Seizing sustainable growth opportunities from tidal stream energy in the UK

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Policy report

June 2023

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Foreword by Nicholas Stern

This is the decade for managing the immense risks of climate change, and delivery on net zero. That means rapidly increasing the share of renewable sources in our energy mix alongside a step-change in energy and resource efficiency. Energy transitions will look different in different parts of the world and will be most sustainable if countries leverage the unique opportunities offered by their local geographies to cut emissions as quickly as possible. As an island nation, the UK has a uniquely rich marine energy resource. Using this resource is an opportunity the UK cannot afford to miss as it works to fulfil its own target of net zero as well as its international commitments under the Paris Agreement.

This report adds to a growing evidence base concluding that tidal stream energy presents a clear sustainable growth opportunity for the UK due to the net zero, energy security and regional growth benefits it offers. Given its predictability, tidal stream energy offers important complementarities with other renewable sources of generation and in turn, the potential to improve the overall resilience of the energy system. The report also showcases the UK's innovative specialisms in tidal stream technologies, pointing out an opportunity for the UK to export its expertise in the future to many other countries around the world that have the potential to deploy tidal stream energy – if it acts quickly to establish a strong domestic sector.

The UK has significant strengths in the innovation of cutting-edge clean technologies like tidal stream, and also in creating policy and regulatory mechanisms to drive net zero. The UK's Contracts for Difference mechanism has been remarkably successful at bringing down the cost of generation from offshore wind. But the country has largely missed supply chain opportunities along the way, despite rising to become a leader in deploying offshore wind. Tidal stream energy is a nascent sector in which the UK currently holds global leadership. There is an opportunity to link domestic deployment ambitions with support for a strong domestic supply chain right from the start, in contrast to the experience with wind power. This kind of approach also has the potential to generate cost reductions for tidal stream energy through learning by doing and economies of scale, in the way that has already been seen in the costs of generation from wind and solar. Identifying and building domestic capacity in its existing areas of strength such as tidal stream should be a strategic priority for the UK in light of an accelerating global race to capture economic benefits from net zero.

As with any new technology, making sure that the development of tidal stream energy contributes to a sustainable and inclusive growth model will require investments not just in physical infrastructure but also in related innovation, skills and natural capital. These investments can be mutually reinforcing and contribute to reducing economic disparities within and across UK regions, as this report demonstrates. Tidal stream energy is especially well-suited to support a just transition to net zero with its advantages for coastal communities facing declines in their traditional industries.

In its *Energy Security Strategy* of 2022, the UK Government committed to exploring renewable opportunities, including tidal, afforded by the country's geography and geology. Realising these opportunities requires a clear and consistent policy programme that provides the private sector with the confidence and certainty to invest in the future of the tidal stream energy sector. In this way, the UK can grow the sector into an important area of global leadership which can help it move back towards the vanguard position on climate that it demonstrated at COP26.

Nicholas Stern

IG Patel Professor of Economics and Government, and Chair, Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science

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List of abbreviations

AR4	Fourth allocation round of the Contracts for Difference mechanism
AR5	Fifth allocation round of the Contracts for Difference mechanism
BEIS	Department for Business, Energy & Industrial Strategy [replaced in 2023 by the Department for Business and Trade (DBT), Department for Energy Security and Net Zero (DESNZ) and Department for Science, Innovation and Technology (DSIT)]
CCUS	Carbon capture, usage and storage
CfD	Contracts for Difference
CO_2	Carbon dioxide
CPC	Cooperative Patent Classification
DESNZ	Department for Energy Security & Net Zero
EINA	Energy Innovation Needs Assessment
EPO	European Patent Office
EMEC	European Marine Energy Centre
GVA	Gross value added
GW	Gigawatt
IEA	International Energy Agency
IRA	Inflation Reduction Act
IStraX	Industrial strategy index
LCOE	Levelised cost of energy
MEC	Marine Energy Council
MEW	Marine Energy Wales
MW	Megawatt
MWh	Megawatt hour
NUTS2	Nomenclature of territorial units for statistics at the level of basic regions for the application of regional policies
OECD	Organisation for Economic Co-operation and Development
OES	Ocean Energy Systems (short for the Technology Collaboration Programme on Ocean Energy Systems operating under the International Energy Agency)
ORE	Ocean renewable energy
PATSTAT	Worldwide Statistical Patent Database maintained by the European Patent Office
PCI	Product complexity index
P&IG	Policy and Innovation Research Group (within the School of Engineering at the University of Edinburgh)
R&D	Research and development
RCA	Revealed comparative advantage
RTA	Revealed technological advantage

