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Centre for Sectoral Economic Performance

Future of Tidal Energy – opportunities and priorities for the UK

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Table of Contents

Executive Summary	**3**
Introduction	**4**
Tidal Stream	**5**
Tidal Range	**11**
References	**18**

Executive Summary

The UK has some of the world's largest tidal resources. This work has determined that the UK holds the second largest tidal range resource in the world after Australia, and the 6th largest tidal stream resource in the World. The UK's tidal range and tidal stream energy resources hold the potential of supplying 230% and 16% respectively of the UK's current electricity demand if projects offering attractive financial returns can be developed to tap into this comparative advantage in tidal energy resource. Financially successful tidal energy projects in the UK could then pave the way to grow the UK's tidal energy sector through exports to countries with good tidal resources. Such export destinations are identified as; Brazil, Argentina, Australia, USA, and Indonesia in the case of tidal stream, and Australia, Argentina and France, Canada and the US in the case of tidal range.

Despite promise the sector has struggled in developing attractive financial projects. The levelized cost of electricity (LCOE) is higher than other renewables such as wind and solar, and revenue uncertainty (electricity price) hamper the bankability of such projects. Subsidies such as Contracts for Difference (CfD) can create price certainty as long they endure for the lifetime of the project, which is easier for tidal stream projects of 25-year duration, but the guarantee of pricing for tidal range projects having 120-year lifetimes is harder to fulfil.

This study shows that it will be challenging for tidal stream to reduce its LCOE to below the costs of solar and wind through the typical learning curves experienced by most new technologies due to the later arrival of the technology relative to solar and wind, and the smaller total future market potential of tidal stream vs wind and solar. This means that tidal stream must seek other revenue streams to compensate and this work has shown that tidal stream can attract a premium of 11-18 £/MWh over solar and wind. This premium is provided by the unique services that tidal can offer over solar and wind due to its predictability which helps in reducing the system integration costs to a power network.

For tidal range technologies the potential to reduce levelized cost of electricity (LCOE) exists but this potential is likely lower than for tidal stream as the technology employed is mature in nature and builds on classical hydropower expertise, nevertheless the sector has identified some cost reduction pathways. Tidal range is likely to attract a price premium due to its predictability when integrated into a power system network much like has been shown for tidal stream, however tidal range can also offer additional services that can attract revenues that are not accessible to tidal stream.

A significant element of the work in this study has focused on environmental impacts of tidal technologies. An exhaustive review of the literature base has not only highlighted pathways by which we can build and operate tidal technologies better to mitigate any negative environmental and conservation issues, but it has also highlighted the many co-benefits of tidal range can offer. Benefits include climate-change induced rising sea-level flood protection, storm-induced flood protection, reduced coastal erosion mitigation costs, improved marshland conservation and ecosystem services provision. The study maps such potential benefits, overlays them on a map and shows how these regions are often co-located with proposed tidal range barrage projects that offer the needed co-benefits to mitigate these risks. This work highlights the need to develop creative ways to factor these benefits into tidal range barrage projects to improve financial attractiveness and bankability.

This study outlines priority actions for the sector if the UK is to grow its low cost, tidal energy electricity generation and exploit this expertise to grow a world leading tidal energy sector that can export its technology and know-how across the globe.

Introduction

The Centre for Sectoral Economic Performance (CSEP) at Imperial College London has recently commissioned 6 studies[1-6] to explore how tidal energy might be successfully exploited to create economic growth opportunities for UK businesses operating in this sector. This report collates the findings from the 6 studies and reports them here in a concise, holistic format. The reader is encouraged to consult each of the 6 individual reports if more detailed information and insight is sought.

The UK possesses the world's largest tidal resources according to several studies. A key question is whether this comparative advantage can be successfully exploited to deliver low-cost renewable electricity and thereby create a world leading sector in tidal energy technology supply, construction and services for the UK and export markets. This report explores the current status of tidal technologies, the challenges and opportunities and assesses whether the sector could become a key growth opportunity for the UK in support of the UK Government's Industrial Strategy.

Tidal energy is a dependable and clean power source that stands out as a compelling alternative to fossil fuels. It offers key advantages over wind and solar, including increased generation efficiency owing to the greater density of water over air, and reliable power production due to the predictable nature of tidal cycles. This reliability facilitates easier integration with existing power grids. Furthermore, tidal energy does not compete with future land use challenges, demonstrating the technology's potential as a reliable and valuable solution in achieving energy needs and sustainability targets.

Like Solar and Wind power however Tidal cannot provide the dispatchable, firm, baseload power that nuclear, hydropower, gas and coal-fired power stations can provide. Tidal, like solar and wind, therefore, requires support from battery storage or rapidly deployable reserve capacity such as gas turbines to ensure grid stability.

Despite such promise, tidal energy projects face barriers to practical implementation and often experience delays or cancellation due to financial, regulatory and political obstacles.

Tidal energy can be categorized into two distinct types: tidal stream and tidal range. Each relies on different mechanisms, and each is suited for different environmental conditions. This report will explore the opportunities and challenges and potential growth pathways for both technologies.

Tidal Stream

Overview

Tidal stream technology harnesses the kinetic energy of tidal currents using turbines. These are typically anchored to the ocean floor but can also be floating or suspended in the water column. Turbines can be either horizontal axis turbines, kites or hydrofoils; cross-flow or vertical axis turbines, with horizontal axis turbines being the most prevalent currently representing 51% of installed technologies by number worldwide and 71% in the UK.

Turbines intercept fast-moving tidal streams, rotating to generate electricity. Ideal locations are typically found where the coastline constricts, such as narrow straits or the often shallow channels between islands where geography accelerates water flow and generates strong tidal currents. While turbines function well individually, like wind turbines, most are conceived to be deployed in arrays.

