliability	Low EOL value; recyclability

⁹³ [Guide to offshore foundations](#), Empire Engineering, 2021

⁹⁴ M Kamidelivand, P Deeney, F Devoy McAuliffe, K Leyne, M Togneri and J Murphy, [Scenario Analysis of Cost-Effectiveness of Maintenance Strategies for Fixed Tidal Stream Turbines in the Atlantic Ocean](#), Journal of marine science and engineering 2023

Figure 33 Offshore wind life cycle costs, risks and timeline⁹⁵

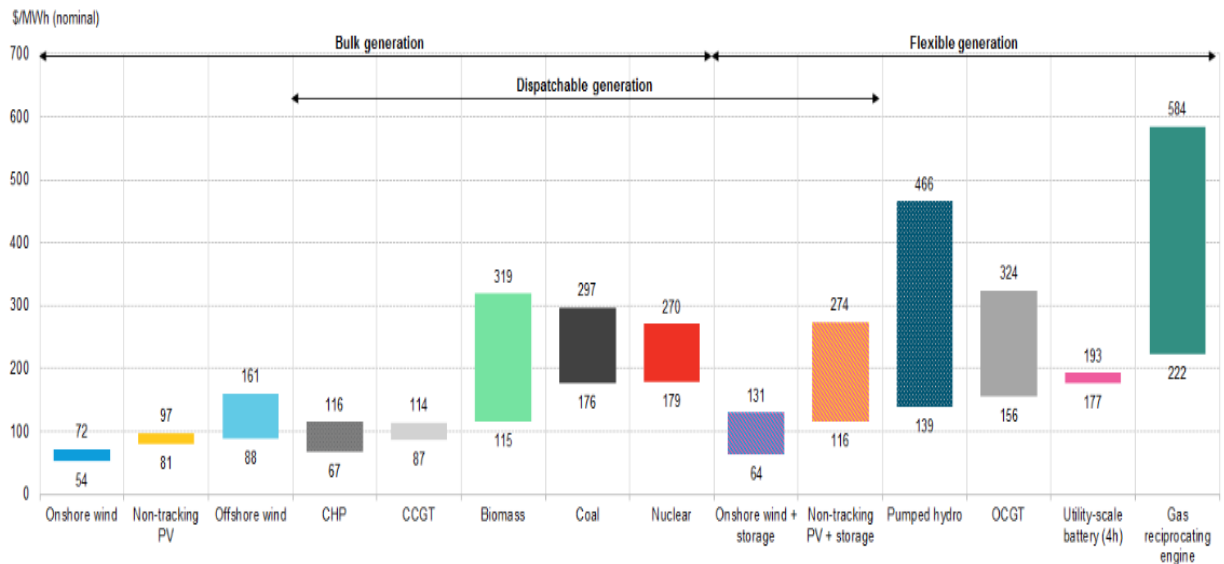


Figure 34 UK LCoE averages (2019)⁸⁰

Figure 34 shows the UK current levelised cost of electricity supply from various energy technologies⁸⁰. According to the Enfait report, the on/offshore wind and solar renewable based generation has reached price convergence in the market, around the region of \$54 to \$161/MWh whereas the cost of tidal energy from pre-commercial deployments is in the region of \$393/MWh to \$894/MWh in 2019⁸⁰. Although tidal energy is not considered as dispatchable generation unless it is combined with battery storage. However, its contribution to the grid is seen as more valuable than intermittent power generation sources.

⁹⁵ V N Dinh, E Mckeogh, [Offshore Wind Energy: Technology Opportunities and Challenges: Energy and Geotechnics](#), 1st Vietnam Symposium on Advances in Offshore Engineering 2019

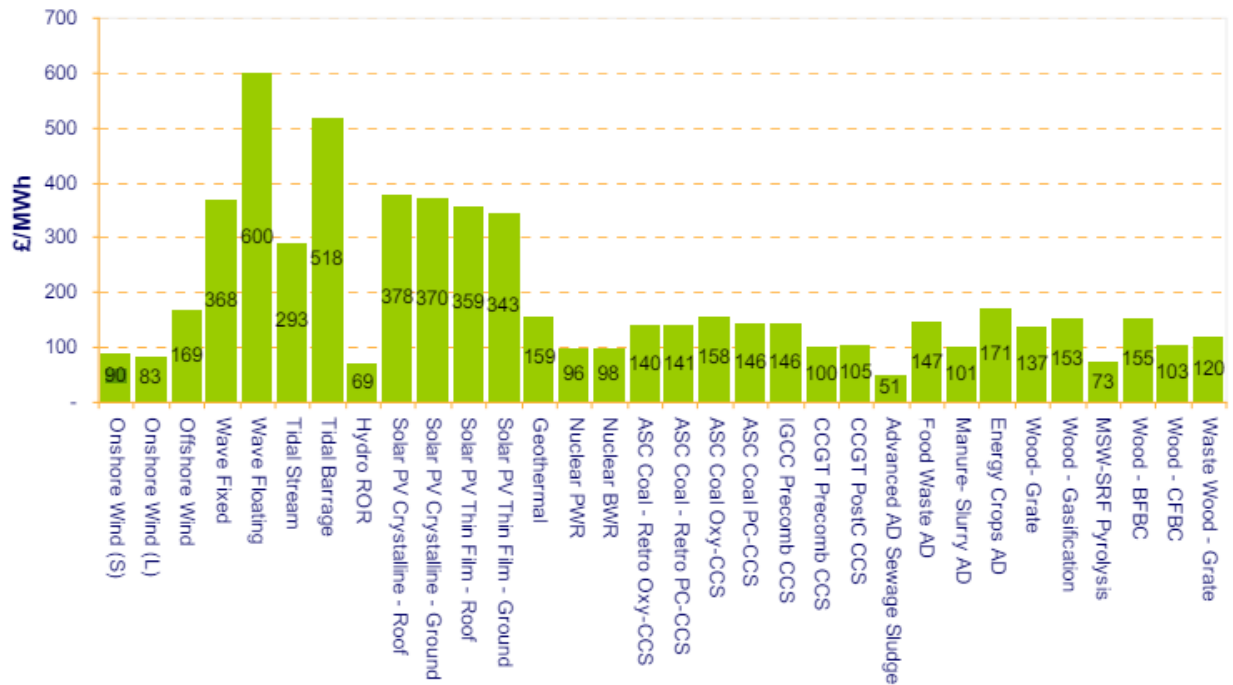


Figure 35 Current estimated LCoE⁹⁶

Mott Mc Donald report⁹⁶ gives a clear comparison of current levels of estimated cost of energy of various technologies in Figure 35, as in year 2011. The cost estimate of tidal stream at 293 £/MWh is based on a technical assessment as there were no commercial scale tidal stream installations in place by then. Tidal stream cost is evaluated with an annual capacity factor of 35-40%.

According to EnFait report, so far, the LCoE for tidal pre-commercial deployments have a wide range of CapEx and OpEx per MW installed. This is due to various reasons⁸⁰ such as:

- Variation in turbine/array capacity – and therefore economies of scale effect.
- Disparity in resource deployment.
- High cost of heavily instrumented monitoring devices and research equipment.
- One off component and material defects.
- Unexpected/planned remediation and repair activities.
- Lack of supply chain knowledge and limited competition in bidding during the turbine build phase.
- Turbine fabricator sharing build learning with developer/turbine designer leading to a lengthening manufacturing timescale and therefore increasing costs.
- Under resourced management teams leading to sub-optimal contracting strategy.
- Lack of experience in large scale fabrication and complex build programming.
- Under estimation of time and labour from engineering scope, the number of components and the complex prototype one-off design verification requirements.

⁹⁶ [Costs of low-carbon generation technologies](#), Mott Mc Donald Report 2011

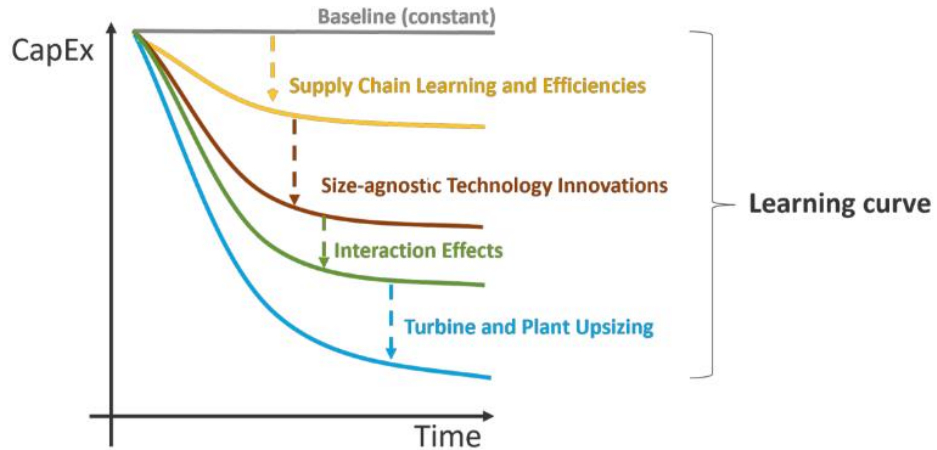


Figure 36 CapEx - conceptual cost drivers⁸⁷

Offshore Wind Reductions in Cost of Energy (FORCE) model calculates a learning rate from available data on installed global offshore wind projects and project cost reductions forward in time based on anticipated future deployment. The learning rate will take into account of combined cost reduction effects from innovations, learning, standardization, and economies of scale in the supply chain and manufacturing, wind turbine upscaling; and interaction effects as shown in Figure 36⁸⁷. A very similar trend is expected to be followed for the tidal stream energy industry as well.

7.1 Tidal Stream Energy cost drivers

Various studies have investigated cost drivers affecting the LCoE of tidal energy and have identified a set of dominant cost drivers. We have outlined the cost drivers from the TIGER project report⁸⁹, the Enfait Report⁸⁰ and the Frazer Nash report¹⁴ as shown in Table 11.

TIGER Project⁸⁹	EnFAIT⁸⁰ project	Frazer Nash¹⁴
Larger rotor diameter and device rated power.	Economies of scale in device rating. Modularity and Scalability advantage.	Larger turbines, both in terms of rotor diameter and rated power
Economies of volume from arrays.	Economies of volume in array size. Learning rates from repeated manufacturing and deployment.	Larger arrays.
Piled foundations, innovative anchors and mooring system designs.		Monopiles for fixed devices. Multiple rotors on a single supporting structure
Advanced rotors and blades. Power train. Next generation materials.		
Improvements in marine operations.	Improved reliability, efficiency and availability.	
	Learning from wind industry in drivetrain. OpEx advantage of distance to shore, dense energy compared to wind	
Reduction in cost of capital		

Table 11 Cost reduction drivers in tidal stream energy as described by the TIGER project; EnFaiT⁸⁰ and Frazer Nash

7.1.1 Cost drivers reported by the TIGER project

The TIGER project report⁸⁹ suggests several technical areas where learning induced cost reduction might occur: The report clearly indicates the potential of each of the cost reduction drivers and their relative potential to contribute to LCoE reduction in Figure 37. A significant 38% LCoE reduction due to larger rotor and rated power devices, 28-50% LCoE reduction with, larger farms and a 20% WACC reduction leads to 10% LCoE. The increased rotor diameter and rated power represents the additive nature of the two individual innovations. Innovations and arrays are the significant contributors to the anticipated cost reduction. However, it is worth noting that increasing rotor diameter is not as simple imagined because it is bounded by the fact that tidal turbines operate in shallow waters.

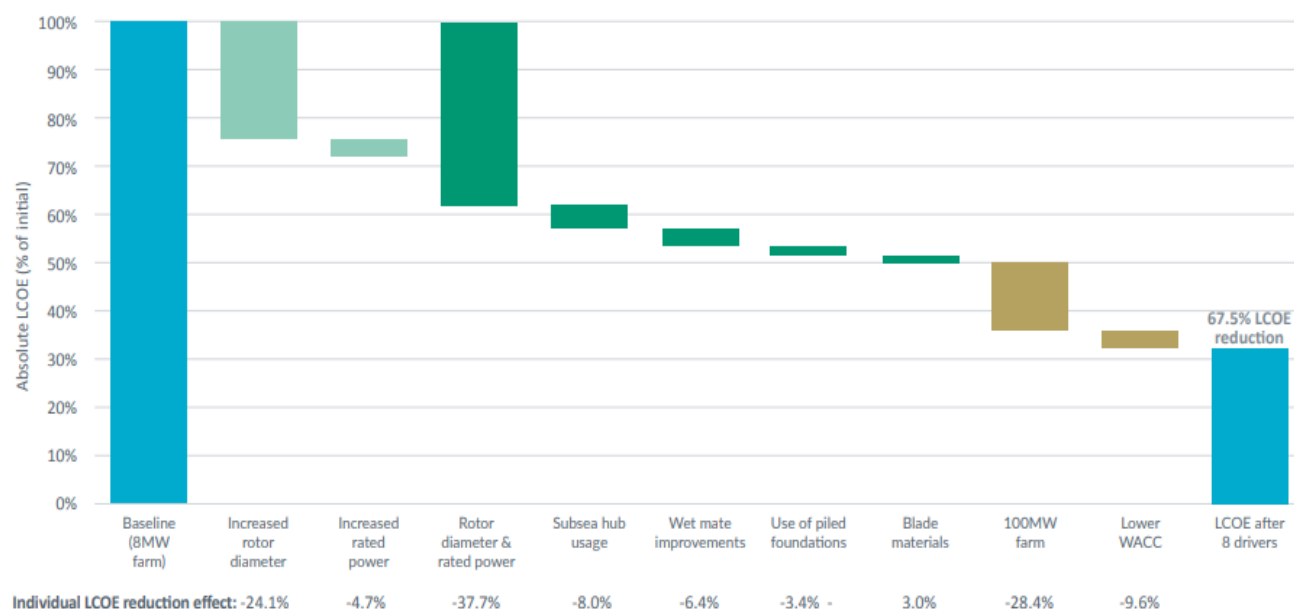


Figure 37 LCoE reduction by cost driver⁹⁸

The cost of financing is a significant contribution to LCoE of a project, over half of the LCoE. A large amount of cost of project has come from the government funding so far, due to lack of private investors confidence. Lenders have a perception that project developers may fail to service project loan because of the risk that the asset could be potentially turn into a defunct stranded asset in the sea. It was found that, if WACC is reduced by 20%, LCoE reduced by 10% which was significant. A reduction in WACC from 8% to 6.4%, means LCoE of tidal stream energy can be reduced by 9.6%⁹⁷. Other estimates indicate that each 1% reduction in WACC can reduce tidal stream energy LCoE by 7%³³.