Summary

Key messages

- **Tidal stream devices typically use underwater turbines to extract energy from moving water driven by tidal currents.** The UK has around 10 MW of tidal stream generation capacity installed, which represents over half of the world's currently operational capacity.
- **As a sizeable domestic renewable resource with high predictability, tidal stream energy has the potential to contribute to sustainable economic growth in the UK,** enhancing net zero efforts, improving energy security and generating jobs across the country.
- **The UK is a specialised innovator of tidal stream energy technologies, ranking fifth in the world on a measure of specialisation based on patenting activity.** The UK is more specialised in tidal stream energy than in other clean technologies, including offshore wind, nuclear, and carbon capture, usage and storage.
- **Investments in tidal stream energy innovation yield higher estimated economic returns for the UK relative to other clean technology areas.** Moreover, returns to investments made in innovation-intensive regions have high spillovers to the rest of the country, so that the economic benefits reach other UK regions too. In this way, investments in tidal stream energy can contribute to regionally-balanced growth.
- **The UK could capture export opportunities from high-value products relevant for tidal stream energy such as turbines, in which it is already specialised.** But with international competition in these markets set to rise, the UK's ability to secure such opportunities while creating new ones, including in related services, will depend on timely investments in the domestic supply chain.
- **Increased support for innovation could keep the UK at the frontier of technological development for tidal stream energy,** giving it the ability to scale up a low-carbon energy source cost-effectively and as quickly as possible in its own waters and its best chance to capture export opportunities when the global market picks up.
- **Scotland is well-placed to lead the development of tidal stream energy,** having an ample marine resource, world-leading research facilities, strong innovation activity in related technologies, and transferable capabilities from its established offshore wind and oil and gas sectors. Expertise developed in Scotland can support the sector's growth in the rest of the UK.

Recommendations for policymakers

- **An explicit statement of government ambition in tidal stream energy would help to drive private sector investment into the domestic supply chain and the delivery of the technology at scale in UK waters.** This stated ambition could be in the form of a domestic deployment target in gigawatt terms, as already advocated by industry.
- **The Contracts for Difference (CfD) scheme can continue to be utilised to scale up relatively established tidal stream technologies in the UK.** A continued ringfencing approach for tidal stream energy, with greater clarity over budgeting given multiple years in advance for each successive allocation round, can accelerate deployment and catalyse drivers of cost reduction for the technology, as previously seen in offshore wind.

- **Government can maximise sustainable growth opportunities from tidal stream energy by coordinating policy across deployment and supply chain development**. In particular, proactive coordination across the Department for Energy Security and Net Zero, the Department for Business and Trade and the Department for Science, Innovation and Technology is needed on this agenda, which could be complemented by introducing non-price factors in the CfD assessment criteria in a way that rewards supply chain development – although this cannot substitute for price-based support.
- **Government should consult with industry to explore which mechanisms can most effectively carry early-stage tidal stream concepts to commercialisation,** building on the UK's innovative strengths in tidal stream technology to create economic benefits.
- **A holistic strategy for the offshore economy that includes tidal stream alongside CCUS and offshore wind is likely to yield greater economic benefits than pursuing any single area alone**. The UK demonstrates complementary specialisms for these three technologies at both a national and regional level.

The current state of tidal stream energy around the world and in the UK

The global development of tidal stream energy to date has been limited by high technology costs, poor access to government subsidies, uncertainty over the technology's environmental impacts and too few examples to build a track record of technology performance over sustained periods. As a result, the sector remains very much in its infancy.

The 10 megawatts (MW) of tidal stream capacity installed in the UK represents more than half of the entire operational capacity of the technology in the world as of 2023, making the UK currently the global leader in tidal stream energy development. The country has both the greatest tidal stream generation capacity (both installed and under development) and the largest quantity of tidal stream technology developers. Countries including Canada, China, France, Japan and the US are also increasingly considering tidal stream as a potentially important supply of domestic low-carbon energy – some with substantial amount of capacity under development.

How does tidal stream energy work?

Tidal stream energy generates renewable energy by harnessing the power of the tides: periodic changes in sea levels due to gravitational interactions between the sun, Earth and moon. It works by capturing kinetic energy from fast-flowing water driven by tidal currents.

In the UK, tidal stream technologies have historically struggled to secure revenue support as they have had to compete against more established technologies under the Contracts for Difference (CfD) scheme. This limited the deployment of tidal stream energy to small-scale demonstration projects for some years. Interest in the sector grew following the Government's adoption of the net zero target in 2019, complementing perceptions of the technology that had already started improving due to some high-profile technology demonstrations and the sector itself becoming better coordinated. Tidal stream technology has also been looked on more favourably recently for its potential energy security benefits in light of rising global energy prices. In 2022, a ringfence for tidal stream energy (of £20 million) was set for the first time in the fourth allocation round of the CfD (AR4), allocating a minimum budget specifically for tidal stream projects within the overall budget of the auction 'pot' in which they compete against other technologies like wave energy and floating offshore wind. The ringfence has resulted in four tidal stream projects with 40.8 MW combined capacity securing revenue support in AR4. An additional ringfence (of £10 million) has been set for Allocation Round 5, the outcome of which will be announced in summer 2023.

The Government is also exploring whether to revise the assessment criteria of the CfD to incorporate non-price factors such as capacity-building, innovation and contribution to energy system flexibility. As tidal stream projects tend to have strong credentials in these terms, proposed changes could make future projects bidding in the CfD more competitive against other technologies. However, with the price differential between tidal stream and other technologies likely to remain high for the foreseeable future, it is unlikely that the inclusion of non-price factors in the assessment criteria would substantially change the ability of tidal stream projects to secure revenue support outside the ringfence for now.