Like solar and wind, tidal stream projects have the potential to be constructed in 2-4 years, a much greater speed than other non-CO2 emitting generation technologies such as nuclear, hydropower and indeed tidal range where timelines of 7-12 years are experienced. This speed supports the accelerated mitigation of climate change.

Tidal stream devices are anticipated to have similar lifetimes of around 25 years like solar panels and wind turbines, but not the 30–40-year initial lifespans of nuclear power plants that can be extended by a further 30-40 years, nor the 120-year lifespans of hydropower or tidal range barrages.

Over the last decade there has been an increased interest in tidal stream technology with the UK and France leading the charge in developing new projects and expertise.

The UK and world tidal stream resource potential

There have been several estimates of the resource potential of tidal energy. Previous studies cover limited geographic areas with varied methods, and rarely report capacity factors, the standard benchmark for other technologies. This work introduces Tidal.ninja, an open-access model for global tidal energy simulation. It combines the TPXO global tidal atlas with physical models of tidal range and stream operation, producing hourly power outputs and capacity factors for various barrage, lagoon and turbine designs. This work presents the first global capacity factor maps for tidal range and stream technologies, including both conventional and novel medium-speed turbines, with extensive validation. From this work the first known global estimate of the annual energy production (AEP) of ~1,200 TWh/year for tidal stream (regions with >20% capacity factor) has been made. For context, 1200 TWh/yr represents 3.6% of current global electricity demand. In contrast to previous work, this work estimates that Brazil, Argentina, Australia, USA, and Indonesia have larger AEPs than the UK, explained by this work's inclusion of seabed depths up to 100 m. The UK's resource is estimated to be 50 TWh/yr at >20%, similar to the 39 TWh/yr estimated for the Carbon Trust. 50 TWh/yr of tidal stream resource in the UK would represent 16% of the UK's current electricity demand. Figure 1 shows a world mapping of tidal stream resources expressed in AEP in absolute terms and as a % of national electricity demand.

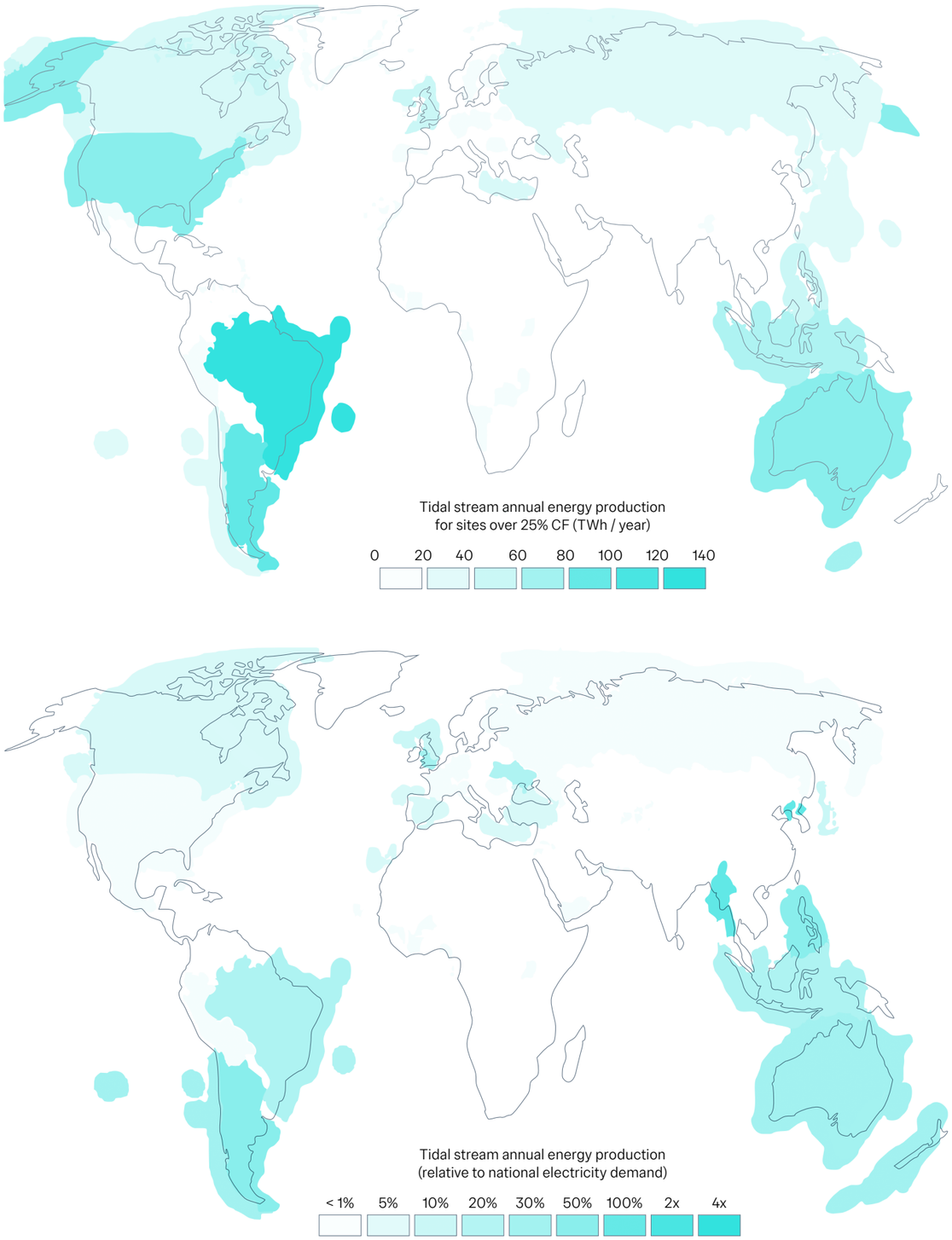


Figure 1 – Global annual energy potential from tidal stream, in absolute terms (top) and relative to current national electricity demand (bottom).