⁹⁷ [Tidal stream site cost reduction report](#), Interreg 2022

The following 10 areas are identified as the most potential LCoE cost drivers in the recent ORE Catapult report⁹⁸.

1. Step Change in Rotor Diameters
2. Subsea Hubs
3. Array Optimisation
4. Innovative Anchors for Floating Devices
5. Step Change in Rated Generator Power
6. Controllers that Optimise Lifetime Turbine Performance
7. Optimised Foundations for Fixed Devices
8. Optimising and Standardising Wet Mate Connectors
9. Condition Monitoring of Cables
10. Optimised Individual Pitch Control

Reviewing world's largest project, MeyGen (MeyGen is both the name of a company and of its largest project) for the rotor blade diameter developments, the first set of phase 1 turbines AH1000 and AR1500 which are currently operational have 18m diameter. The next generation AR2000 turbines have 20-24m diameter are operating at 3.05m/s delivering 2 MW power⁹⁹. 26 m diameter turbine rotors are currently under development, these are expected to hugely improve tidal energy efficiencies¹⁰⁰, life. It is known that the tidal power generated is proportional to radius squared. increasing the rotor diameter of the current MeyGen phase 1 turbines from 18m to 24m is expected to increase energy production by 34%¹⁰¹. But this increase in rotor diameter cannot continue to increase unlimited as its bound by the operating station depth, which is usually situated in shallow water.

When the rated power of a 24 m rotor diameter turbine at MeyGen increased from 1.5 MW to 2 MW, the annual energy production per turbine is expected to increase by 17%¹⁰¹. Turbine blades are a potential area for cost reduction, as these can account for up to 30% of turbine CapEx. Due to its bespoke nature, tidal turbine blades cost 3 to 4 times the cost of a wind turbine blades³³.

Tidal energy systems could potentially use bilge pump to prevent water ingress due to wear or leakage through the seals due to harsh operating conditions. Bilge pump does add to the capital cost, however, it improves reliability therefore improving the capacity factor¹⁰². Overall, it reduces planned and unforeseen operation and maintenance expenses leading to reduction in LCoE. Smaller tidal turbines find the cost of a bilge pump addition expensive.

In order to reduce the cost, the key challenge would be to reduce the maintain the structural size and weight of steel while maintaining the turbine's performance. Installation and maintenance cost would reduce notably as tugboats could replace the expensive installation vessels. Floating TSE devices can be towed to site for low-cost installation, flexible repositioning and decommissioning.

Hub height is another important parameter in the reduction of cost of energy. Approximately 75% of the stream energy is in the upper 50% of the water column, according to the data on the

⁹⁸ [Tidal stream technology roadmap](#), ORE Catapult 2024

⁹⁹ [SAE Renewables News](#) 2019

¹⁰⁰ [European Composites Industry Association](#) accessed June 2024

¹⁰¹ DS Coles and T Walsh, [Mechanisms for reducing the cost of tidal stream energy](#). In Proc. 13th European Wave and Tidal Energy Conf, Italy, September 2019.

¹⁰² [Tidal Generators](#), Chapter in Advances in Modelling and Control of Wind and Hydro generators Book, 2020

typical vertical boundary layer profiles at tidal stream energy sites. Floating devices position their rotors in this higher energy region of the water column, enabling energy yield to be maximized for a given site. It is estimated that energy production increases by approximately 2% per a metre increase in hub height¹⁰¹.

7.1.2 Cost drivers reported by the EnFAIT project

A report by the EnFAIT project⁸⁰ highlights that cumulative cost reductions are tied to a wide range of influences that can drive cost down, including manufacturing scale, operational efficiencies, improved reliability and availability, and fundamental design changes.

A very similar cost drivers are identified in the report prepared for Department for energy Security and Net Zero¹⁴.

Economies of scale, economies of volume, increasing the size of arrays, improved efficiency in volume manufacturing processes, financing improvements such as reduction in hurdle rate. Turbine Scale (rotor diameter and power), array size, financing costs, grid costs, innovation, infrastructure investment, marine operation, project lifetime, site dependant factors, regulatory constraints and load factor all are key cost reduction areas.

Whether these expectations will turn out as expected in future, is very much based on the assumptions of future deployment and developments.

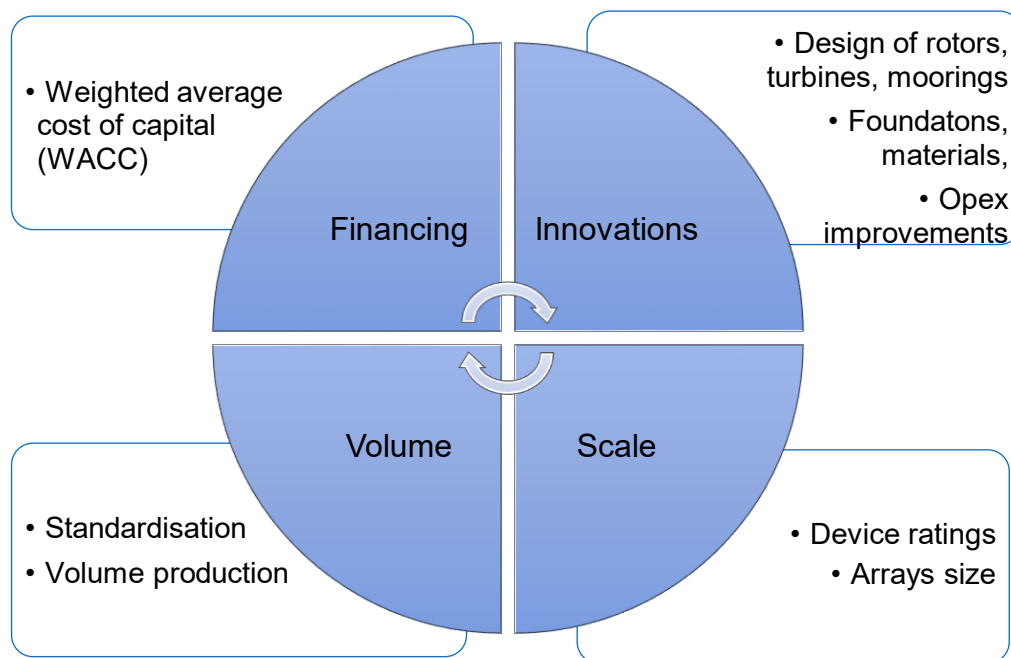


Figure 38 Cost reduction drivers - Tidal Energy

Figure 38 highlights a summary of key cost reduction drivers. These drivers will play a significant role in reducing the unit cost of tidal energy produced. As it is an emerging technology, it is difficult to know at this time, which drivers will play out to be major drivers.

LCoE reductions can be achieved by increasing array size. By increasing the number of turbines, production cost per unit will decrease. For example, reducing the fixed costs

associated with vessel mobilisation and onshore substation integration, which are spread over more devices.

The array induced LCoE reduction in upscaling the turbine array size from 2-10 MW to 20-200 MW projects was estimated at 40%⁸⁰. Research from the TIGER project estimated a 28% LCoE reduction when increasing farm size from 8 MW to 100 MW⁸⁹.

Enfait project assessed a first of a kind commercial array by considering a learning rate of 10% and 7% for CapEx and OpEx respectively covering a project development phase of 50 installations over a period of time that could be realistically be built within a 10-year time frame⁸⁰. Overall, arrays achieved a 30% reduction in the cost of tidal power and the Enfait project is on target to achieve 40% by project end. Achieving 95% availability as against the 80% is also seen promising.

As can be observed from Figure 39, It was found that on enabling future tidal arrays, the economies of scale from first of kind array installation is forecast to be in the region of \$182/MWh for 20 MW to 200 MW capacity and \$300/MWh for projects with a 2.0 MW to 10 MW capacity⁸⁰. However, a 10 MW can also be useful in addressing demand profiles which are largely dependent on expensive diesel fired power generation. From weak and off grid supported by diesel power project experience, the cost of delivered power is in the region \$416/MWh to \$650/MWh. 2.0 MW prototype deployments are currently in the region of \$393/MWh to \$894/MWh. These values are stated to be estimated based upon the limited amount of data reviewed and the dollar values are quoted just to align with currencies stated in the rest of the document. It is therefore felt possible that tidal energy in time, could well replace these high-cost diesel power market segments⁸⁰.



Figure 39 LCoE of Tidal arrays against other renewables benchmarking⁸⁰

Overall, it is estimated that LCoE for larger arrays could fall below \$114/MWh by the time 1 GW of capacity has been installed (50 installations in a span of 10 years) which is broadly in line with ORE Catapult's May 2018 report's projection of LCoE of £90/MWh by 1 GW of installed capacity.

Due to the emerging nature of technology, there is still a high level of unplanned events taking place during the design, build, implementation and operation phases that are seen as high cost events.

Capacity factor is defined as the annual actual electricity generated by a power plant divided by the maximum possible electricity generation of that plant. The maximum possible electricity generation of the plant is calculated by multiplying the capacity of the system by the number of hours in a year which is 8,760 hours.

Capacity factor can be improved through progress in blade aerodynamics, control systems, forecasting and maintenance strategies are all applicable to some degree to tidal stream. This is reflected in an increasing capacity factor profile over deployment.

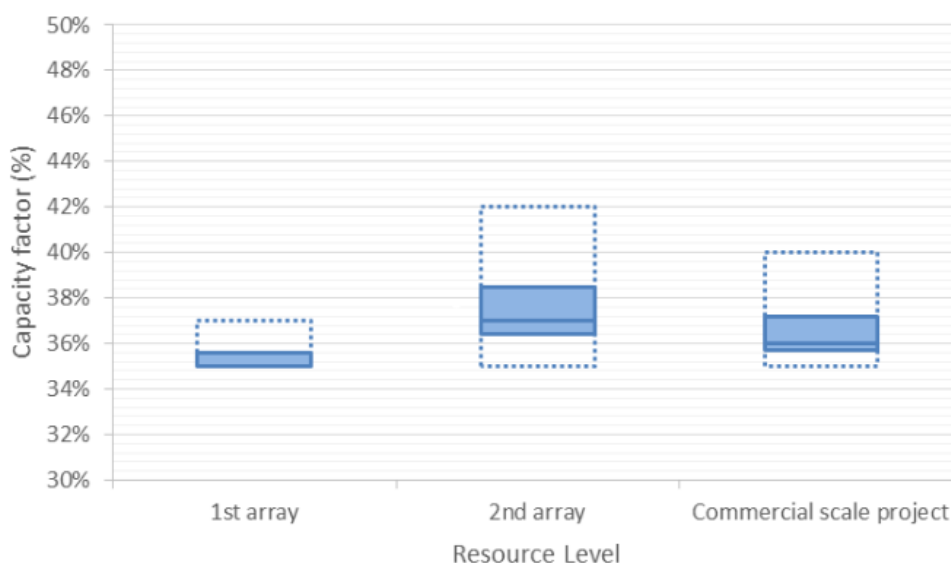


Figure 40 Capacity factor vs stage of development⁹¹

The annual energy production from an array of devices is a function of capacity factor and availability. The capacity factor of a tidal device could be around 25-35% for medium to high resource sites and 30-40% for high resource sites, with some studies indicating even 50% capacity factors⁹¹. Another study stated an average capacity factor of 29.9%, ranging anywhere between 23.3 and 43.6%¹⁰³. Most tidal energy schemes are characterised by low capacity factors, usually in the range of 20-35%. By the time of commercialization, tidal projects are estimated to have a capacity factor ranging between 35-40% for projects between 3-90 MW capacity range as can be observed from Figure 40⁹¹. Figure 40 also shows a slight increase in capacity factor between 1st array and 2nd array deployments. However, the commercial target sees a slight reduction in anticipated capacity factor. This may be due to use of less energetic resource locations /less suitable sites for larger scale deployments. This is also due to an

¹⁰³ Z L Goss, D S Coles and M D Piggott, Economic analysis of tidal stream turbine arrays: a review, General economics 2021

inversely proportional trend between average device capacity factor and overall array size. The farm shadow effect causes a reduction in the net energy production as it reduces the resource available to the devices located behind the first row. It has been suggested that the levels of uncertainty associated with estimates at this stage of technology development could be in the order of $\pm 30\%$, which are shown as dotted line extensions around. This is based on the analysis of industry averaged data for first array, second array, and long-term project targets.

Another factor that helps in LCoE reduction is the use of a flooded or wet gap generator. This is expected to reduce the operation and maintenance costs hence improving the capacity factor which in turn would reduce LCoE. This architecture can potentially improve colling and reduces dependency on ancillary systems, thereby improving reliability¹⁰².