Prospects for the global tidal stream energy market

The size of the future global market for tidal stream energy will be dictated to a large extent by the natural resource that can be practicably exploited. Estimates of the global tidal stream resource vary widely, but there is reasonable agreement that it is equivalent to upwards of 100 GW of generating capacity. However, there is also agreement that the capacity that can realistically be deployed in the short term is only a small fraction of this amount: only a few gigawatts by 2030. The global market for products and services relating to tidal stream energy will likely remain small over this time accordingly, but is expected to pick up in the longer term, potentially representing over £10 billion annually by 2050 (according to an estimate that assumes 50 GW of global deployment by that year). The extent of the global market that the UK will be able to capture will depend on the development of the necessary supply chains domestically and internationally over the coming years.

The business opportunity for the UK from tidal stream energy is expected to be smaller, both in the near and long term, than the opportunity from some other clean technologies relevant to the UK's net zero strategy, such as carbon capture, usage and storage (CCUS), nuclear and offshore wind. Therefore, channelling investment into and unlocking the business opportunity from tidal stream energy is likely to require explicit direction and support from policy.

The potential for tidal stream energy to support sustainable growth in the UK

Pursuing tidal stream energy has the potential to contribute to four strategic objectives in support of sustainable growth in the UK:

1. **Achieving a net zero energy system**

Domestic deployment of tidal stream energy can directly contribute to efforts to reduce emissions from the UK's energy system, in turn helping to unlock growth pathways consistent with net zero for a range of sectors. Tidal stream energy is low-carbon and available in abundant quantities in the UK, potentially able to meet around 11% of the country's current annual electricity demand. Tidal stream energy can also be part of a cost-effective pathway to decarbonise the UK energy system if industry achieves its stated cost-reduction ambitions through economies of scale, economies of volume from larger farms, and accelerated learning: the same drivers that have already led to dramatic cost reductions in renewable technologies such as offshore wind.

While tidal stream generation is currently more expensive than mature renewable energy sources, substantial cost reductions – estimated at over 40% – have already been achieved despite little or no revenue support being accessed to date. Continued investments in tidal stream innovation could further improve technological performance and unlock cost-effective pathways to scale up this potentially important source of low-carbon energy in the UK. As our analysis shows, the UK has greater innovative specialism in tidal stream energy than in any other clean technology area assessed – including offshore wind, CCUS and nuclear.

2. **Ensuring energy security**

As a sizeable domestic renewable resource, tidal stream energy can contribute to reducing the UK's reliance on energy imports and exposure to volatile prices in global energy markets. This would provide benefits in terms of both increased energy security and progress towards the net zero target. Modelling by the Offshore Renewable Energy (ORE) Catapult shows that expanding the capacity of tidal stream energy on the grid can reduce the amount of dispatchable gas needed to balance the system. Tidal stream energy also has some unique properties that make it well-suited to complement and enable the more efficient use of other variable renewables on the grid, in turn improving overall system resilience and reducing balancing costs: namely, tidal stream as a natural resource is not affected by the same sources of variation that affect the more established renewables on the grid (mainly wind and solar) and, unlike wind and solar, it is highly predictable far into the future. Indeed, analysis by the Policy and Innovation Group has found that a more diverse power generation mix, including tidal stream energy (and also wave energy, another marine source), would be consistently more available and better able to meet demand than a generation mix that does not include marine sources. Tidal stream energy also has the potential to support energy security in the UK from a supply chain perspective if the currently high levels of domestic content can be maintained as the market expands. Many tidal stream energy projects in the UK to date have been delivered with over 80% UK-based content.

3. Capturing export opportunities

Tidal stream energy was highlighted in the UK's 2023 *Independent Review of Net Zero* as an area in which the country is a first mover and could create distinct advantages in the future. The UK is already exporting its tidal stream technologies abroad but the export opportunities when these technologies reach the stage of mass deployment globally are highly uncertain and tied to the strength of the UK's wider industrial base. There is growing concern that the UK is losing industrial competitiveness and becoming a less attractive place to invest in the global race to decarbonise in the face of ambitious policy packages introduced elsewhere to support such investments, including the US Inflation Reduction Act and the EU's Green Deal Industrial Plan in particular.

The majority of countries that have already deployed or are looking to deploy tidal stream energy domestically (e.g. China, Japan, the US) are large exporters of the relevant products themselves. Exporters may struggle to break into the domestic markets of these countries unless they demonstrate a certain level of specialism in exporting such products. Furthermore, over half of the 10 countries most specialised in exports of products relevant for tidal stream energy do not have any notable domestic activity explicitly relating to tidal stream energy, or even a substantial natural tidal resource to begin with (e.g. Denmark, Slovenia, Germany). This finding likely reflects these countries' existing capabilities in other areas such as offshore wind, whose supply chains have strong overlaps with that of tidal stream energy. Therefore, if tidal stream grew to become a meaningful export market, the UK would likely face competition not only from countries looking to deploy the technology in their own waters but also from countries that have specialisms in a wider range of similar or relevant technologies, and who may decide to transfer such capabilities to build dedicated manufacturing capacity for tidal stream products.