Costs

The costs of electricity generating technologies are most often compared in terms of their levelized cost of electricity (LCOE) expressed in £/MWh or $/MWh. LCOE takes into account the operating costs, capital costs, lifetime and cost of capital and it measures the overall average cost to build and run a power plant over its entire life, divided by the total electricity it is expected to make. The current LCOE figures for tidal stream as revealed by the CfD strike prices in the recent UK Allocation Round 6 auction stands high at £172/MWh, which compares unfavourably to competitor technologies such as floating offshore wind at £129/MWh, bottom-fixed offshore wind at £58/MWh, onshore wind at £39/MWh, and onshore solar at £51/MWh. Clearly LCOE costs need to fall if tidal stream is to become competitive and more investible. Also, costs need to fall to keep electricity prices low for electricity users and in particular households and manufacturing industries. Costs have dropped in recent years from the £198/MWh strike prices in the AR5 Allocation Round Auction to the £172/MWh in AR6. The question is whether further reductions are possible.

Cost reduction pathways

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. We have already seen the costs of tidal stream drop as this nascent technology has been deployed and we would expect it to fall further based upon what we have seen previously in many other technology fields including other renewable energy technologies. Learning rates have been observed to hold true over large increases in installed capacity. A learning rate is defined as the change in cost for a doubling of cumulative market. Learning rate predictions include an assumption on several of the following drivers of cost reduction.

- 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 over the past has estimated a varied set of learning of rates in the range of 5-17% cost reduction per doubling of cumulative market size. The European TIGER project LCOE projections 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 to an ORE catapult report.

Figure 2 shows the learning rates of wind and solar industries. These are super imposed with tidal projections from the TIGER project. It highlights the vast difference between the global potential estimates by Atlantis (23 GW), DMEC (500 GW) and this work (600 GW). Tidal stream at the current strike price of £172/MWh ($230/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, which is far greater than the global resource estimates of this work and past work have determined, the tidal price could be well above wind and solar achieved prices, unless a much higher learning rate is experienced as installed capacity grows. Furthermore, Figure 2 teaches is that tidal stream can never achieve lower LOCE's than wind and solar unless the costs of the latter begin to rise.

Other important factors also impact LCOE. The cost of capital is one such factor, with debt financing being preferable to keep the cost of capital lower. Most renewable technology deployment have been predominantly debt financed (85% debt on average). This work has also shown that location, and technology selection can have an impact on LCOE. Figure 3 shows the lowest LCOE locations for tidal stream deployment in the UK for two technology types.

The LCOE challenge for tidal stream is huge. In the short to medium term, alternative technologies such as solar and wind will continue to outperform tidal stream and be more bankable to investors at lower CfD auction prices. As such solar and wind will and be able to offer lower wholesale electricity prices to the grid. So, we must ask what additional benefits can tidal stream offer over existing competitor renewable technologies to offset higher LCOE figures?