7.1.3 Technology and site specifics

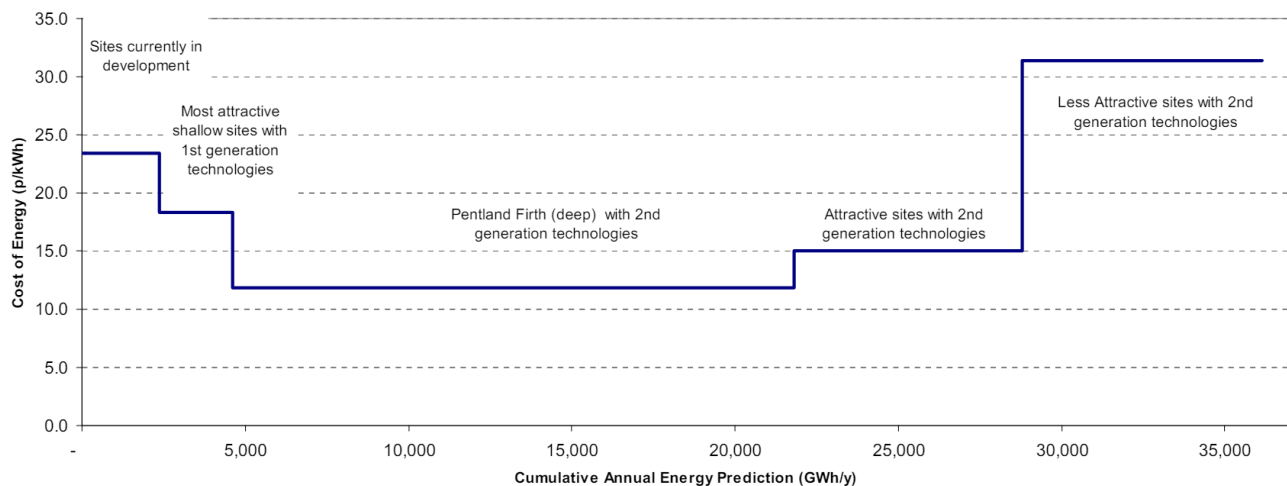


Figure 41 cost of energy vs technological factors¹⁰⁴

Figure 41 shows how technology level variation can significantly affect the cost of electricity produced by that technology¹⁰⁴. Around 30 sites, have been analysed for the factors including, technology advancement level, distance from the shore, deployment sequence, environmentally imposed velocity and range limits, and economically feasible velocity limits. It is observed that generation technology advancement does affect the cost of tidal energy produced which is to be expected and not unusual. As the technology evolves, the cost is expected to and has clearly reduced. Cost of energy has reduced from the first to second generation technologies. There is a stark variation when the site suitability varies. The site-specific factors such depth, distance to shore, environmental and economic constraints do affect the cost of electricity produced, and their impact can be so much so that it can create a bigger impact, than the benefit created by the advancement of technology, causing a cancellation effect.

It is common and understandable that the optimal site selection criteria would always choose the most suitable tidal sites at first, which will lead to faster installation times, improved reliability, better capacity factors, higher annual energy produced, hence lower cost of energy

¹⁰⁴ [UK tidal current resource and economics](#), Carbon Trust report, 2011

produced. So, the data available at the initial stages is only from the most attractive sites. Relying on this data would become questionable, as the same results will not apply to less suitable sites.

In any tidal project cost estimation, the input parameters are very device specific, technology specific and site specific. The LCoE calculations and prediction curves have a huge level of uncertainty associated with them. As the technology is still emerging, although some components have reached maturity such as HATT, there are so many more parameters that need to attain maturity of technology. Experience in installations to maintenance can change the scenario. However, it is difficult to assume that the projections can definitely be positive.

7.2 Example of a Tidal Project Timeline

MeyGen PLC, is one of the major developers in the UK, has the Crown Estate's offshore lease for a tidal project which is also called MeyGen and the company expects MeyGen project to become the world's largest tidal stream project at 398 MW¹⁰⁴. The project is located at Pentland Firth, a site between Scotland's northernmost coast and the island of Stroma. The phase 1 part of the project is operational at 6 MW comprising four 1.5 MW turbines. Allocation Round 4 in 2022 saw 28 MW awarded (to become phase 2) with a further 22 MW in Allocation Round 5 (phase 3) and an additional 9 MW in AR6. Thus 59 MW of turbine capacity is currently under development. The remainder of the anticipated 339 MW has not yet had support agreed.

The timeline involved from project conception to operational stage is worth noting. Figure 42 highlights the key milestones achieved to date as part of project development.

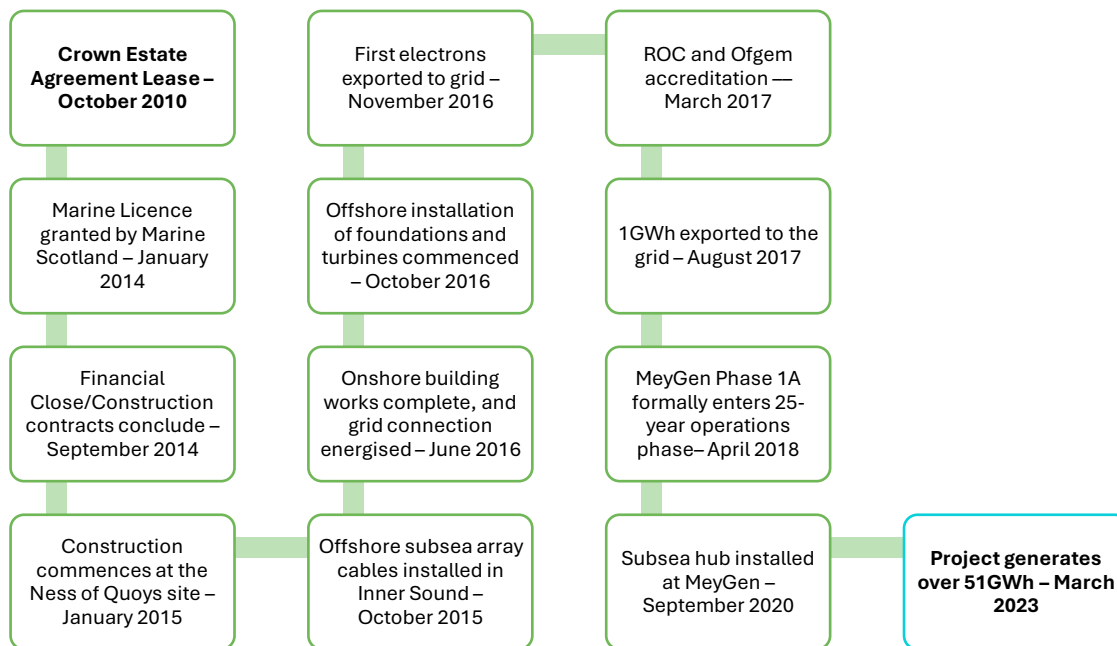


Figure 42 MeyGen project timeline

MeyGen project phase 1 took nearly 13 years which is longer than typical in other renewables but may be explained by the first-of-a-kind nature of this project. The time window from Crown

Estate lease (conception) to commencement of construction appears to be 5 years. Excluding planning phase, the time for construction itself was a year, which is considered rapid. The time spent awaiting the government and market support is worth noting, as it is more than 6 years. Although, it can be argued that as it first of a kind project, the technology is developing and there is a long time-window awaiting government support for these projects. This time window signifies the huge dependence of the industry on the government support. The UK Energy roadmap 2011 also confirms that R&D cost risks, securing the investment, supply chain infrastructure development and planning consents do play a major role in the time taken before the project commencement.

The supply chain for the Phase 1 of the MeyGen project was spread across the United Kingdom, Europe and North America. Up to 55% of the project's operational expenditure is sourced locally. 43% of the project's capital expenditure was in Scotland.

Offshore wind projects can take anywhere from 12 to 15 years to become fully operational¹⁰⁵. Construction alone can take from 7-11 years. The time to connect to grid is one of the challenging phases and time consuming, up to 5 years, but with new supporting strategies in place, it is expected to reduce to 6 months.

8 Tidal Range Energy

8.1 Introduction

This report so far has concentrated on Tidal Stream Energy, extracted with turbines in open water that work on the flow of the tides. This section will concentrate on Tidal Range Energy, extracted with turbines in the wall of a barrage and lagoon that generate electricity from the height difference between high and low tides¹⁰⁶. In the case of a **tidal barrage**, a hard barrier placed at a strategic point across an estuary with a high tidal range, thus creating an impoundment upstream of the barrage in conjunction with the banks of the estuary. In the case of a **tidal lagoon**, the lagoon is a completely artificial offshore impoundment constructed in shallow water areas with a high tidal range.

Globally, a small number of bespoke projects built in 1960s and 1970s, are still in operation with La Rance 240 MW of capacity in France, 20 MW Annapolis station in Canada (now closed), 4 MW Jiangxia station in China and 1.7 MW Kislaya Guba station in Russia^{106 107 122}. Later in 2012, South Korea opened the world's largest tidal barrage with a capacity of 254 MW at Sihwa lake, but nothing has been built since.

New technologies developed for tidal range power generation include tidal reefs, tidal fences and low-head tidal barrages. Tidal reefs have a smaller head difference, 2 m to 3 m, than a typical tidal barrage which has a range above 5 m. Smaller head difference has the advantage of reduced impact on the environment, easier construction due to the lower pressure exerted on the structure and applicability in many more regions of the world. On the downside, a lower head means less energy available for a given area and generally lower turbine efficiency. Low-head barrages operate at a head as low as 0.5 m to 1 m. Tidal fences consist of a collection of

¹⁰⁵ [Offshore news](#), accessed June 2024

¹⁰⁶ [Turning the Tide - Tidal Power in the UK](#), Sustainability development commission archives 2007

¹⁰⁷ [Jiangxia tidal power plant](#), Tethys 2023

individual vertical axis turbines connected to each other within a fence structure. The fence itself would ideally be placed between the mainland and a nearby island, or between two islands, and the distinction between tidal stream and tidal range is less distinct for a tidal fence and is arguably both. The tidal reefs, fences and low-head tidal barrages are still in their early stages of development and are with yet to demonstrated or demonstrated only at very small scale.

The US government's national ocean service published a listing of 50 locations from around the world, where the largest difference between low and high tide range have been observed and the top 20 locations are listed in Table 12¹⁰⁸. The highest tidal ranges in the world are observed in Canada followed by UK and France, all in the northern hemisphere. The southern hemisphere does not have a similar tidal range because the continents are further apart and there is little ocean constriction.

No	Location	Country	Mean Range (feet)
1	Burnt coat Head, Bay of Fundy, Nova Scotia	Canada	38.4
2	Horton Bluff, Bay of Fundy, Nova Scotia	Canada	38.1
3	Amherst Point, Bay of Fundy, Nova Scotia	Canada	35.6
4	Parrsboro, Bay of Fundy, Nova Scotia	Canada	34.4
5	Hopewell Cape, Bay of Fundy, New Brunswick	Canada	33.2
6	Joggins, Bay of Fundy, Nova Scotia	Canada	33.2
7	Leaf Lake, Ungava Bay, Quebec	Canada	32
8	Port of Bristol (Avonmouth), United Kingdom	UK	31.5
9	Grindstone Island, Bay of Fundy, New Brunswick	Canada	31.1
10	Spencer Island, Bay of Fundy, Nova Scotia	Canada	30.5
11	Newport, Bristol Channel, United Kingdom	UK	30.3
12	Sunrise, Turnagain Arm, Cook Inlet, Alaska	US	30.3
13	Burnham, Parrett River, United Kingdom	UK	29.9
14	Bristol Channel, United Kingdom	UK	29.5
15	Rio Gallegos (Reduccion Beacon), Argentina	Argentina	29
16	Hudson Bay, Canada	Canada	28.5
17	Herring Cove, Bay of Fundy, New Brunswick	Canada	28.3
18	Granville, France	France	28.2
19	Bristol Channel, United Kingdom	UK	28.1
20	Leaf Bay, Ungava Bay, Quebec	Canada	28

Table 12 Highest Tidal range sites in the world¹⁰⁸

The geographic spread of high tidal ranges in the Europe and North America are illustrated in

¹⁰⁸ [National ocean service data NOAA's Center for Operational Oceanographic Products and Services.](#) accessed 13/08/2024

Figure 43 and

Figure 44 respectively¹⁰⁹. Figure 45 shows the number of sites (not range or capacity) in each of the represented countries.