The UK has export specialism in several complex products relevant for tidal stream energy, including hydraulic turbines which are central to the technological foundation of tidal stream plants. There are also many other complex products relating to the turbine structure and powertrain in which the UK does not currently have export specialism but could develop specialism in the future if necessary investments in the supply chain are made, given the UK's proximate productive capabilities for these products. Furthermore, while the UK's revealed comparative advantage in products relevant for tidal stream energy at the aggregate level is currently lower than its comparative advantage for those relevant for nuclear and CCUS, some of the products for tidal stream energy are higher in complexity. A targeted approach to develop supply chain capacity and capture export opportunities specifically from such complex, high-value products could yield important growth opportunities for the UK.

The UK is also among the most specialised innovators in tidal stream energy, ranking fifth on revealed technological advantage globally (calculated based on countries' total patenting activity between 1980–2018). From around 2000 until 2011, the UK's annual patenting in tidal stream increased faster than other innovative economies (except for the US). Despite signs that the UK's patenting in tidal stream energy has been in decline in recent years, it is still one of the few early movers in this area, which remains a fairly small area of patenting globally.

Tidal stream energy has the highest estimated average returns to public investments in innovation among all the technology areas analysed (ranging from AI to clean cars to hydrogen). If the UK positions itself at the forefront of tidal stream technology development through further investments in innovation, it can maximise opportunities to export some specific high-value products alongside its specialist knowledge and services abroad when the global market picks up.

4. Regionally-balanced growth

Tidal stream resource has a good geographical spread across the UK. This carries the potential to benefit coastal communities, many of which have long been a focus for regional development policies. If underpinned by investments in developing local supply chains, the deployment of tidal stream energy in the UK can contribute to regionally balanced growth in support of the Government's levelling up agenda. There are also transition opportunities for oil and gas workers who could find employment in the tidal stream energy sector given the similarities in required skills. Arguably, tidal stream energy already appears more prominently in economic growth policies at a regional level under the devolved administrations than it does at the national level. For example, the Scottish Government's draft *Energy and Just Transition Plan* published in January 2023 includes a specific vision for marine energy.

Scotland demonstrates leadership in tidal stream innovation, with North Eastern Scotland and the Highlands and Islands holding the highest patenting intensities in tidal stream energy in the UK. The Highlands and Islands consist of Orkney which is home to Pentland Firth and the European Marine Energy Centre (EMEC), where world-leading research and demonstration in tidal stream is conducted. Other regions with high patenting intensity include Northern Ireland, Cumbria, Devon, and Cornwall and the Isles of Scilly. These are among the relatively less productive regions of the UK overall, which suggests capitalising on their innovative specialisms in this emerging technology could generate local benefits and contribute to regionally-balanced growth.

Returns to investments in tidal stream innovation made in regions outside of the so-called 'golden triangle' (consisting of the historically innovation-intensive cities of London, Cambridge and Oxford) are particularly high for these regions and do not tend to spill outside. In contrast, investments in tidal stream innovation made in the golden triangle appear to generate very high spillovers for other regions, with potential levelling-up benefits. Moreover, locations that patent intensively in tidal stream energy tend to also patent intensively in offshore wind and oil and gas. Patenting in the latter was also found to correlate with patenting in CCUS at the regional level.

Overall, investments in tidal stream energy innovation have the potential to support regionally-balanced growth across the UK through direct returns to public investments, regional spillovers and synergies with other offshore sectors in coastal regions. A joined-up strategy for tidal stream, offshore wind and CCUS (which involves the offshore storage of carbon dioxide) could yield greater economic benefits than pursuing any one area alone.

Conclusion

Tidal stream energy is well-suited to complement wider efforts to achieve net zero and enhance energy security in the UK while supporting regionally-balanced growth across the country. The sector can also open up export opportunities for the UK when the global market picks up.

The UK should pursue tidal stream energy underpinned by a strong domestic supply chain to maximise sustainable growth opportunities from this emerging technology. This would require rapidly developing the UK supply chain's capacity to deliver domestic projects cost-effectively and at scale, while continuing to invest in technological innovations to drive further cost reductions. Retaining a scalable domestic supply chain would be a low-regrets approach that gives the UK the ability to act according to how the global market pans out, quickly scaling up in areas where it is likely to be internationally competitive.

In the context of a domestic market constrained by the size of the natural resource that can be practicably exploited, an export opportunity set to remain limited in the short term, and competitive pressures from other countries on the rise, driving investment in the UK's supply chain for tidal stream energy requires explicit support from policymakers.