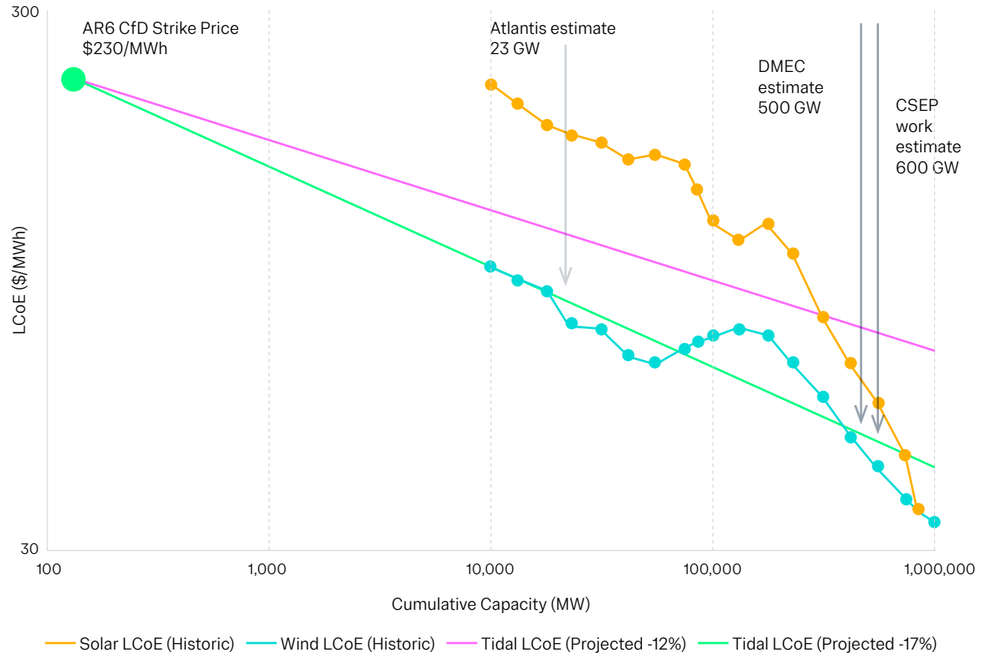


Figure 2 – Comparison of learning rates of Wind, Solar and Tidal Stream

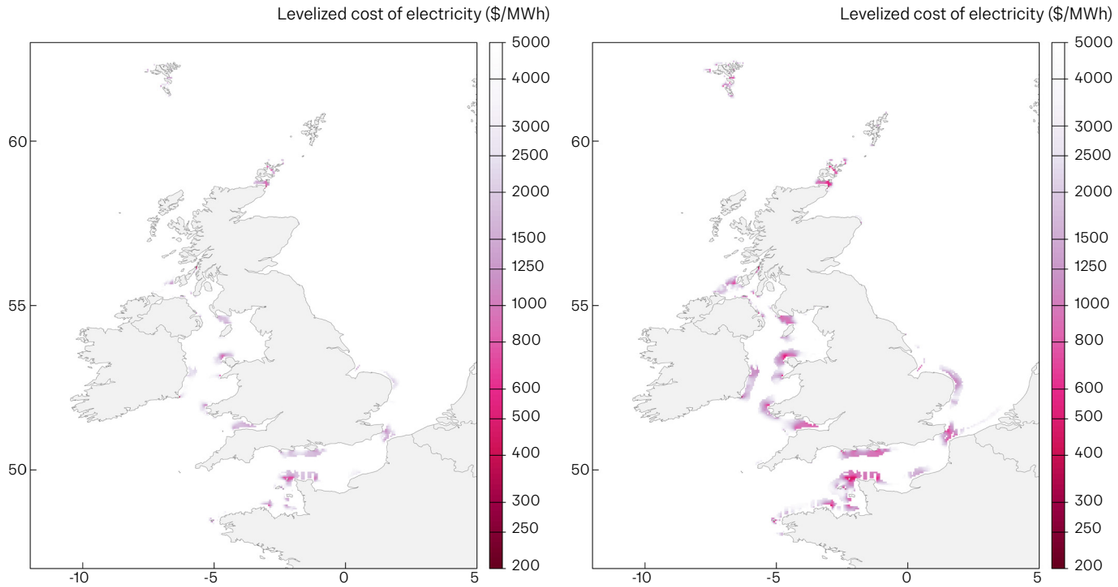


Figure 3 – Levelized cost of electricity from tidal stream across the UK, modelled using capacity factors from the 2 MW MCT machine (left) and the 1 MW TTS machine designed for medium-speed (right).

Revenue premia

In this study we ask what system cost/benefits tidal stream energy could offer to a power system, given that it is highly predictable compared to solar and wind, with a focus on the UK. To study the challenges and opportunities associated with a wider deployment of tidal stream technologies in the UK, this study develops a modelling framework that both identifies effective locations for tidal stream generation deployment and quantifies their system-level benefits for the power system of Great Britain (GB). The framework integrates high-resolution resource assessment based on Geographic Information Systems (GIS), multi-criteria spatial optimisation based on Non-dominated Sorting Genetic Algorithm II (NSGA II), and power system modelling to evaluate the contribution of tidal stream generation to system operation.

Simulation results show that deploying 1.5 GW of tidal stream capacity – on an energy-equivalent basis in place of wind and solar PV – reduces variable renewable curtailment by 0.6 TWh, displaces a comparable volume of gas-fired generation, and lowers total system operating costs by £65 million per year. Furthermore, analysis of electricity market impacts indicates reductions in average generation costs of up to £1.0/MWh in high-cost zones, alongside relatively stable technology-specific market capture prices for tidal stream generation compared to wind and solar. Although the effect of adding tidal stream generation on prevailing market prices was observed to be relatively small due to the small volume of generation added to the system, the effects quantified through the System Integration Cost (SIC) were much more pronounced, with the system benefit of tidal stream relative to a mix of wind and solar PV generation estimated at £11-18/MWh.

The £11-18/MWh premium that tidal stream can attract over solar and wind goes some of the way to closing the LCOE gap between the technologies, but it shows that more work on LCOE reduction in tidal stream is required to improve the competitiveness off the technology.

Environmental and social impacts

Objections to proposed tidal energy schemes often stem from perceptions of adverse ecological impact; a topic which lacked a comprehensive evidence synthesis. Added to this is the nuance that the early evidence arises from construction stages of tidal range installations rather than from their later operational stages or from tidal stream devices. The steep learning curve in both construction and operation, however, that marine energy has experienced now enables more informed choices and substantial mitigation.

It is essential to learn from established tidal energy projects to understand the demonstrated ecological and ecosystem effects and integrate this knowledge robustly into their planning and implementation. In doing so, negative impacts on marine ecosystems can either be avoided, minimised or mitigated, and the long- term ecological sustainability of tidal energy as a renewable source can be enhanced. This work aimed to synthesise the available evidence of effects that tidal range and stream technologies have had on marine environments through a combination of systematic and exploratory literature approaches. This evidence base will then provide foundations for environmental impact assessments of future projects.

Fifty-four articles were included in this review and produce a nuanced picture accompanying a steep learning curve in both tidal power system construction and operation. A summary of the ecological effects of tidal stream for which evidence was found in this review can be found in Figure 4.

Few of the widespread concerns around tidal stream are substantiated by evidence or in long- term monitoring of existing projects. There is evidence of some animal behavioural changes around tidal stream turbines, though many apprehensions either remain unsubstantiated or result in neutral effects on marine ecosystems. Several positive ecological effects are identified such as enhanced seabird foraging hotspots surrounding tidal stream turbines.

This work provides the foundations for environmental impact assessments of future tidal projects and may enable more informed choices and facilitate a priori mitigation planning.