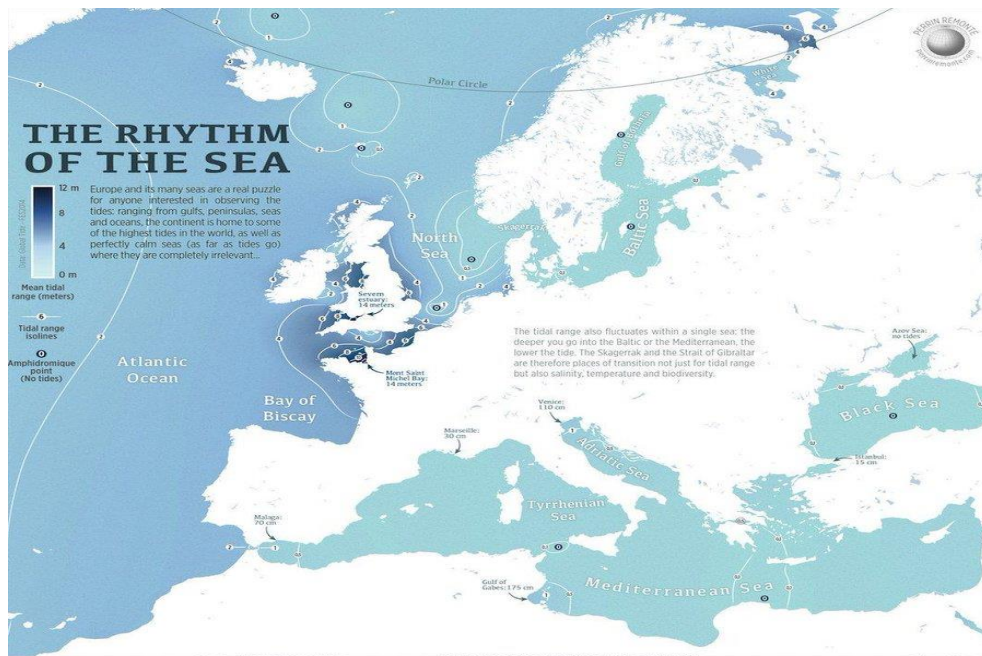


Figure 43 Tidal ranges in Europe¹⁰⁹

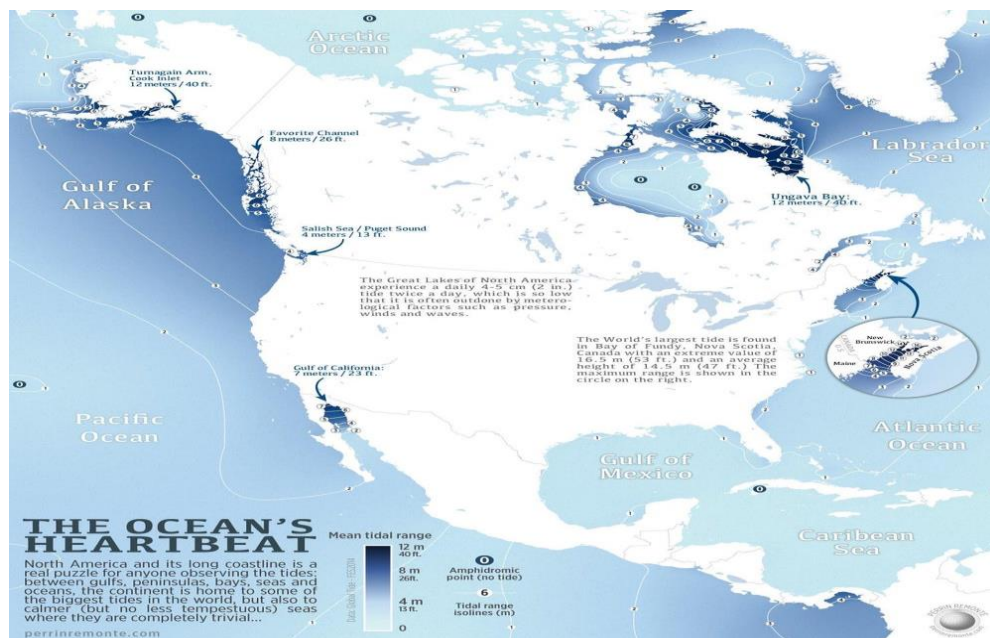


Figure 44 Tidal ranges in North America¹⁰⁹

¹⁰⁹ [Perrin Remonte post](#) 2024

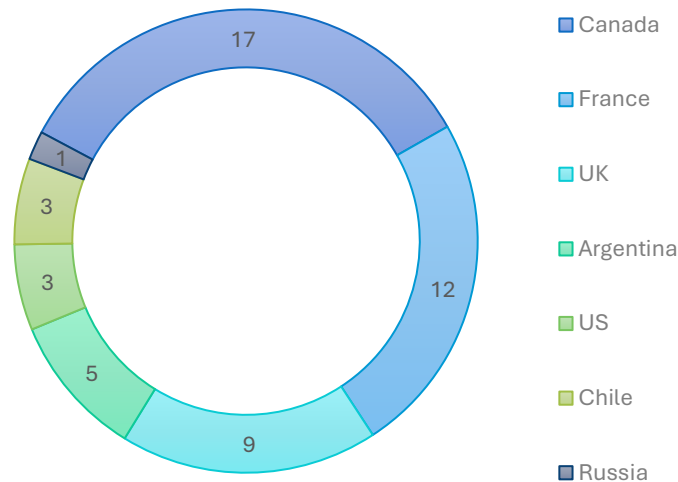


Figure 45 World top 50 tidal range sites by country (number of sites)

By 2012, worldwide tidal range deployment was around 520 MW and is still maintained at 500 MW, post the closure of Annapolis tidal station. Plans exist for tidal barrage projects in India, Korea, the Philippines and Russia adding up to around 115 GW¹⁰⁶ but these are yet to materialise. Tidal barrage resource potential in the UK is estimated to be around 45 GW according to a Crown Estates report¹¹⁰. UK tidal lagoon potential is estimated to be around 14 GW¹¹⁰. A recent article states that the global inherent potential of tides is up to 3,000 GW¹¹¹. However, depending on the location and the potential for conversion, the available actual capacity of tidal barrages is between 120 and 400 GW. NESO'S 2024 Future Energy Scenarios assumes that a contribution in the range of 3 GW to 5 GW of tidal range energy is being estimated by 2050¹¹².

8.2 Tidal Range Projects – Active and Proposed

The major projects around the world, active and planned, have been reviewed to understand the tidal conditions at the sites, the capacities of the projects and any important issues that were encountered during the development of these projects.

8.2.1 Sihwa Lake, South Korea (Active)

Sihwa lake tidal barrage in South Korea originally started off as a sea wall in 1994¹¹³. An artificial lake was built as a land reclamation project to cater for the needs of three new cities formed as a result of significant industrialization. The sea wall forming the artificial lake, was built for flood protection and to fulfil agricultural irrigation needs. However, cutting of fresh water supply coupled with industrial and domestic waste has quickly contaminated the water significantly, leading to marine life extinction and huge ecological issues in the isolated lake.

¹¹⁰ [UK Wave and tidal key resource areas project – Summary report](#), Crown Estates Report 2012

¹¹¹ [Britannic news](#) 2017

¹¹² [Severn estuary commission report](#) 2025

¹¹³ [The rebirth and eco-friendly energy production of an artificial lake: A case study on the tidal power in South Korea](#), Eun soo park and Tai sik lee, Energy reports journal 2021

The government had to convert it to a sea water lake, enabling sea water exchange to sustain the marine life and the idea of tidal power station emerged.

In 2012, it was transformed into a tidal barrage power station with a power capacity of 254 MW, with ten turbines each at 25.4 MW. It is currently the world's largest tidal power station. Taking into account the timing of the tidal rise and fall, it achieves a capacity factor of 25% (ratio of energy yield over a period to product of power capacity and the period). The project is widely estimated to have cost \$298 million¹¹⁴. However, another government source indicated that it was a \$560 million project funded by the South Korean government¹¹⁵. The difference may be coming from the inclusion of the original sea wall construction. This leads to two substantially different costs of project of being either \$1.17 million per MW or \$2.2 million per MW. When it completed, it was then considered the world's most expensive power plant. The capital cost of an online wind farm completed in 2019 stands at £1.61 million per MW and an offshore windfarm stands at £4.49 million per MW¹¹⁶. Combined Cycle Gas Technologies (CCGT) cost \$1.1 million per MW and CCGT with Carbon Capture and Usage (CCUS) cost around \$3 million per MW¹¹⁷.

At Sihwa Lake, the sluice gates are closed as the tide begins rising, isolating the reservoir at its lowest level. At high tide, the sluice gates are opened allowing water to flow from the West Sea to Sihwa Lake via the ten turbines. It generates one way power twice a day at high tide. The submerged bulb turbines are driven in an unpumped flood generation scheme. Generating on tidal inflows only, is unconventional and produces less electricity than generating on the outflow also. However, it has been said to be chosen to balance a complex mix of existing land use, water use, conservation, environmental and power generation considerations.

Following the success of Sihwa Lake, South Korea lined up several more tidal projects for development. A large tidal project at Incheon Bay was proposed with a capacity of 1,320 MW comprising 44 turbines, each with a capacity of 30 MW¹¹⁸. The projected development cost in 2010 was estimated to be \$3.4 billion, planned to be entirely covered by private funding¹¹⁹. This project had to be halted as the government withdrew support, in part because there were significant environmental concerns¹¹⁵.

Another tidal project of 520 MW was proposed at Garolim Bay, and while it successfully passed environmental criteria, it was considered economically unviable¹¹⁵.

8.2.2 La Rance Tidal Power Station, France (Active)

The Rance tidal power station was a world's first and is now the world's second biggest tidal power station located on the estuary of the Rance river in Brittany, France¹²⁰. The station commissioned in 1966, has a peak rating capacity of 240 MW. A cross-sectional of the barrage is shown in Figure 46. Power is generated from 24 bulb turbines, each with a diameter of 5.35 m and rated at 10 MW. La Rance is a two-way, ebb and flood generation plant. Bulb turbines can also pump water for energy storage or water management reasons¹²⁰.

¹¹⁴ [Tidal energy technology brief](#) 2014

¹¹⁵ [Technology case study: Sihwa lake tidal power station](#) 2016

¹¹⁶ [The costs of offshore wind power](#) 2020

¹¹⁷ [Projected costs of generating electricity 2020](#) IEA 2020

¹¹⁸ [Clean development mechanism project design document](#), UNFCCC 2011

¹¹⁹ [The Korea times News](#) 2010

¹²⁰ [La Rance tidal power plant 40 year operation feed back](#), 2009

During its 60 years of its operation, it has undergone a thorough survey of ecological impacts which were initially serious and that led to efforts to re-establish the ecological equilibrium. Sedimentation was also notable for affecting the tidal range. The experience with the plant highlights that the ecological balance is delicate and depends heavily on the operation modes of the power plant, that dictates the water level. After 50 years of operation, the electrical control system was the only part that needed replacement. Otherwise, the plant needed minimal maintenance. Currently, with the capital cost paid off, La Rance is one of the cheapest energy producers in the Europe.

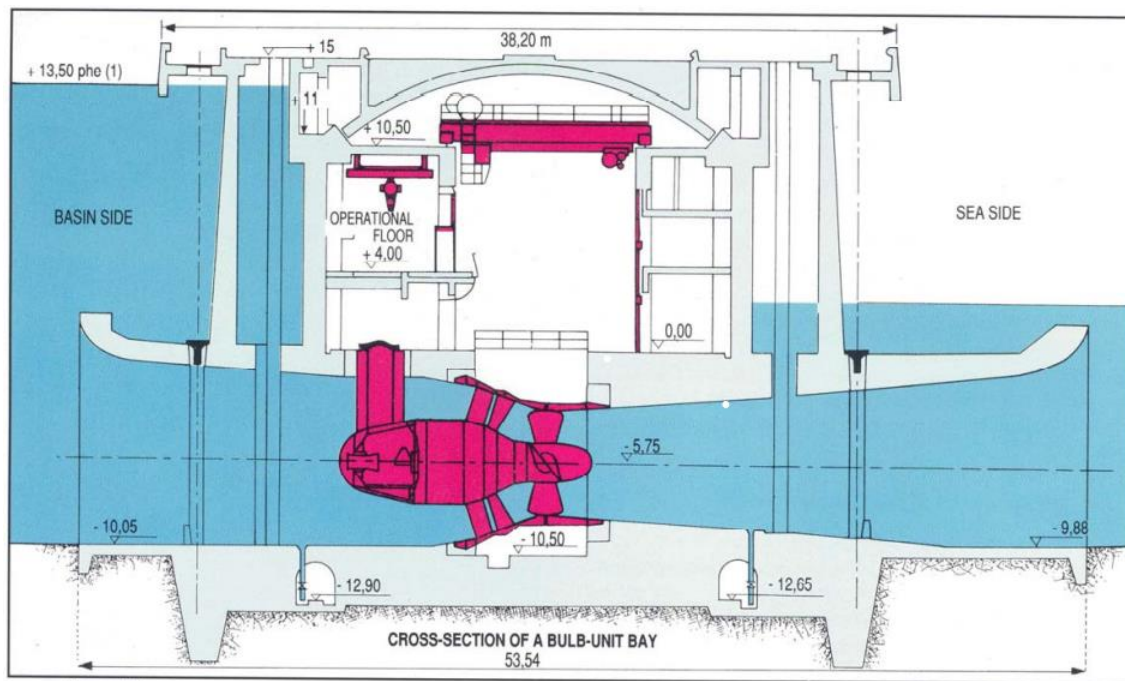


Figure 46 La Rance station, bulb turbine cross-sectional view¹²⁰

8.2.3 Annapolis Tidal Station, Canada (Closed)

The Annapolis tidal power station located in the Bay of Fundy, Nova Scotia became operational in 1984. The power station utilises a 1960 built causeway, which was originally designed to serve as a transportation link as well as flood prevention mechanism¹²¹. This project started as a government pilot project to trial tidal turbines and assess their impact on marine life. At a capacity of 20 MW, it was an ebb-only generation plant and was not grid connected. It used to be the third largest tidal barrage station in the world before its closure in 2019¹²². The reservoir was filled at flood tide through sluice gates that are closed once the tide has reached its highest level. At the ebb tide, the water in the reservoir was released through the turbines leading to power generation. In such a single cycle, power was generated for only four hours per day. The environmental issues included suspended sediment, scouring in the channels and at adjacent shorelines, flood flow management, and impact on the passage of anadromous fish through the barrage. There were concerns with increased basin water levels included interference with

¹²¹ [Power technology article](#) 2014

¹²² [Annapolis tidal station](#), Tethys 2024

existing agriculture, flooding, and accelerated rates of bank erosion¹²³. Apart from the literature from early on years of operation, not much is available on later operation years. In 2019, the Annapolis tidal barrage station closed after 34 years of operation due to equipment failure¹²².

8.2.4 Severn Barrage, UK (Proposed)

The Severn Estuary is the estuary of the River Severn as it flows into the Bristol Channel between Southwest England and South Wales. The tidal range here is one of the highest in the world at 14 m. A barrage here has a potential power capacity of approximately 10 GW. In 2007, the Sustainable Development Commission published a report looking at the potential of tidal power in the UK, including proposals for a Severn Barrage¹²⁴. The Severn Estuary call for proposals in 2008, received 10 proposals that included barrages, land connected lagoons, offshore lagoons, a tidal reef, and a tidal fence¹²⁵. The schemes included a Cardiff-Weston barrage (8.6 GW), Shoots barrage (1.05 GW), Beachley barrage (0.6 GW), Welsh grounds lagoon (1 GW) and Bridgewater Bay lagoon (3.6 GW). Technical risk, construction cost, environmental impact and supply chain risk (in terms of materials, turbines, vessels, skills, grid connection) were assessed. The Cardiff-Weston barrage, the largest scheme, had the lowest projected cost of energy but also the largest impact on the habitat and birds. The Bridgewater Bay lagoon had the lowest anticipated environmental impact. The Shoots barrage with lower energy yield has intermediate impact on the environment.