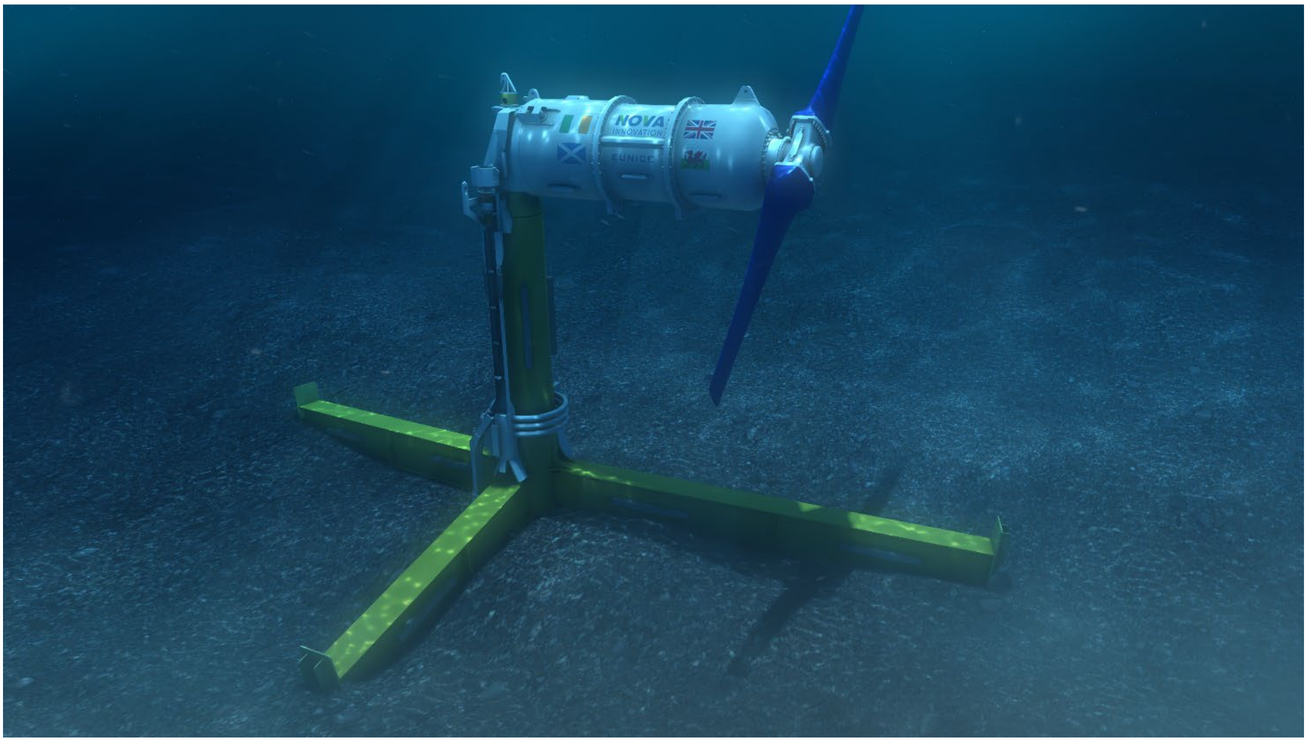
1. Introduction

This report assesses the potential contribution of tidal stream energy to sustainable growth in the UK, drawing on a review of the existing literature and new analysis of trade and patents data. This assessment is used to determine whether tidal stream energy constitutes a strategic priority for the UK, or whether the policy efforts necessary to develop the sector might be better spent elsewhere.

What is tidal stream energy?

Tidal stream energy (sometimes referred to as tidal current energy) is a way of harnessing renewable energy from the tides: periodic changes in sea levels due to gravitational interactions between the sun, Earth and moon. It works by capturing kinetic energy from fast-flowing water driven by tidal currents. This is most effective in areas where tidal currents are intensified by topographical features including headlands, inlets and straits, or other places where the shape of the seabed forces water through narrow channels (EMEC, n.d.).

Figure 1.1. Visualisation of a tidal stream turbine



Source: *Nova Innovation*

Tidal stream devices come in various designs but the industry has generally converged around concepts featuring turbines on a horizontal axis (Ocean Renewable Energy [ORE] Catapult, 2022). These are similar to wind turbines but they extract energy from moving water rather than air, and tend to be smaller in size and capacity (around 1–2 MW as opposed to 8–12 MW for an offshore wind turbine) (see visualisation in Figure 1.1). Similar to wind farms, multiple tidal stream turbines can be deployed in the same location to form arrays. These can either be fixed on the seabed or have floating foundations.

The UK context

The UK is currently the global leader in tidal stream energy development, having deployed the world's first commercial-scale tidal turbine in 2008 and holding over half the world's currently operational tidal stream capacity. With an ample tidal energy resource, the UK could scale up the technology, grow its emerging domestic supply chain and enjoy first-mover advantage in export markets. However, the UK is not alone in its ambition to develop tidal stream energy: countries including Canada, France, China, Japan and the US are also considering it as a potentially important source of low-carbon energy. The UK could quickly fall behind if other countries act faster to develop their own industries for tidal stream technology.

Tidal stream energy and sustainable growth

Background

This report builds on an ongoing series on sustainable growth opportunities for the UK jointly produced by the Grantham Research Institute on Climate Change and the Environment and the Centre for Economic Performance, more recently also joined by the Programme on Innovation and Diffusion (POID) and the Productive and Inclusive Net Zero (PRINZ) programme. The analysis mirrors the sectoral 'deep dive' approach of two previous reports in the series, focusing on the possibilities for sustainable growth in the sectors of carbon capture, usage and storage (CCUS) (Serin et al., 2021) and zero-emissions passenger vehicles (Unsworth et al., 2020). The choice of tidal stream energy as the current sector of focus is also informed by previous reports in the series, which have found that tidal stream energy yields favourable results on several measures such as innovative specialism, returns to public investments in innovation and regional spillovers, which are tied to sustainable growth potential in the UK (see Rydge et al., 2018; Martin and Verhoeven, 2022; Curran et al., 2022).