Ecological risk	Tidal stream
Turbine–animal interaction (e.g. collision)	Neutral: Marine mammals (harbour porpoises and seals), exhibit local avoidance behaviour, though not found to alter overall population distribution. Fish interactions indicate low collision risk, no injuries reported. Turbine did not prevent transit of animals through the channel; no 'barrier' effect Overall, findings suggest minimal direct interactions and a tendency for local avoidance among marine species
Underwater noise	Neutral: Minimal physiological harm to hearing and minimal behavioural alterations. Operational tidal turbines create localized noise, unlikely to significantly affect marine animals beyond their immediate area. Acoustic emissions are below ambient levels at busy port sites Negative: Turbine noise and pile driving reduce local seal foraging success by impairing detection of prey. Operational tidal devices limit listening space for some marine mammals, local disruption of communication and navigation
Hydrodynamics	No evidence of effect
Sediment changes or erosion	Negative: At some less appropriate sites, risk of erosion likely higher due to the removal of fine sediment binding
Water quality	No evidence of effect
Habitat alteration	Positive: Anchor structures provide benthic substrate Negative: Local avoidance from seals adjacent to turbines implies habitat loss
Species/community changes	Positive: Physical structure promotes fish aggregation and a localised foraging hotspot, increasing seabird numbers

Figure 4 – Summary of the ecological effects for tidal stream for which evidence was found in this review.

Tidal Range

Overview

The governing principle of tidal range power production is centred around the impoundment of water to harness the gravitational potential energy of an artificial head difference caused by tides. Tidal power plant (TPP) operation involves the release of water from a higher level to a lower level through turbines to generate energy; achieved through an ebb- only, flood- only or two- way mode of operation. An ebb- only generating process impounds water at high tide, creating an artificial head difference as the exterior water level decreases, and releases the impounded water through turbines to convert the gravitational potential energy into electrical energy. The flood- only process is similar to this but excludes water at low tide and activates the turbines at high tide. Two- way generation combines both modes to produce power on both the ebb and flood phases of each tidal cycle. Although this translates to shorter generating times each way, there is a consistent trend of greater energy production. Tidal range technology currently only exists in the form of barrages, defined by the impoundment of an area of water within an estuary by the construction of a wall. The possibility of lagoons, describing an impounded area of water along a coastline by a much longer wall, has also been investigated, though not yet applied.

Two commercial- scale tidal range plants exist in the World. La Rance power station in France was completed in 1966 and has a 720 m barrage housing 24 turbines with a total capacity of 240 MW. This generates ~600 GWh annually, meeting ~0.12% of France's energy needs, and producing some of the cheapest electricity in Europe. Following completion of the plant in 1967, operation was two- way until 1975 when the mode changed to ebb only until two- way operation was resumed in 1983. The Sihwa Lake power station in South Korea has a capacity of 254 MW with an annual power output of 550 GWh. This TPP, completed in 2011, was born as a mitigation strategy for the recovery of the heavily polluted and ecologically devastated man- made freshwater lake (Kim et al., 2018), which had been created in 1994 by building a 12.7 km seawall at Gyeonggi Bay. Operation is flood- only with sluicing during the ebb phase.

Unlike tidal stream, tidal range barrages are more akin to hydroelectric dams. Their technology is mature and capital costs are significantly higher and project execution timelines longer (5-10 of active construction, and 10-15 from initial planning to completion) but, the generation capacity is correspondingly higher. Tidal range barrages are also expected to have lifetimes similar to hydropower dams of 120 years or more, much longer than the anticipated 25 years of tidal stream units.

The UK and world tidal resource potential

In this work, the Tidal.ninja global tidal energy simulation was also used to estimate tidal range resources worldwide. This work presents the first global capacity factor maps for tidal range technologies with extensive validation.

The global potential for tidal range stands at over 10,000 TWh/yr, considering all locations with seabed depth <30 m in depth and energy density >10 kWh/m2. With a stricter threshold, considering only areas with energy density >50 kWh/m2 (equivalent to a minimum tidal head of ~5 m) as in [11], global potential falls to 4,627 TWh/yr, enough to meet 15% of current global electricity demand [107]. There is broad agreement between this work and previous studies on the countries with the greatest tidal range resource; for example, we estimate a 733 TWh/yr resource in the UK, compared to 734 TWh/yr. However, we estimate Argentina's resource to be 11 times larger than in (677 vs. 62 TWh/yr) than one past study. In this work Australia is found to have the world's largest tidal range resource, followed by the UK, then Argentina and France, Canada and the US.

The 733 TWh/yr of tidal range resource in the UK would represent 230% of the UK's current electricity demand. This number is much higher than past reported potentials by the Crown Estate of 45 GW for tidal barrage and 14 GW for tidal lagoons, which if we assume a 29% capacity factor would result in a resource of 149 TWh/yr or 47% of UK current electricity demand. It should be noted that NESO's 2024 Future Energy Scenarios assumes a contribution of 3-5 GW (or 1-2 % of UK electricity demand) to be on stream by 2050, showing the potential upside of this technology. Figure 5 shows a world mapping of tidal stream resources expressed in AEP in absolute terms and as a % of national electricity demand.