In October 2010, a summary report of the feasibility of the various proposed Severn Estuary projects was published by Department of Energy and Climate Change¹²⁶. The report stated that a tidal power scheme in the Severn Estuary could cost as much as £34 billion and it was then concluded it was high-cost and high-risk in comparison to other renewable power generation methods. That said, the annual generation from Cardiff-Weston barrage alone could have supplied about 5% of UK annual electricity supply.

In 2012, a consortium called Corlan Hafren resurrected the idea of a Cardiff-Weston barrage plan but with some differences. However, the House of Commons' Energy and Climate Change select committee concluded that the case for a barrage was unproven and stated that Hafren Power could not provide a robust and independently verified evidence of the economic, environmental and technological viability of the project¹²⁷.

The technical feasibility of Severn Estuary projects is well established, UK government reviews^{128, 129} indicated that it is not economically feasible, alongside unresolvable questions regarding serious environmental impact. Those reports also found that there were substantial flood risk mitigation benefits but at the time these were seen as marginal in comparison to the economic viability of the project. However, considering climate change and rising sea level concerns, this conclusion should be revisited.

According to the Severn Estuary Commission, the Severn estuary has the potential to meet up to 7% of the UK's total electricity needs¹³⁰. In November 2024, the crown estate has pledged to give £150,000 to support the Severn estuary commission's study to explore the potential for

¹²³ [Assessing the Environmental Impact of the Annapolis Tidal Power Project](#), W.Tidmarsh, Water Science & Technology 1984

¹²⁴ [Severn barrage proposals](#), Sustainable development commission 2007

¹²⁵ [Severn estuary feasibility study report](#), Gov UK 2010

¹²⁶ [Severn tidal power feasibility study: conclusions and summary report](#) DECC 2010

¹²⁷ [The corlan Hafren tidal barrage](#) RSPB 2013

¹²⁸ [Severn Tidal Power Feasibility Study Conclusions](#), Department of Energy and Climate Change, 2010

¹²⁹ [Energy and Climate Change – Second Report](#), Parliament UK 2014

¹³⁰ [Severn estuary commission update](#) 2024

sustainable energy from the Severn estuary¹³⁰. The Severn estuary commission, operating with support from UK and Welsh government, comprises of wide range of experts from engineering, environment and finance fields. The commission investigated into the potential environmental impact, socio-economic factors, financing models, and energy production implications. The commission has concluded that sustainable tidal range energy production at Severn estuary is feasible, and RAB model would be the most appropriate financial model that can balance investor needs, consumer protection ensuring project viability¹¹².

8.2.5 Swansea Bay Tidal Lagoons, UK (Proposed)

A Swansea Bay Tidal Lagoon was proposed as a 320 MW plant, with sixteen 20 MW turbines, generating two-way power¹³¹. This pathfinder project, ahead of other larger projects, was expected to cost £1.3billion. An artist's impression on the view of tidal lagoons on Swansea Bay is shown in Figure 47. The tidal lagoon project was expected to provide flood protection and coastal erosion protection for the Swansea Bay area. The potential of tidal lagoons on Swansea Bay has been evaluated in a government commissioned report by a former energy minister, Charles Hendry¹³². This independent review of tidal lagoons also explored the potential for 5 additional projects around the UK at Cardiff, Newport, Colwyn Bay, Bridgwater Bay and West Cumbria.



Figure 47 Artist's view of Swansea tidal lagoons¹³³

Figure 48 gives a pictorial view of the proposed Swansea Bay lagoon tidal project¹³³. The lagoon fills and empties as the tide rises and falls, producing two-way energy independent of the direction of the flow. The lagoons were expected to be built to last for about 120 years. Other low carbon technologies have lifetimes between 25 and 60 years. Thus, a typical tidal lagoon is expected to last more than double that of a typical solar or wind power plant. This pathfinder project received a positive backing from Charles Hendry's report, who stated that tidal lagoons could potentially play a cost-effective role in the UK's energy mix, help deliver competitive low carbon energy and provide substantial opportunities for the UK supply chain¹³³. However, concerns were raised in the Parliament that the project no longer represented value for money.

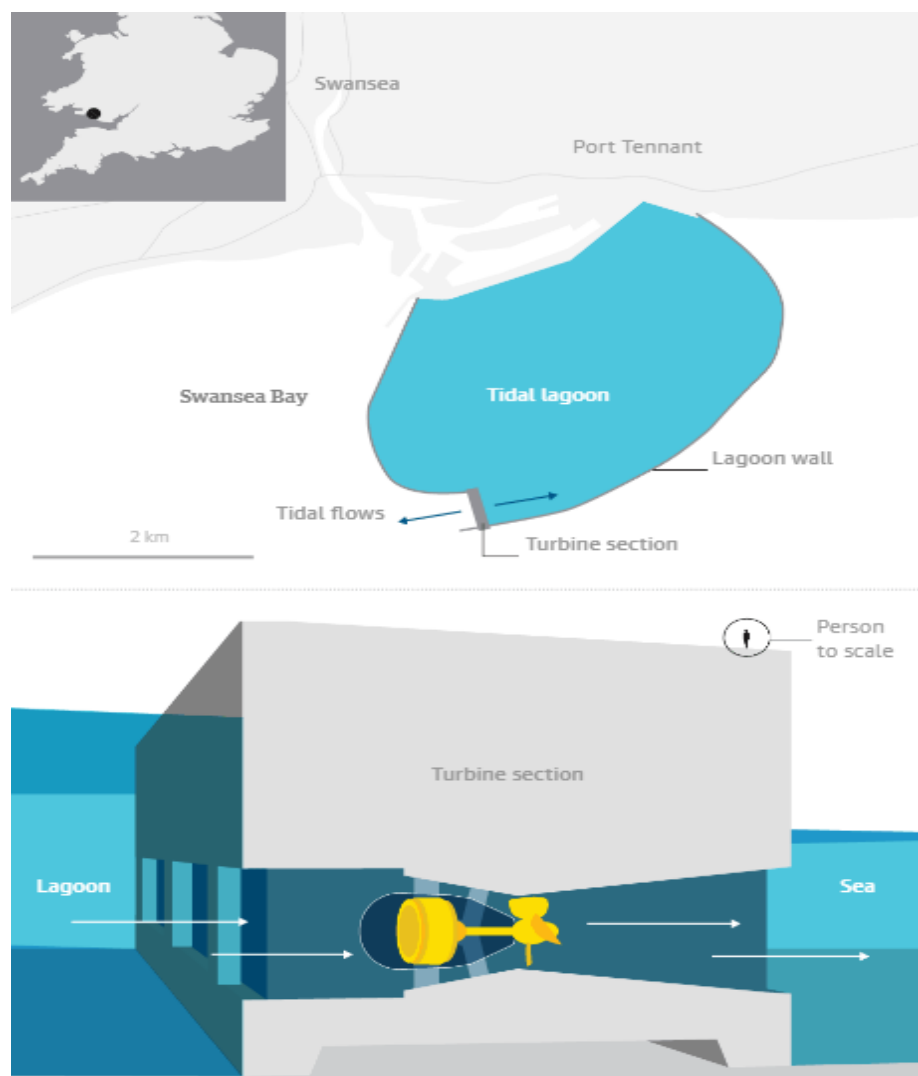
¹³¹ [GEplus news](#) 2022

¹³² [The Role of Tidal Lagoons](#) The world press 2016

¹³³ [Guardian news](#), 2017 accessed August 2024

The developer did secure a funding promise of £200 million from the Welsh government in 2018. However, the funding was halted as the secretary of state stated that the project did not represent value for money. Despite the withdrawal of Government support, the developer continued the pre-commencement work, but the project development consent order expired in 2020. The developer entered into legal proceedings in 2021, the legal battle was lost in December 2022¹³⁴ and the project development was officially suspended in 2022.

The Hendry review made 30 recommendations to the UK government in order to successfully deliver tidal lagoons. These include an allocation by a competitive tender process for large scale tidal lagoons; informing the consenting process with a National Policy Statement for tidal lagoons similar to Nuclear new build and the establishment of a new body (Tidal Power Authority) at arms-length from Government with the goal to maximise UK advantage from a tidal lagoon programme¹³².



¹³⁴ [The new civil engineer](#), News article 2022

Figure 48 Swansea Tidal lagoon project

According to a fact sheet prepared by Department of Business, Energy and Industrial Strategy in 2018, the Swansea bay tidal lagoon at 320 MW capacity with a capacity factor of 19% and cost of £1.3 billion, can be displaced by a 120 MW, £400 million offshore wind project¹³⁵. This projection has considered the lifetime of offshore wind project to be 25 years, which meant the project had to be re-equipped 2.4 times to equal the tidal range lifetime of 60 years. There are three uncertainties to this comparison. First, the assumption on lifetime being 60 years, whereas the tidal lagoon project can easily last 120 years. Second, the assumption on capacity factors of Offshore wind and tidal lagoon projects to be 50% and 19% respectively, are a bit high for offshore wind and slightly low for tidal lagoon. Other reports indicate capacity factors closer to 40% and at least 25%¹³⁶. Third, the actual cost per kW of offshore wind in 2022 is nearly 2,600 £/kW as against the assumed 1,486 £/kW¹³⁷ but since then, these prices have been affected by post-pandemic supply chain challenges. Re-examining the factsheet in the light of these three differences can significantly improve the case of tidal lagoon project against an equivalent offshore wind project.

Subsequent to discontinuation of the Swansea Lagoon project, the Welsh Government received another proposal for a 128 MW lagoon at the Port of Mostyn, Wales. This would have eight 16 MW turbines and cost £590 million¹³⁸. An environmental survey has taken place to study the ecological impact, yet some environmental groups were raising concerns that the development could harm wildlife in the Dee Estuary, which is a site of special scientific interest¹³⁹.

8.2.6 Mersey Barrage, UK (Proposed)

A Mersey Barrage was proposed by Peel Holdings, but after a feasibility study in 2011 similar conclusions on it being unviable were reached as for the Severn Barrage. However, in December 2022, the mayor of the Liverpool City Region signed a Memorandum of Understanding with the city region and K-water of South Korea (who built and operate the Sihwa Lake Tidal Power Station¹⁴⁰) to re-examine the prospects. A proposed 120-year lifetime barrage is considered and is said to have potential to become world's largest tidal barrage. The planning process works including application for a development consent order are continuing as of March 2024¹⁴¹.

Overall, grid constraints were not considered to be as a significant issue for Severn Barrage and other proposed barrages as shown in Figure 49 and in general, for tidal range projects in the UK as the resource location is generally closer to high-capacity transmission lines and to demand centers¹⁰⁶. That conclusion may change as offshore wind farms proliferate and all onshore transmission capacity close to the coast becomes a target for a connection. The tidal barrages and, to a lesser extent tidal lagoons, are likely to be larger capacity projects when compared to a tidal stream array, making grid connection costs a smaller part of the overall project cost.

¹³⁵ [TLP Tidal Lagoon Programme: Factsheet](#) Department of business, energy and industrial strategy 2018

¹³⁶ [Global offshore wind capacity factors](#) Statista 2023

¹³⁷ [Offshore wind power installation costs](#) Statista 2023

¹³⁸ [Port of Mostyn](#) 2020

¹³⁹ [BBC News](#) 2020

¹⁴⁰ [ITV News](#) 2022

¹⁴¹ [Liverpool City Region Combined Authority](#) 2024

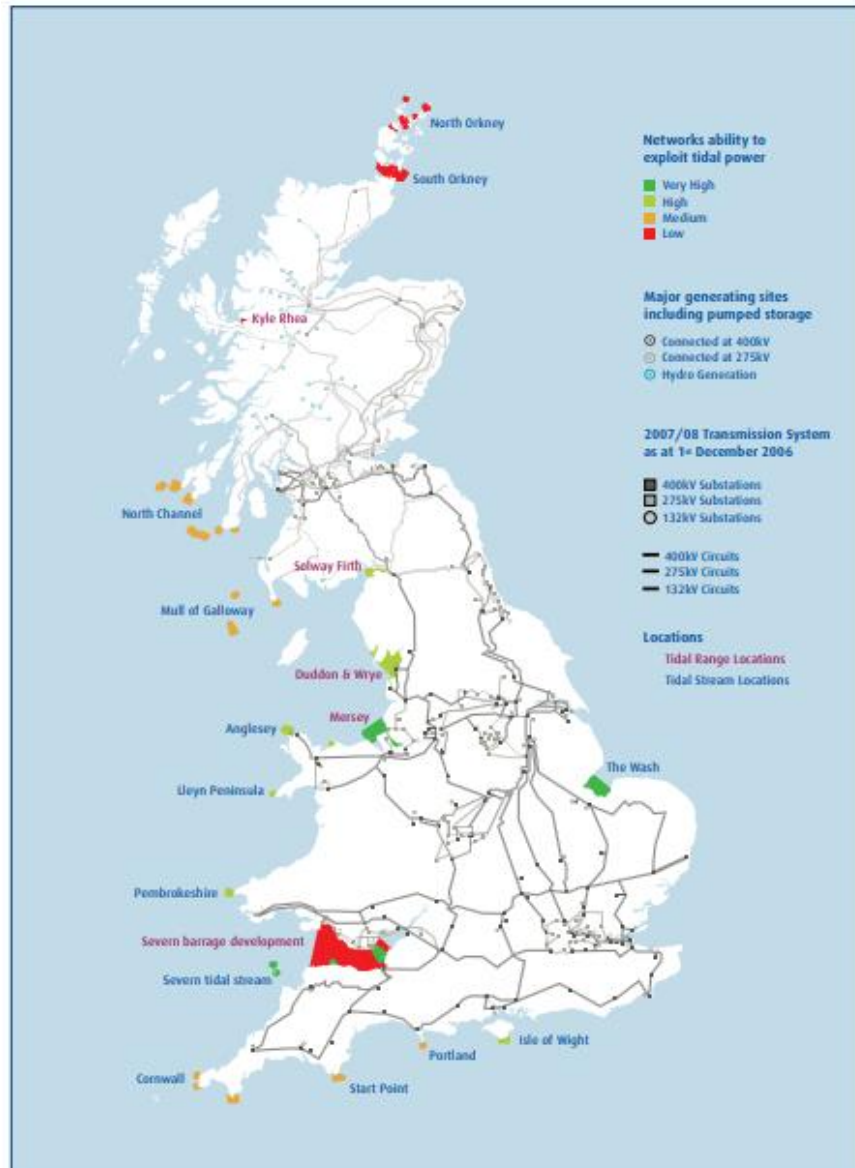


Figure 49 UK transmission network- tidal power integration constraints

8.2.7 Thames Estuary, UK (Potential)

The Thames Barrier was built as a defence mechanism from floods and exceptional high tides because of the prospect of large and frequent storms in the North Sea. Thames Barrier has been closed 221 times for flood defence purposes, since it became operational in 1982¹⁴². However, as with many of the Thames estuary's tidal defences, end of life is expected to be reached between 2030 and 2060. Climate change can lead to serious consequences such as rising sea levels, ocean warming and more storms in the North Sea etc. The new Thames Estuary 2100 Plan as shown in Figure 50, is looking at long term goals such (i) managing tidal flooding, (ii) ensuring resilient communities, (iii) protection and enhancement of the river Thames, tidal tributaries and flood plain, (iv) delivery socio, cultural and economic benefits, and