A note on scope: exclusion of tidal range technology from the analysis

Tidal *range* technology is another way of harnessing energy from the tide. While tidal stream energy converts the kinetic energy from tidal currents into useable energy, tidal range concepts harvest the potential energy created by the difference in water levels between high and low tide (International Renewable Energy Agency, 2014). This requires a basin that can hold large volumes of water, which can be created by building a barrage equipped with turbines and gates across an estuary or bay, or by forming a tidal lagoon. Energy is generated by releasing the water to flow through the turbines once an optimal difference in water levels is reached between the basin and the sea outside. The operating principle of tidal range resembles that of traditional hydropower plants.

Despite harnessing energy from the same natural resource, tidal stream and tidal range are fundamentally different technologies. Tidal stream energy is modular in nature and has the potential to benefit from cost reductions through economies of scale and volume as well as learning from successive projects. Tidal range, on the other hand, is a civil engineering project associated with long timelines and high upfront capital costs (which can be prohibitive in the absence of innovative financing options). There are also only a limited number of suitable sites for tidal range projects in the UK, further limiting the technology's potential to benefit from the levers of cost reduction that are available to tidal stream energy. Therefore, this report focuses exclusively on tidal stream energy, which demonstrates greater and comparatively near-future innovation potential and economic opportunities for the UK than tidal range.

Structure of the report

Section 2 reviews the current status and future outlook of the global and domestic markets for tidal stream energy to shed light on the potential growth opportunity the sector represents for the UK.

Section 3 reviews the existing literature on the extent to which tidal stream energy can contribute to meeting four objectives that are of strategic importance to enabling sustainable growth in the UK:

1. Achieving a net zero energy system
2. Ensuring energy security
3. Capturing export opportunities
4. Securing regionally-balanced growth.

Section 4 then presents new analysis on the UK's relative performance in the exports of products relevant for tidal stream energy using data on global trade.

Section 5 analyses the UK's relative performance in the innovation of related technologies, using patents data.

Section 6 provides conclusions and policy recommendations.

2. Outlook for tidal stream energy: globally and in the UK

Current status of tidal stream energy around the world

Development of tidal stream energy is in its infancy globally. This is primarily due to technology costs that are currently high, limited access to subsidy support, uncertainty over environmental impacts, and limited examples demonstrating the technology can operate for sustained periods of time without the need for maintenance intervention (Coles et al., 2021). Although they may be limited in number, several demonstrations have achieved significant milestones in sustained operation, including the MeyGen project off the north coast of Scotland, which has delivered over 51 gigawatt hours (GWh) of power since coming online in 2018 and Nova Innovation's Shetland Tidal Array, which has been generating power continuously since 2016 (SAE Renewables, 2023; Nova Innovation, 2023).

Only a few countries are active in the tidal stream energy landscape, as shown in Table 2.1. The UK is at the forefront of tidal stream development in terms of its active installed capacity, capacity under development, and the number of tidal stream technology developers based in the country. The UK is only rivalled by France and Canada in terms of tidal stream capacity under development, and by the US in terms of number of tidal stream technology developers. However, even the UK's leading position represents a relatively small-scale sectoral development. The 10 megawatts (MW) of tidal stream capacity currently installed in the UK is less than 0.1% of the practical tidal stream resource that the UK and the Channel Islands have been estimated to represent (11.5 gigawatts [GW]) (Coles et al., 2021).

Tidal stream is expected to remain a relatively small sector even when more of this resource is realised, for example when compared with offshore wind, which already represents almost 14 GW of the UK's generation capacity and continues to expand (Department for Energy Security and Net Zero [DESNZ], 2023c). Furthermore, the 28 developers of tidal stream technologies identified in the UK constitute a small proportion of the over 7,000 total firms operating in low-carbon energy generation in the UK (Curran et al., 2022).

Table 2.1. Active installed capacity, capacity under development, number of tidal stream technology developers and national policies relevant for tidal stream energy by country[1]

Country	Active installed capacity (MW) (as of 2023)[2]	Capacity under development (MW) (as of 2023)[3]	Number of tidal stream developers (as of 2020)[4]	National policies relevant for tidal stream energy[5]
UK	10.1	40.8	28	**Fifth allocation round of the CfD scheme:** tidal stream was placed in the auction pot reserved for less-established renewable energy technologies and allocated a ringfenced minimum budget (for a second time since its inclusion in the fourth allocation round), making tidal stream projects more likely to place successful bids.
China	1.7	0.45	-	**Release of 14th Five-Year Plan for Renewable Energy Development:** includes plans for the continued implementation of tidal stream and wave energy demonstration projects and exploration of the application of ocean energy systems on islands.