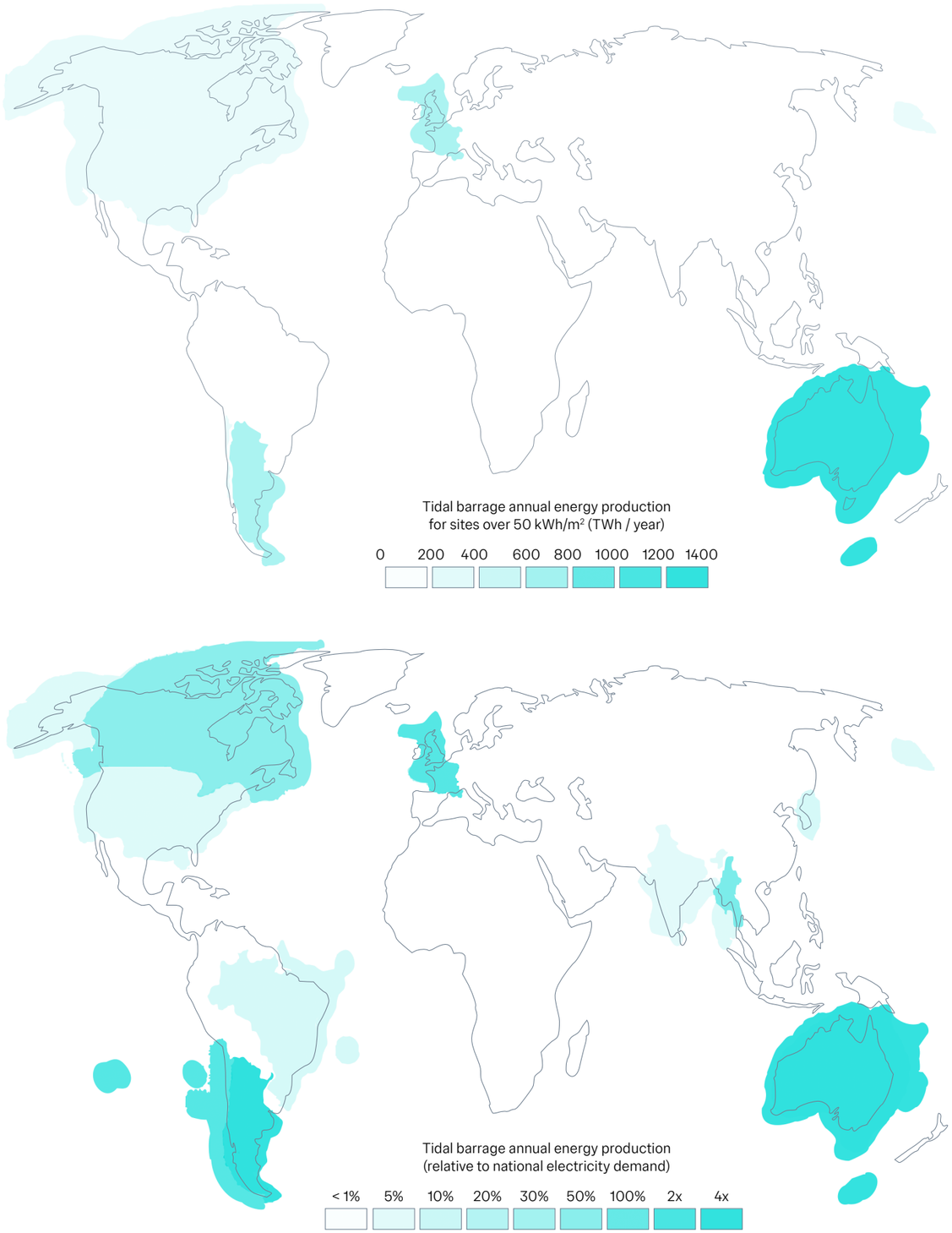


Figure 5 - Global annual energy potential from tidal range, in absolute terms (top) and relative to current national electricity demand (bottom).

Costs

During this work research has revealed little information regarding the LCOE of tidal range electricity. One report has been found that claimed that typical tidal range schemes can be expected to have a unit energy cost of around £100/MWh. This is significantly lower than recent CfD strike prices for tidal stream energy discussed earlier, yet still substantially above recent CfD prices for offshore wind, which is now at £59/MWh. Various tidal range projects have been proposed in the UK these being.

- Swansea Lagoon
- West Somerset Lagoon
- Cardiff Lagoon
- North Wales Lagoon
- Mersey Barrage & Liverpool Bay Lagoon
- Morecombe & Duddon Barrage
- Wyre Barrage

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

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 as 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.

Cost reduction pathways

The major 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%. 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%.

Environmental and social impacts

As mentioned earlier, objections to proposed tidal energy schemes also often stem from perceptions of adverse ecological impact; a topic which lacked a comprehensive evidence synthesis. Added to this is the nuance that the early evidence arises from construction stages of tidal range installations rather than from their later operational stages. The steep learning curve in both construction and operation, however, that tidal energy has experienced now enables more informed choices and substantial mitigation.

A better understanding of ecological effects is now essential as tidal range energy projects are considered for wider deployment. This study has shown that the tidal range resource potential is large and therefore has the potential to meaningfully contribute to the renewable energy portfolio in several countries with the largest tidal range resources such as Australia, the UK, Argentina, France, Canada and the US. With such immense potential, we must learn from established tidal range projects to understand the demonstrated ecological and ecosystem effects and integrate this knowledge robustly into their planning and implementation. In doing so, negative impacts on marine ecosystems can either be avoided, minimised or mitigated, and the long- term ecological sustainability of tidal range energy as a renewable source can be enhanced. This work synthesises the available evidence of effects that tidal range technologies have had on marine environments through a combination of systematic and exploratory literature approaches. This evidence base will then provide foundations for environmental impact assessments of future projects. A summary of the ecological effects of tidal range for which evidence was found in this review can be found in Figure 6.