¹⁴² [Guidance: Thames Barrier](#) UK Government 2024

(v) tackling the climate and the resultant nature crisis by establishing sustainable, restorable, eco-friendly solutions¹⁴³. In addition to these key objectives, it would be a great benefit if the flood defence mechanism can also act as tidal barrage producing renewable energy. This project then becomes very similar to the Sihwa Lake tidal barrage project.

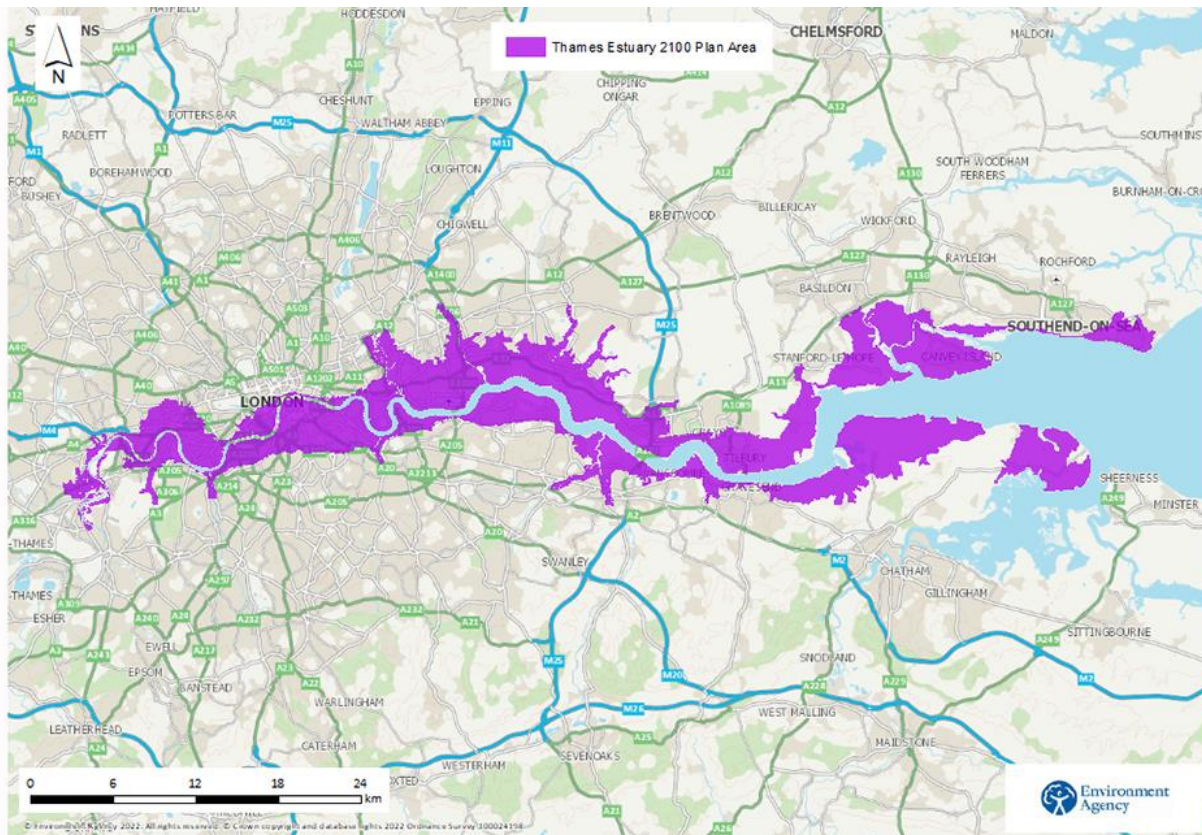


Figure 50 Thames Estuary 2100 area from Twickenham in the west to Southend-on-Sea and Sheerness in the east¹⁴³.

8.2.8 Tidal Lagoon Challenge, UK

The Tidal Lagoon Challenge is a funding programme, with a grant of £750,000 to tidal lagoon projects that can demonstrate the potential to remove the current environmental barriers and help to quantify a potential benefit of tidal lagoon development¹⁴⁴. This programme was initiated by the Welsh government in 2023.

Two bids were successful, one on the engineering and technical side and another in the environmental category. The project pursued by the Offshore Renewable Energy Catapult uses modelling to quantify the value of developing tidal range power. The Swansea University consortium is looking into the potential of removing the environmental concerns using fish tagging and monitoring to test the effectiveness of acoustic fish deterrence as a mitigation measure for tidal range deployment.

Overall, there is an understanding that a lack of authoritative evidence on the long-term potential of lagoons and there are no demonstrable projects of significant size. Therefore, In

¹⁴³ [Thames Estuary 2100](#) UK Government 2023

¹⁴⁴ [Tidal Lagoon Challenge](#), Low carbon energy programme, 2023, Govt. of Wales, UK.

2007, sustainable development commission report seen tidal lagoons as an unproven, streamlined concept, with costs yet to be standardized¹⁰⁶.

8.2.9 Grevelingen Dam, Netherlands (Proposed)

The Grevelingen Lake tidal range project at the island of Schouwen-Duivenland has a proposed capacity of 1.6 MW and cost of \$10 million. It proposes to incorporate some capacity for pumped storage of energy, so is sometimes described as a hybrid generation and storage project. The six fish-friendly turbines, operate as ultra-low head barrage, with a range difference of only 0.5 m to 1 m. Knowledge gained from its operation will feed into large future energy concepts such as dynamic tidal power and Delta21 pumped-storage. This project is under development as a joint venture / consortium project with EMEC¹⁴⁵.

Delta21 as shown in Figure 51, is a solution for energy storage, water safety, nature restoration and recovery. It is a high-water defence with energy storage system built with pumping station and a lockable barrier. It is a pumped hydroelectric storage facility rated at 1.8 MW and acts a storm surge barrier as well.

¹⁴⁵ [International waters](#), [Offshore energy Biz](#) 2021

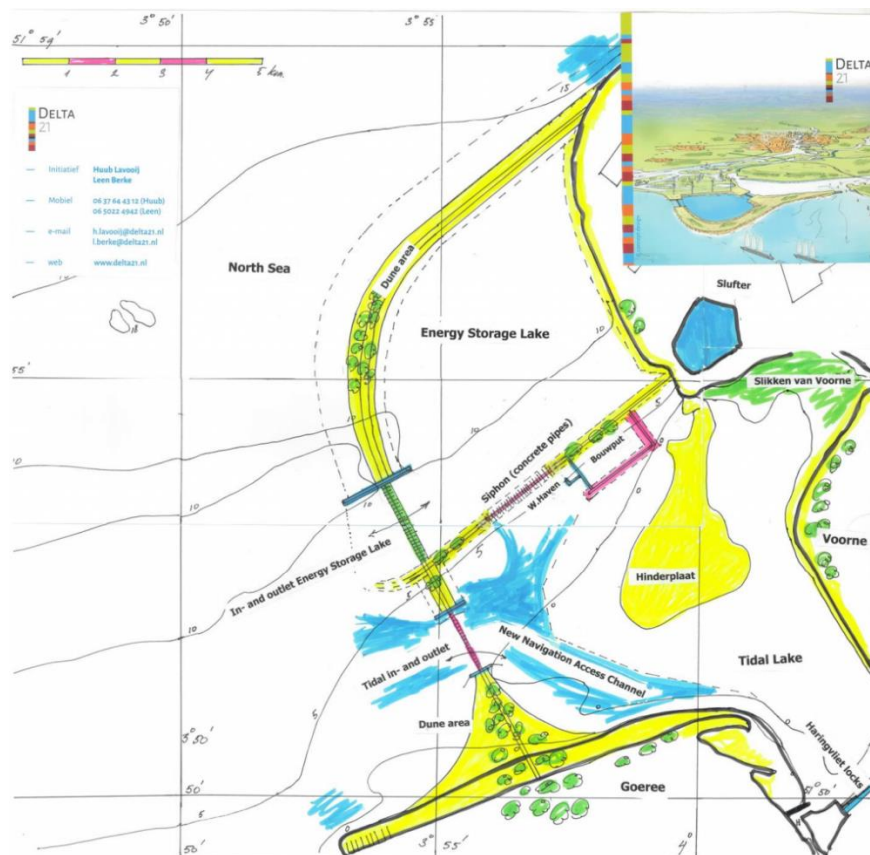


Figure 51 Delta21Dutch project¹⁴⁶

¹⁴⁶ [Delta Futures Lab](#) accessed September 2024

8.2.10 Discussion

This section discusses the two different types of tidal range generation, ebb and flood generation and hybrid forms of tidal range plants.

The annual generation of a plant is a function of capacity factor. The capacity factor of a conventional tidal barrage is generally around 25%, which is low in comparison to other intermittent sources of energy like wind and especially offshore wind. The type of turbine, a station uses, does influence its annual energy yield and thus its capacity factor. Ebb generation using one-way flow is shown Figure 52¹²⁰. By the use of reversible turbines, that generate power on bidirectional flows, the efficiency can be improved as can be observed from Figure 53. This further improves the energy yield. Looking at the plants in operation globally, Sihwa Lake is run as a flood generation plant, Annapolis station ran as an ebb generation plant and La Rance is ebb and flood, two-way generation plant.

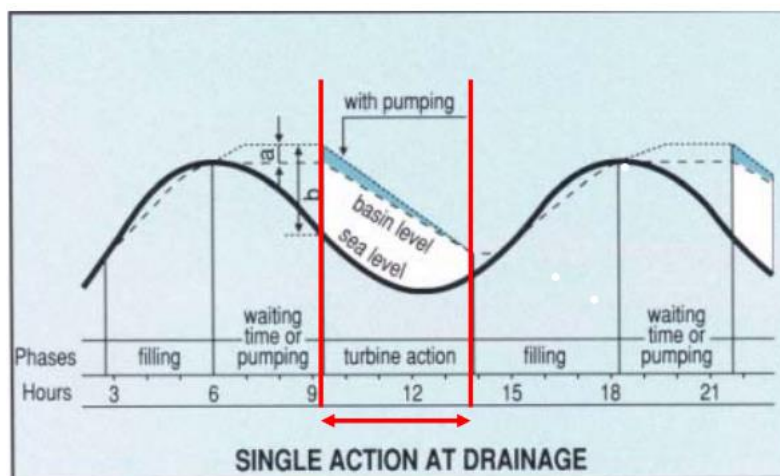


Figure 52 Ebb generation - tidal barrage¹²⁰

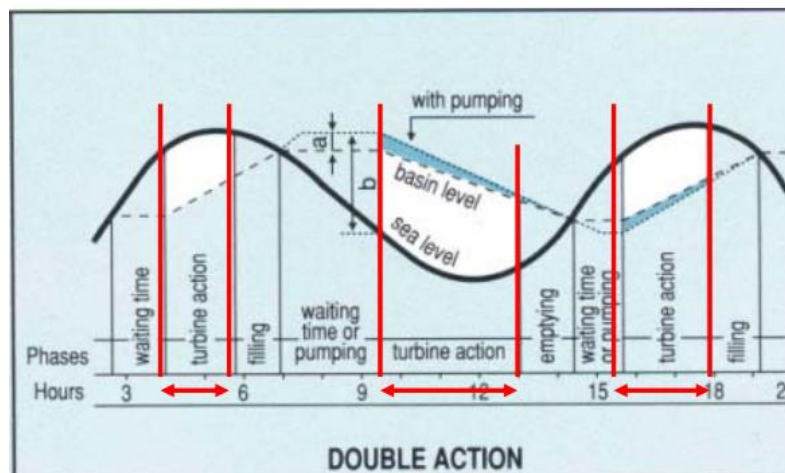


Figure 53 Ebb and flood generation - tidal barrage¹²⁰

A few novel forms of tidal power extraction is being tested as dynamic tidal power and in hybrid modes.