Netherlands*	1.29	0.15	4	**Stimulation of Sustainable Energy Production and Climate Transition (SDE++) scheme:** offers subsidies for the generation of renewable energy. In 2022, subsidies for ocean energy options ranged from 0.0547 to 0.0852 €/kWh.
France*	1	31	7	**Innovative experimentation contract for renewable energies:** supporting innovation in renewable energies, especially for ocean energies and floating offshore wind, and including simplification and accelerated attribution of feed-in tariffs for small projects. **'Investment for the Future' programme:** provides market incentives through grants and loans, accounting for differences in the technological maturity of projects.
Canada	0.7	31.38	5	**Offshore Renewable Energy Regulations (ORER):** new legislation that enables the Canada Energy Regulator to review and authorise activities related to renewable energy in Canada's offshore areas. **Investment tax credit for clean technologies:** a refundable 30% investment tax credit will be made available for clean technologies including tidal stream.
Japan	0.5	-	2	**Fourth Ocean Basic Plan (2022–2026):** reiterates that national efforts should be made to reap benefits from maritime resources including wave and tidal stream, with a particular focus on development in remote islands. The plan has been approved in April 2023 and builds on the third Ocean Basic Plan (2018–2022).
US	-	5.08	24	**Inflation Reduction Act of 2022:** expected to have a significant impact on the development and financing of clean energy projects in the US over the next decade. **Water Power Technologies Office's Marine Energy Program:** to fund research and development to improve the reliability and affordability of marine energy technologies while tackling challenges faced by US marine energy stakeholders.
Norway	-	-	7	-
Australia	-	-	5	**Australian Offshore Electricity Infrastructure Bill 2021:** provides a consistent and transparent regulatory regime for the construction, operation and decommissioning of offshore renewable energy projects and transmission infrastructure.
Germany*	-	-	4	-
Ireland*	-	-	3	**Offshore Renewable Energy Development Plan (OREDP):** highlights Ireland's focus on stimulating industry-led projects for ocean energy.
Spain*	-	-	3	**Roadmap for the Development of Offshore Wind and Energy in Spain:** sets the foundation for a new legal framework for the licensing of renewable marine energy plants.
Sweden*	-	-	2	**Swedish Energy Agency's national ocean energy programme (2018–2024):** with a total budget of €10.4m, resulting in 21 funded projects to date

				addressing environmental issues, improved eligibility and durability, cost reduction, testing in marine environments and improved operation and maintenance.
European Commission				**Horizon 2020 call for demonstration of sustainable tidal energy farms:** with €40 million EU funding. **Innovation Fund:** one of the world's largest funding programmes for the demonstration of innovative low-carbon technologies; calls were launched in 2022 to help with the demonstration of highly innovative first-of-a-kind projects. **REPowerEU Plan:** setting out a series of measures to rapidly reduce dependence on Russian fossil fuels and accelerate the green transition while increasing the resilience of the EU energy system. **Green Deal Industrial Plan:** designed to provide a more supportive environment for scaling up the EU's manufacturing capacity for net zero technologies and products required to meet Europe's climate targets, including measures to simplify and fast-track permitting processes to deploy such technologies.

Notes: *Countries marked with an asterisk are also covered by policies adopted by the European Commission as listed in the bottom row.*
[1] Only countries with more than 0.5 MW of tidal stream capacity already installed and/or those with more than one tidal stream developer identified are included.
[2] Based on Ocean Energy Systems Annual Report 2022 (Ocean Energy Systems [OES], 2023).
[3] Same as above.
[4] Based on EMEC (2020).
[5] A non-exhaustive collation of countries with national policies in place that may be relevant for tidal stream energy. Examples are drawn from the Ocean Energy Systems Annual Report 2022 (OES, 2023) only for countries included in this table (refer to footnote 1 for the inclusion criteria).

Future outlook of the global market for tidal stream energy

The size of the future global market for tidal stream energy will be dictated to a large extent by the natural resource that can be practicably exploited. However, estimates of the global tidal stream resource vary widely and are often presented without supporting evidence for how the estimate was calculated (Coles et al., forthcoming). Tidal stream resource estimates are also commonly combined with those of other marine energy technologies, such as wave or tidal range, without clarity over the contribution of each individual technology (ibid.).

Despite some divergence across different sources, there is reasonable agreement that the global tidal stream energy resource is equivalent to upwards of 100 GW of generating capacity (see e.g. Wani et al. [2020] and Atlantis Resources [2015]). Furthermore, the Ocean Energy Systems programme by the International Energy Agency has set out a vision to develop 300 GW of generating capacity from tidal stream and wave energy combined by 2050 globally (OES, 2017). These kinds of numbers are significant but are dwarfed by the total technically extractable power that has been estimated for offshore wind[1] at over 71,000 GW (Energy Sector Management Assistance Program, 2022).

Another point of agreement across different sources is that the tidal stream energy generation that will realistically be deployed in the short term is a small fraction of the total estimated resource. For example, a scenario produced by Ocean Energy Europe (2020) designed to represent

[1] Includes floating offshore wind.

a 'high growth' case for ocean energy sees only about 2.4 GW of tidal stream capacity deployed globally by 2030. But, looking further ahead, they estimate that the global market for ocean energy (including both tidal stream and wave) will be worth €53 billion per year by 2050 (ibid.). In a UK-commissioned analysis, the global tradeable market specifically from tidal stream energy is estimated to be worth almost £13 billion annually by 2050, assuming 50 GW of capacity is deployed globally by that year (Vivid Economics, 2019e). The extent to which the UK would be able to capture a future market of this size would depend on the development of the UK's supply chain over the coming years. The next section includes a discussion of some studies that have attempted to quantify the business opportunity for the UK.

Despite ambiguity around the exact magnitude of the global resource and uncertainty on the size of the future market, there is sufficient confidence about the locations most likely to host substantial tidal energy deployment in the future. This discussion will therefore focus on these tidal energy 'hotspots', identified in Figure 2.1 below, rather than attempt to make quantitative judgements on how tidal stream markets in different countries will evolve.