Ecological risk	Tidal range
Turbine–animal interaction (e.g. collision)	Neutral: At La Rance there is free movement of erratic or migratory organisms through the sluices and turbines, normal migratory fish behaviour and evidence that a lack of fish passes has not impaired passage of organisms. Similarly, at Kislaya Guba, most fish were able to pass through the turbine Negative: At Annapolis Royal, high levels of fish mortality (almost half) were reported through a number of experiments, with one species being entirely eradicated. At La Rance, silver
Underwater noise	No evidence of effect
Hydrodynamics	Positive: Reduced storm surge and coastal flooding risk within basin Neutral: Reduction in tidal currents in impoundment, flood and ebb currents are locally amplified upstream of sluice gates and downstream of the turbines respectively Negative: Reduced tidal range, reduced water exchange with the sea, artificial tidal regime, tidal phase shift, extended periods of slack water, fresh water discharge zone pushed upstream. Higher mean water level, decreased drainage ability and local flooding
Sediment changes or erosion	Positive: Improvement in sedimentary organic matter characteristics at Lake Sihwa—remediation from anoxic conditions Neutral: Redistribution of sediments linked to altered drainage and turbine currents and the prolonged durations of slack water Negative: Erosion of shoreline due to higher mean water level at Annapolis Royal. Displacement of sandbanks which were previously awash at low tide, erosion of riverbeds and an increase in sedimentation rates in upper estuary at la Rance. At Lake Sihwa, the total residual sediment flux remains negative (into the lake) and attributed to the mean advection processes associated with the discharge
Water quality	Positive: Destratification, reduced turbidity, and water circulation in basin improved through two-way operation at la Rance. Substantial water quality improvement at Lake Sihwa due to increased seawater exchange rates Neutral: Water quality has remained consistent and there has been a horizontal and vertical biological distribution readjustment. The freshwater–saltwater interface is pushed further upstream during summer at la Rance
Habitat alteration	Positive: Increased community richness and stability of sediments in/on sandbanks and mudflats promoted by reduced tidal amplitude and storminess Neutral: Increased sediment deposition and redistribution of sandbanks and mudflats Negative: Higher low-water level submerges portion of intertidal zones. Some portion of substrates can become permanently submerged, losing this habitat
Species/community changes	Positive: Benthic biomass, diversity and density increased (reflecting the biological penetrability of the dam). Plant plankton production downstream of the barrage and invertebrate production on mudflats at la Rance is high. Increased fish species richness at la Rance compared to other local estuaries and bays, and the basin is now designated a wetland of international importance with respect to waterbird and overwintering bird numbers Neutral: Alteration in fish community composition and distribution at la Rance, however, community structure has remained relatively stable in the long term. Novel, stable benthic community at Kislaya Guba, taking 16 years of consistent operation to establish, and corresponding to reduced water exchange with sea

Figure 6 - Summary of the ecological effects for tidal range for which evidence was found in this review.

In this work few of the widespread concerns regarding the environmental impacts of tidal range projects are substantiated by evidence or in long- term monitoring of existing projects. There is evidence of alterations in hydrodynamics and sediment flux at tidal range power plants, though many apprehensions either remain unsubstantiated or result in neutral effects on marine ecosystems. Several positive ecological effects are identified such as greater productivity and species diversity within tidal range basins. Maintaining a tidal regime as close as possible to its prior state appears key to minimising adverse ecological effects and has been a major learning point for tidal range.

Once again and as with the findings for tidal stream, this work provides foundations for environmental impact assessments of future tidal range projects and may enable more informed choices and facilitate a priori mitigation planning.

Co-benefits of tidal range energy beyond electricity sales

In addition to electricity sales, tidal range projects can offer many co-benefits. The reliability and predictability of tidal energy can attract a price premium as we have seen in the case of tidal stream, and although not modelled in the scope of this work, we would expect tidal range to provide similar power system integration benefits as tidal stream, and their exact magnitude would need to be evaluated. Figure 6 also highlights several additional benefits of tidal range namely.

- Reduced storm surge and coastal flooding risk within basin which can offer.
  - Lower mitigation costs
  - Reduced insurance payouts
  - Reduced repair and recovery costs

- Provision of revenue attracting ecosystem services and conservation benefits through.
  - Improvement in sedimentary organic matter characteristics at Lake Sihwa, via remediation from anoxic conditions
  - Destratification, reduced turbidity, and water circulation in basin improved through two- way operation at La Rance. Substantial water quality improvement at Lake Sihwa due to increased seawater exchange rates.
  - Increased community richness and stability of sediments in/on sandbanks and mudflats promoted by reduced tidal amplitude and storminess
  - Benthic biomass, diversity and density increased (reflecting the biological penetrability of the dam).
  - Plant plankton production downstream of the barrage and invertebrate production on mudflats at la Rance is high. Increased fish species richness at La Rance compared to other local estuaries and bays, and the basin is now designated a wetland of international importance with respect to waterbird and overwintering bird numbers

This work outlines some of the key co-benefits that may be provided by tidal barrages, highlighting their potential to play a key role in the renewable energy transition. Beyond energy generation, tidal barrages can offer protection to vulnerable coastal areas, which are increasingly threatened by climate change. Rising sea levels (RSL) and more frequent, intense storm surges are expected to lead to greater flooding and inundation of key coastal zones. These areas are not only home to valuable natural ecosystems but also support high human population densities and critical infrastructure. Assessment of the dual role of tidal barrages by examining their potential to provide both renewable energy generation and coastal protection in an example of an Integrated Nature-Climate Action (INCA). This was done through a spatial analysis in ArcGIS Pro, in which four primary maps are visualized and layered—tidal range, marine and coastal conservation areas, population density, and sea-level rise/flood risk—to identify regions in the UK with the greatest potential for tidal barrage projects to deliver broadly the range of these associated co-benefits. Initially the current predictions of the effects on the UK coast of climate change are outlined, then the principal barriers to progress in TPP development, as well as some of the potential benefits that they may deliver to coastal protection are addressed. Using the UK as a case study, our mapping uses superimposition to highlight areas which maximise the co-benefit potential of TPP development. Figure 7 shows the superimposed areas along with the 5 potential tidal range barrage projects that are co-located within these regions and where positive co-benefits could be realised. These tidal range projects could supply 10% of the UK's electricity needs.