Recently, plans have emerged for a combined form of tidal range and current power generation, which is called 'dynamic tidal power'. It utilises the difference between the potential energy and kinetic energy of tides¹⁴⁷. Dynamic tidal power does not require a high tidal range, it operates by extracting energy from tidal propagation along the coastal line. A dam is built perpendicular into the sea, as a T or Y shaped construction, that can block the horizontal acceleration of tides, creating a natural range. As it has no enclosed area, it is an ecologically much friendlier design. This technology mostly is in research stage, no full-scale prototype has been tested yet, to establish its technical feasibility.

Tidal hybrid deployments are forms of tidal range technologies when their design and deployment is combined with the planning and design of new infrastructure for coastal zones. Project proposals for hybrid applications exist in Canada (British Columbia), China, the Netherlands (Grevelingen), Norway (E39 road project) and the UK (Bristol Channel)¹⁰⁶. The subsidiary projects such as these serve to improve the value to the tidal power project. While these hybrid add on projects are location specific, it is clear that due to shared costs, these add value to the main project.

8.3 Costs of Tidal Range Energy Projects

Tidal barrage projects are clearly capital intensive due to large civil engineering works. They are somewhat similar to hydroelectric projects in terms of construction and cost distribution. Their lifetime operation and maintenance costs are a small percentage of their capital expenditure. Typical values of OpEx range from 1% to 4% of the investment cost per unit power¹⁵². Large hydropower projects will typically average around 2% to 2.5% and small hydro power projects costs vary from 1% to 6%.

Tidal barrage projects have longer lifetimes than most conventional generation technologies and the barrages built in 1960s are still operational without any issues. The energy capacity and power capacity, hence the size of the barrage have a direct impact on project costs. The range (height difference high and low tides) and enclosed area dictate the amount of annual energy generated and dictate the height and length of the barrage.

As shown in Table 13, there are only few examples of tidal range power generation worldwide, and these projects are often designed based on local requirements, so the costs vary¹¹⁴. The available costing spectrum of tidal range limited and is largely dominated by two large plants in operation, the La Rance barrage in France and the Sihwa lake barrage in South Korea. The La Rance, which was commissioned in 1966, had construction costs of around 340 \$/kW in 2012 values. The Sihwa Lake barrage had construction costs of 117 \$/kW in 2011 values. Sihwa Lake used an existing dam for the water entrapment and added the power generation technology so that is a likely reason that costs were much lower compared to the La Rance project. La Rance project also operates as a highway, reducing distance travelled to cross the river by 30 km, and some element of the cost is attributable to the roadway. It is often difficult to separate out the generation project costs when they are hybrid applications. Electricity production costs for La Rance and Sihwa Lake barrage are 0.04 \$/kWh and 0.02 \$/kWh, but again these should be treated as site-specific and not generic¹¹⁴.

The construction cost estimates for proposed tidal barrages vary widely, from 150 \$/kW in Asia to around 800 \$/kW in the UK as observed from Figure 54. It highlights the range of construction

¹⁴⁷ [Energy education](#) 2016, accessed 2024

cost variation in different countries. However, the site-specific nature, hence the geographical location, plays a key role in determining a project costs alongside site specific nature of the resource. Hybrid schemes involving highways, coastal protection or water management can reduce the cost of the energy element of the scheme. However, the overall cost will be higher than an energy-only scheme and environmental impacts will be greater.

Figure 55 summarises capacities and costs of active and projected tidal barrage projects worldwide. Russia has a massive 87 GW project planned, but those plans have not progressed very far. Because of the large size difference between this and projects in other countries, the capacity is plotted on logarithmic scale on x-axis in Figure 55. For the project in Russia, various sources have indicated incoherent capacities, exceeding 100 GW. One source records that two dams, a north dam (21 GW) and south dam (87 GW), will be built which together are expected to cost \$260 billion¹⁴⁸. However, the first phase is expected to be a nominal 300 MW plant leading to a second phase of 21.4 GW¹⁴⁹. If both dams are built as planned and operational at full scale, transporting such significant amount of electricity to load centres will be a further significant challenge. There is said to be a plan to resolve the transmission and use issue by forming a consortium with Japan, China and South Korea to study the options for long distance international transmission¹⁵⁰. However, the cost of transmission infrastructure at this scale could easily outweigh the revenue from sales of electricity. However, a later plan published took a different approach in which the tidal power output was expected to feed into production of hydrogen and ammonia¹⁴⁸. There is little official confirmation of the current state of the project.

Name	Country	Capacity (MW)	Power Generation (GWh)	Construction costs in \$ million	Construction costs \$/kW
Projects Operating					
La Rance	France	240	540	817	340
Sihwa Lake	Korea	254	552	298	117
Projects Proposed					
Gulf of Kutch	India	50	100	162	324
Wyre Barrage	UK	61.4	131	328	534
Garolim Bay	Korea	520	950	800	154
Mersey Barrage	UK	700	1,340	5,741	820
Incheon Bay	Korea	1,320	2,410	3,772	286
Dalupiri Blue	Philippines	2,200	4,000	3,034	138
Severn Barrage	UK	8,640	15,600	36,085	418
Penzhina Bay	Russia	87,000	200,000	328,066	377

Table 13 Estimated construction costs of tidal barrages¹¹⁴

¹⁴⁸ [Sea News](#), Russia 2021

¹⁴⁹ [H₂ Clean Energy](#) accessed Oct 2024

¹⁵⁰ [Reporter News](#) 2021

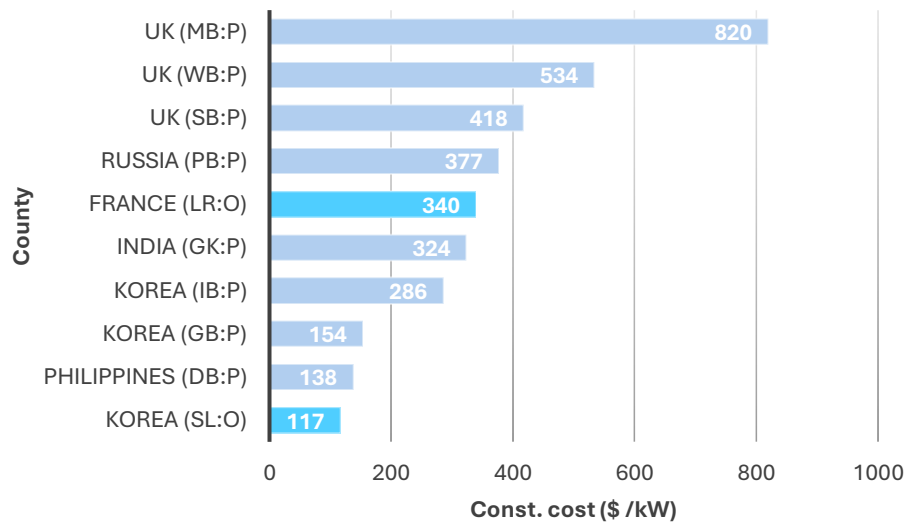


Figure 54 Tidal barrage project costs - World (2012 values) (P: Proposed, A: Active)

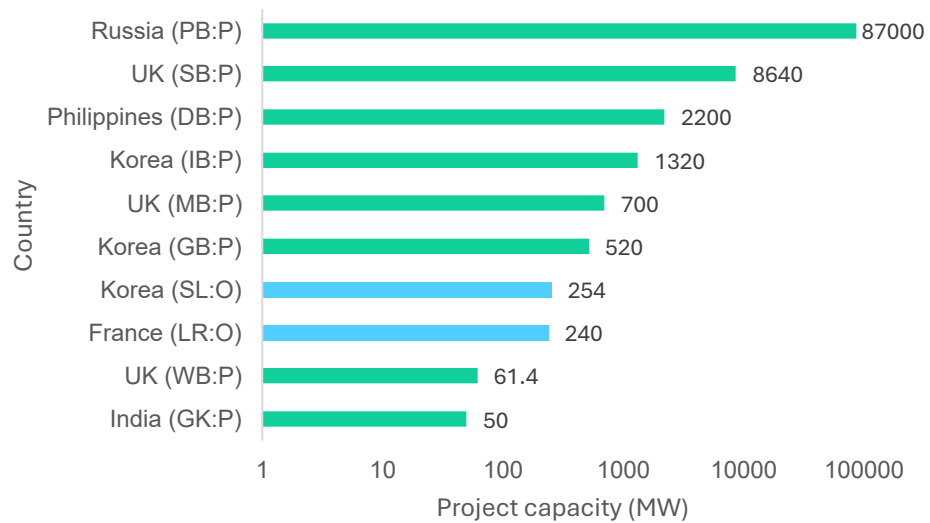


Figure 55 Tidal range project capacities – World (P: Proposed, A: Active)

Proposed tidal range projects in the UK	Capacity (GW)	Estimated Annual Energy (TWh/yr)	Approx. Cost (£ Billion)	Ratio of Cost to Annual Energy
Swansea Lagoon	0.3	0.5	1.3	2.6
West Somerset Lagoon	2.5	6.5	8.5	1.3
Cardiff Lagoon	3	6	8.1	1.35
North Wales Lagoon	2.3	5	7	1.4
Mersey Barrage & Liverpool Bay Lagoon	1 to 5	2 to 7	3 to 9	1.30
Morecambe & Duddon Barrage	4.0	7.2	10	1.4
Wyre Barrage	0.1	0.2	0.4	2.0

Table 14 UK tidal range cost estimates- comparison¹⁵¹

It is claimed that typical tidal range schemes can be expected to have a unit energy cost of around £100/MWh¹⁵¹. This is significantly lower than recent CfD strike prices for tidal stream energy as discussed earlier in section 5, yet still substantially above recent CfD prices for offshore wind, which is now at 59 £/MWh. Various tidal range projects were proposed in the UK for a long period of time as shown in Table 14.

Most of the projects met concerns regarding financial viability and to some extent environmental concerns. So, most of the projects did not come into development, except for Mersey Barrage, which is currently in development.

In 2010 prices, large hydropower plants with storage typically cost between \$1050/kW and \$7650/kW while the range for small hydropower projects is between \$1300/kW and \$8000/kW¹⁵². Subsequently, large hydro plants cost around 20 to 190\$/MWh and small hydro plants cost from 20 to 270 \$/MWh.

British Hydro Power Association states some key requirements to effectively harness UK's tidal range potential¹⁵³. These include

- Ensure investors' confidence with strategic partnership between industry and the government
- Ensure stable price mechanism to support long-term projects
- Create a favourable policy mechanism
- Develop a roadmap for tidal range
- Strategize industry to ensure that the supply chain is largely on-shore in the UK
- Build on work undertaken through the Tidal Lagoon Challenge
- Create a tidal range accelerator (utilising funding streams such as the Green Industrial Growth Accelerator)

¹⁵¹ [The Marine Renewable Energy Committee response on tidal energy](#) 2020

¹⁵² [Renewable energy cost analysis: Hydro power](#), IRENA 2012

¹⁵³ [British Hydro Power Association](#) website 2024

- Develop a pilot demonstration scheme to accelerate progress in areas such as regulations and remove/reduce planning restrictions for test sites
- A pilot test site, which would be supported by a CfD price stabilisation mechanism
- Work on a regulated asset base model as a mechanism to advance GW-scale tidal range projects

Marine Energy Wales has expressed similar concerns highlighting the urgent need for a suitable policy support mechanism, in a call for evidence on technological innovations and climate change - tidal power¹⁵⁴.

The majority cost of tidal range schemes is in the civil engineering elements that account for around 60% and the turbine generators and electrical equipment around 30%. There is scope for significant cost cutting of at least 20% from the use of new design methods and construction techniques¹⁵¹.

Cost is also dependant on the operation mode of the energy generation. In comparison to ebb only or flood only, the combined ebb and flow generation ensures the habitat is moving without getting stranded. In case of the former modes of operation, the habitat replacement itself will cost significantly adding up to the project overall costs.

8.4 Prospects for Tidal Range Energy

Renewable energy technologies in general are dominated by capital costs and have little in the way of operational costs. That is true for tidal range but with the difference that the capital costs are extremely high and so payback periods are long. Fortunately the lifetime of the civil engineering structures are also very long but nonetheless the investment decisions are difficult and involve assessments of multiple risks over very long periods. Hybrid developments such sea defence, water management, infrastructure for coastal zones, are another way of ensuring economic effectiveness of the tidal projects.

The energy produced by a given tidal range scheme depends on tidal range height of the site, the volume of enclosed water and the turbine capacity matters also in terms of realising the energy in the inter-tidal period.

Although much of the technology for tidal range energy is familiar, notably dam walls and ducted turbines, new design methods and construction techniques are expected to reduce costs by up to 20%. Improvements to energy yield may come from use of bidirectional over unidirectional turbines, optimisation of operation in terms of start head and pumping with one report suggesting that annual energy produced could improve by 30%¹⁵¹.

Environmental impacts will be important in decision making. A barrage can limit the wave fetch and protect against flooding from higher tide levels caused by sea level rises. However, on the downside, barrages could lead to worse flooding upstream as it stops the drainage from the land. A barrage can potentially damage estuaries, estuary-based industries through changed tidal flows and sedimentation. Where shipping is permitted, locks are needed to allow ships to pass and also reduced water depths at times could prevent existing shipping from accessing docks in South Wales and Bristol although facilitating navigation could be included as a further objective in the optimization of operation, perhaps with an associated reduction in energy yield.

¹⁵⁴ [Marine Energy Wales response](#) 2020

Although barrage and lagoon technologies are well established in terms of technical maturity, barriers such as site consents due to ecological issues need to be addressed because they can cause significantly delay with consequences for project costs. Research into the environmental impact would help reduce the risks during project development. Multiple government bodies work in coordination with the developers and technology providers in order to address the issues.