Future policy and planning have then been considered, emphasising the need for systems thinking and integrated solutions that address both climate change adaptation and renewable energy goals. This study highlights the potential of tidal range barrages to be a long-term solution for coastal resilience and sustainable energy generation.

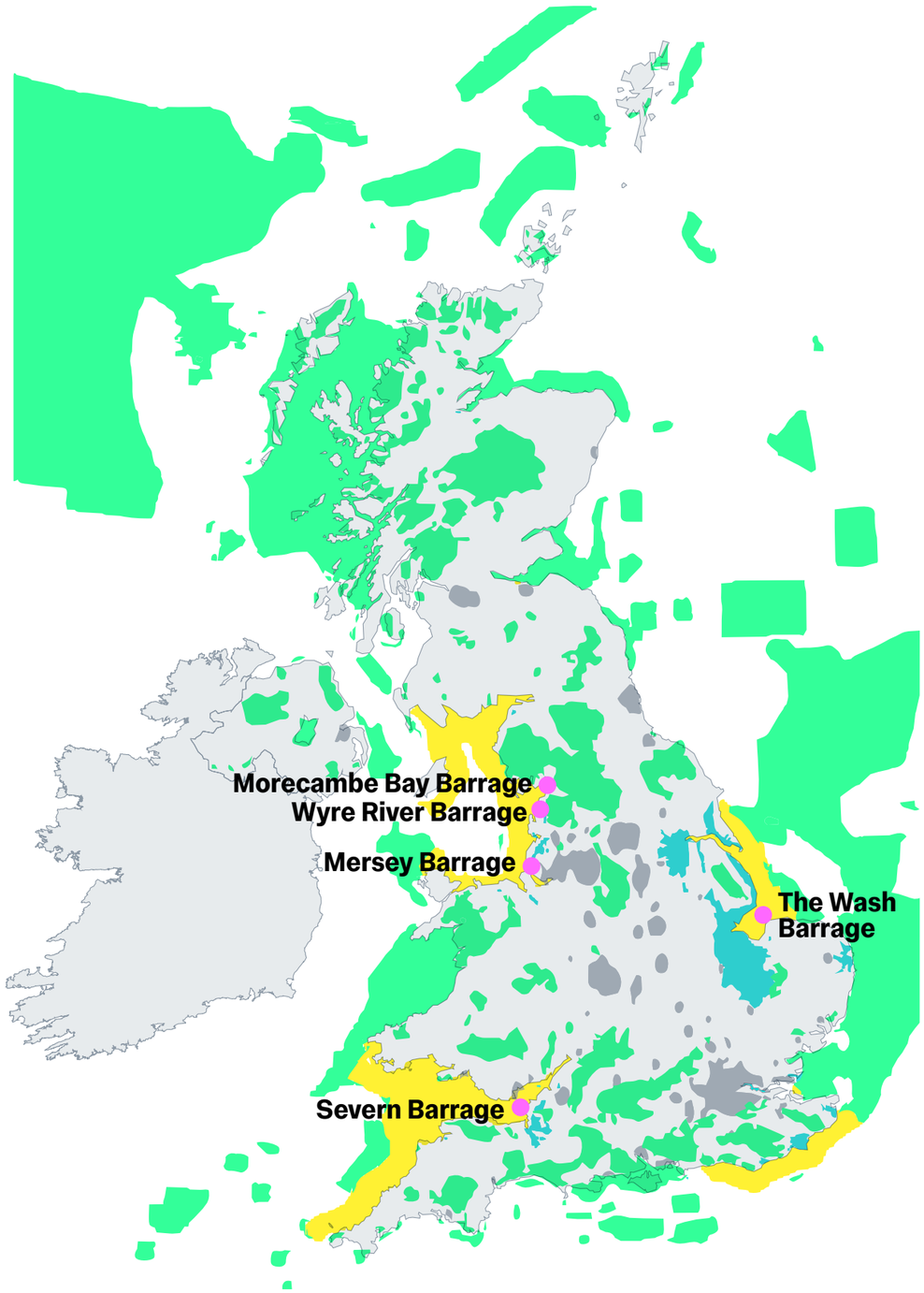


Figure 7 - Combined UK map of the factors considered in this work.

Recommendations

This work suggests the following priority actions for the tidal energy sector if the UK is to develop its low cost, tidal energy electricity generation and exploit this expertise to grow a world leading sector that can export its technology and know-how across the globe.

For Tidal Stream:

1) Determine pathways to access greater learning curve rates than solar and wind have historically had so that reduced Tidal stream levelized cost of electricity LCOE's can be attained at greater speed.

2) Factor in and find a mechanism to access the system integration cost (SIC) revenue premiums of £11-18/MWh that tidal stream can attract in any project business case.

3) Integrate learnings from past environmental studies to improve and enhance future project designs.

For Tidal Range:

1) Develop a mechanism to allow tidal range barrage projects to receive a financial return from long life and non-energy benefits such as climate induced rising level flood protection, storm induced flood protection, reduced coastal erosion mitigation costs, improved marshland conservation and ecosystem services provision.

2) Determine the SIC revenue premiums that tidal range can attract in any project business case and design a mechanism to access them to improve any business case.

3) Continue to research pathways to lower LCOE costs.

4) Integrate learnings from past environmental studies to improve and enhance future project designs.

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