A UK based engineering company, Verderg has designed fish friendly ultra low head tidal turbines, operating within a height of 5 metres¹⁵⁵. The compact turbine is claimed to offer lower investment cost, shorter payback periods and improved project returns. Such turbines are suitable for decentralised mini-grids or connecting to the national grid. This 'plug and play' solution is said to be ideal for micro, mini and tidal range projects. In 2010 VerdErg's then-embryonic technology was shortlisted by the UK Government as one of three technologies to be assessed in the UK government's Feasibility study conducted on Severn tidal power. An innovative fence arrangement, Spectral Marine Energy Converter was proposed by VerdErg, comprising a series of vertical columns on the Cardiff-Weston alignment at a proposed installed capacity of 7500 MW¹²⁶. Other than this, there is no evidence of further tidal deployments.

The CfD mechanism has proved very successful at targeting support to various technologies as they exploit learning rates. This has worked well on technologies which have small energy conversion devices (panel and turbines) that are built in high number and where lifetimes are in the region of 25 years. It is widely held that CfD would be an ineffective support mechanism for tidal range projects unless extended to unrealistically long periods given the very high capital cost and likely 120 year project lifetime. Alternative support, such as making the project part of a regulated asset base as is the case for Sizewell Z nuclear power station, might be more appropriate.

In 2023, a consortium comprising of Severn Estuary Tidal Bar Limited, Cardiff University, Liverpool John Moores University, and the Tidal Range Alliance has received UK government funding of £800,000 to advance the optimization and testing of the very low head turbines¹⁵⁶. In a more recent announcement, Government pledges to work with tidal range industry to take advantages of the UK's high potential in tidal range resource¹⁵⁷.

NESO's 'Strategic case for tidal range' aims to build a strong and holistic knowledge base around the potential development, and impacts of, tidal range energy in Great Britain, with a priority placed on grid operability. This is seen as a positive trend towards tidal range development in the UK¹⁵⁸. This project assessed the potential impact on the GB consumers of each of the different scenarios, 1.5 GW (low), 5 GW (medium), 8 GW (high), including no tidal range deployment at all. Different delivery models and subsidy mechanisms have been considered to explore the potential delivery requirements of the studied scenarios. The results indicated that, when wholesale market costs, balancing costs and subsidy scheme costs are considered together, tidal range generation did not appear to deliver significant savings. Results showed that up to 8 GW of additional tidal range capacity on the system could be achieved with minimal impact on constraint and balancing cost. Tidal range energy at certain high generation locations with favourable thermal constraints could reduce the LCOE offering better value to the consumer

¹⁵⁵ [Verderg](#) UK 2024

¹⁵⁶ [Energy People News](#) 2023

¹⁵⁷ [New Civil Engineer News](#) 2024

¹⁵⁸ [Strategic case for tidal range energy](#) NESO 2025

Co-located battery energy storage systems can be an added advantage in terms of whole energy costs. Although, not quantified it is felt that the tidal assets that can be synchronously connected to the GB grid have the potential to provide inertia, Short Circuit Level, and reactive power, and therefore reduce the need for NESO to procure services to address shortfalls. This will result in reduced system costs and ultimately lower cost to the consumer.

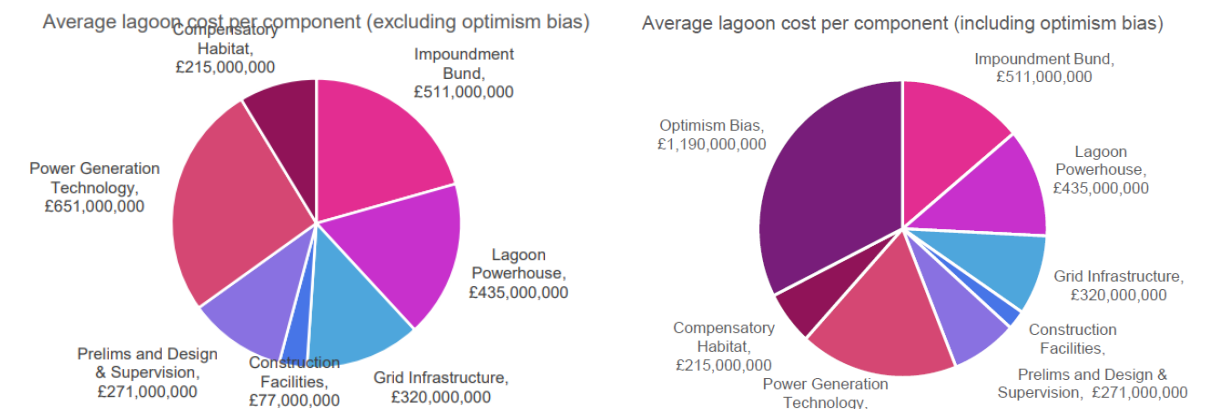


Figure 56 Average Lagoon cost per component excluding and including optimum bias (Source: NESO¹⁵⁸)

The Breakdown costs Breakdown costs per component averaged across the tidal range generation assets excluding and including optimum bias are as shown in Figure 56. The optimum bias considers that the tidal range generation assets assumed to be a non-standard civil engineering project where the environmental costs and existing technology, not requiring much innovation and lesser design complexity due to familiarity of the engineering design.

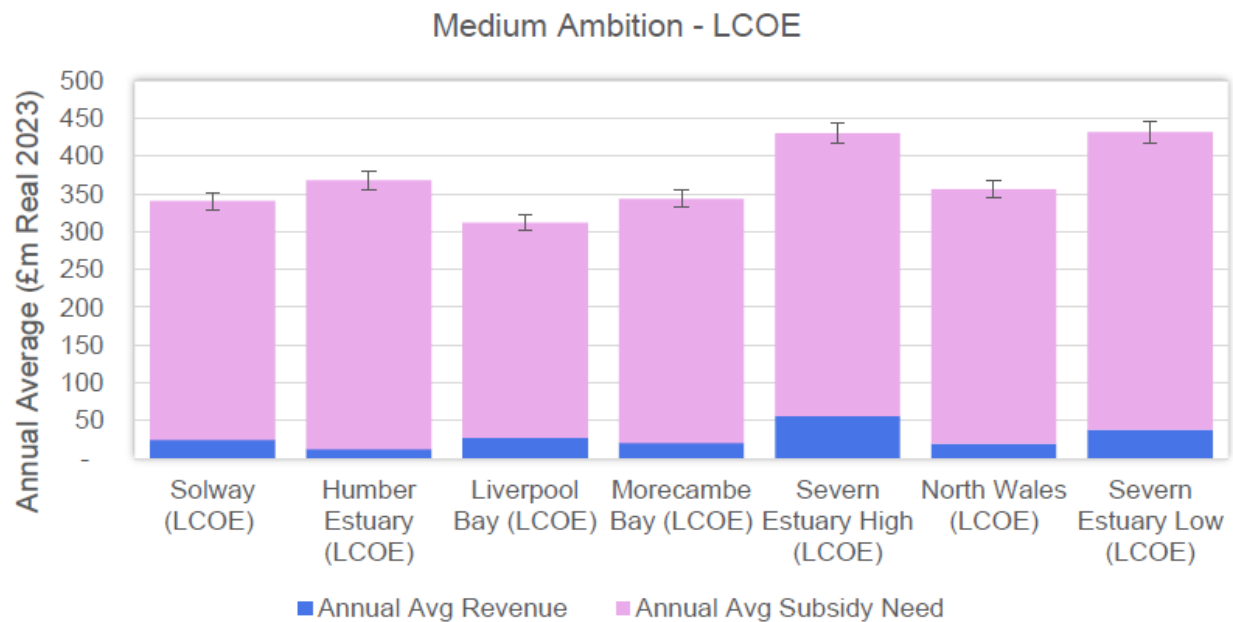
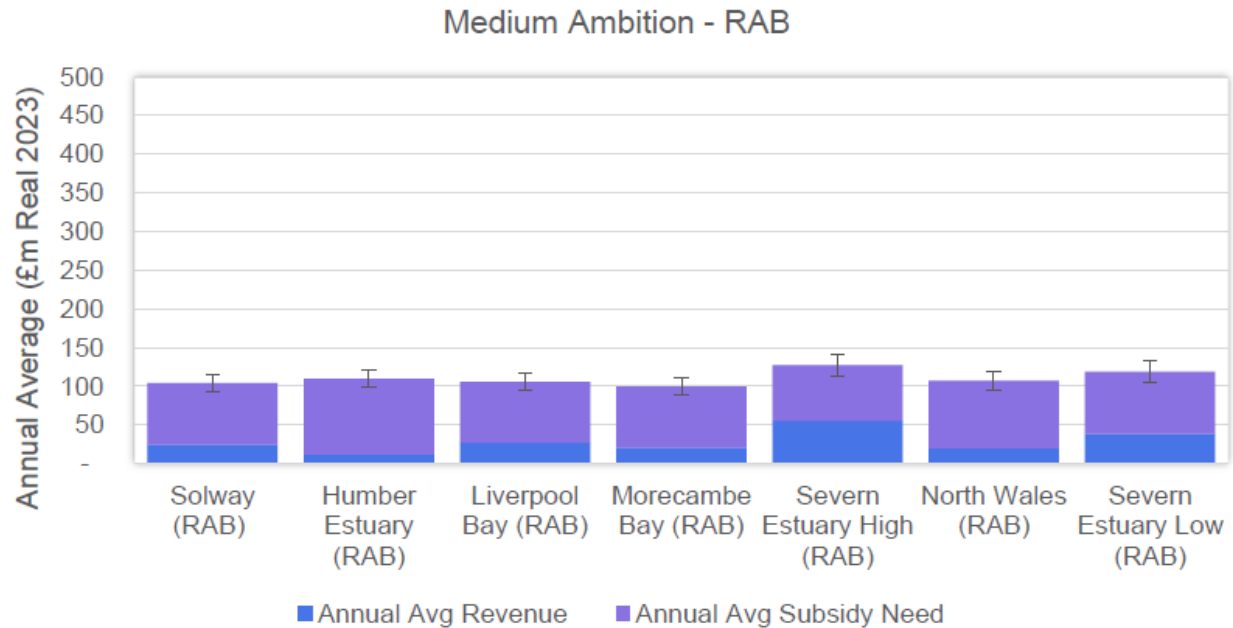


Figure 57 Tidal generators by support mechanisms (source: NESO¹⁵⁸)

NESO analysis assessed the average annual revenues and implied subsidy for each asset in the medium ambition scenario is shown in above. The implied subsidy needs for some assets are higher than the others, because of their locations with lower tidal range and thus reduced energy output. Interestingly, the tidal assets can reduce each other's income due to the combined dampening of the wholesale price thus the sum of the tidal assets can have an impact on the wholesale price which in turn significantly reduces revenues. It is also highlighted that the implied subsidy requirement is heavily dependent on LCOE assumptions and the funding model.

9 Conclusions

An important prelude to considering the potential of tidal energy to add value to the UK economy is to estimate the size of the market. There is consensus over the estimates of UK tidal stream energy resource as being in the region of 10 GW. However, the world potential estimates have not reached consensus with example estimate ranging from 23 GW to 500 GW. The current operational capacity in the UK stands at a very modest 10.4 MW and the capacity presently under development in the UK from CfD Allocation Rounds 4,5 and 6 is 41 MW, 53 MW and 28 MW respectively, giving an expected total 132 MW by the end of 2029.

It is anticipated by the ORE Catapult and others that learning rates will bring down costs of tidal energy and follow similar trajectories to those observed in the wind and solar industries, that is, a reduction in LCOE in the region of 15% reduction for each doubling of installed capacity. However, this is not certain; perhaps tidal energy has already benefited from some learning in offshore wind, or, conversely, perhaps it will learn faster by accelerating learning from that sector. An important point is whether the total tidal resource available will put a ceiling on the installed capacity that is so low that cost reductions do not bring the LCOE into a range competitive with existing technologies. The installed capacities of wind and solar have reached 1,000 GW and 1,400 GW and deployment continues at very high rates. If tidal stream is limited to only 500 GW then cost reductions might be impressive on their own terms, to 20% or even 10% of today's costs, but still be far behind wind and solar. In the recent CfD allocation rounds in the UK, tidal cleared at £172/MWh, floating offshore wind as £129/MWh and bottom-fix offshore wind at £58/MWh. It is clear that more rounds of subsidy support will be needed to move tidal into a competitive position.

Designs for tidal stream energy conversion devices are still evolving which is what gives hope for cost reductions. Currently, 3-bladed horizontal axis turbines are the front runners which mirrors design of wind turbines. Improvements may come in terms of increases in rotor diameter, stronger rotor blades, improved foundations and fixings, materials better able to withstand harsh operating conditions, and improvements in operations and maintenance. OpEx does have a significant impact on the LCoE of tidal stream energy and needs to be a focus of cost reduction alongside CapEx. The technical innovation, volume and scale of operation would definitely help reduce the overall cost of tidal stream energy in future. But the overall resource of tidal energy is far less when compared to the size of solar or wind resources. The extent of achievement of learning curve cost reduction is going to be far lesser in case of tidal stream due to the smaller size of its resource, when compared to the solar or wind resource size globally. The site specific nature of the resource is a key element that will have to be taken into account as the resource is dependent on the tidal velocity at that area. This influences the overall turbine planning and its economics.

Tidal range generation with barrages or lagoons has not been studied as widely as tidal stream. There are only two operating projects worldwide so it is difficult to establish the generic costs. The technology is mature in terms of the civil engineering and ducted turbine designs since there is commonality with hydroelectric generation on inland reservoirs and with artificial bays. The costs of construction are very high which makes payback periods stretch out to circa 120 years which largely explains why only two projects have been built. There are possible co-uses of a barrage such as flood defense and transport links and while this may improve the benefit-cost ratio, will also complicate the planning process.

Despite the current hurdles, the absence of weather related variability in tidal energy brings additional value in an electricity system that may go some way to offset the higher LCoE but would need recognition in a capacity market or similar to realise that.

The next stages of work on tidal energy within CSEP, to be conducted over the next 9 months will assemble further evidence on (i) the value of tidal energy within an electricity system, (ii) the environmental impacts of tidal energy projects, and (iii) the volume and disposition of resources worldwide.