Figure 2.1. Locations with the greatest potential for tidal energy around the world

Source: Based on Danish Hydraulic Institute (work commissioned for Atlantis) taken from Almeida (2013), with Faroe Islands and Chile added by authors upon expert consultation. Map created with mapchart.net.

On the one hand, there are several countries identified to have substantial tidal stream resources but that do not yet show signs of an emerging domestic sector – e.g. Brazil, Argentina and New Zealand (see Table 2.1). These countries represent untapped export markets for the UK and other countries developing supply chains for tidal stream energy. On the other hand, there are countries like Germany and Norway that do not themselves have a substantial natural resource needed to deploy tidal stream domestically but are still actively pursuing the development of the technology. This suggests that the competition for export markets awaiting the UK will not be limited to countries with a tidal stream sector of their own.

Apart from France, the other countries that are home to substantial tidal energy resources are located geographically far away from the UK. This is unlikely to entirely restrict the export opportunity, and the UK has already exported goods and services relating to tidal energy to countries such as Canada, China, Japan, Philippines, Singapore and the US (RenewableUK, 2018). Exports of services (e.g. design and engineering, project development) and of small, high-value and easily transportable goods (e.g. electrical components) are less likely to be affected by geographical distance (ORE Catapult, 2018). But there would still be important implications (especially on cost and workforce) to be tackled proactively if the UK were to establish itself as a competitive exporter of tidal stream technologies to other regions. Current dynamics suggest that the global market for tidal stream energy will be highly complex and multifaceted when it picks up.

Future outlook of the business opportunity for the UK from tidal stream energy

Several studies have attempted to quantify the potential growth opportunity for the UK from the tidal stream energy sector. We provide a summary of some key examples in Table A1 in the Appendix of this report. Among these, the Energy Innovation Needs Assessment (EINA) commissioned by the (then) Department for Business, Energy and Industrial Strategy, which has been influential in shaping the UK's policy approach to the sector to date, estimated that exports relating to tidal stream energy could contribute up to £35 million of gross value added (GVA) to the UK economy annually by 2030 and £540 million annually by 2050 (Vivid Economics, 2019e). In another study by the Supergen Offshore Renewable Energy (ORE) Hub and the Policy and Innovation Group (P&IG) (2021), exports relating to tidal stream energy are estimated to add between £2.5–12.7 billion of GVA to the UK economy on a cumulative basis by 2050.

The EINA study includes equivalent estimates for other clean energy sectors. We have chosen three of these – CCUS, nuclear and offshore wind – as useful comparators to put the export-related business opportunity from tidal stream into perspective. Our choice of these sectors is informed by the UK Government having prioritised CCUS and nuclear for public funding in its Spring Budget of 2023 (HM Treasury, 2023), and its longstanding support for offshore wind deployment through the CfD scheme. The annual GVA from export markets is estimated at £3.6 billion for CCUS, £1.3 billion for nuclear and £1 billion for offshore wind by 2030 (Vivid Economics, 2019d). By 2050, exports relating to the same three sectors are estimated to be able to add £4.3 billion, £700 million and £2.3 billion annually to the UK economy respectively (ibid.). Overall, the potential economic opportunity for the UK from exports of products and services relating to tidal stream energy can be significant, but it is set to remain much smaller – both in the near and the long term – than the equivalent opportunity from some other clean energy technologies that are important to the UK's net zero strategy.

The business opportunity for the UK from the domestic market for tidal stream energy is not sized in the EINA, but is estimated by the ORE Catapult to be £1.6 billion GVA on a *cumulative* basis by 2030 (subject to partial offsetting by revenue support) (ORE Catapult, 2018).[2] This compares with EINA estimates of *annual* GVA for the UK from CCUS, nuclear and offshore wind domestic markets at £310 million, £4.7 billion and £1.4 billion respectively by 2030 (Vivid Economics, 2019d). While the estimates from the two different sources are not directly comparable, it can be seen that the economic benefits expected from the domestic market for offshore wind in a single year by 2030 are similar to the economic benefits expected from tidal stream energy on a cumulative basis over many years to 2030. However, the ORE Catapult estimate of the economic opportunity from the domestic market for tidal stream energy assumes 100 MW of UK deployment per year by 2030 while the UK's practical resource is much larger, estimated to be over 11 GW, as previously discussed. The tidal stream energy market could therefore be greater when domestic deployment truly picks up – which would realistically happen after 2030. Supergen ORE Hub and P&IG (2021) estimate a cumulative GVA of £2.5–4.5 billion from 6 GW of tidal stream deployment in the UK by 2050, while another study suggests the UK might be able to extract over £20 billion of cumulative GVA from 2030 through to 2050 from its domestic market in an optimistic scenario in which it "gets everything right" (P&IG and Energy Systems Catapult, 2019).

Even though tidal stream energy is likely to yield a smaller overall business opportunity for the UK than some other clean energy technologies, its contribution to job creation might be higher at the project level. For example, based on data from the delivery of an actual tidal stream device, ORE

[2] Although this study breaks down what the economic benefits from just the domestic deployment of tidal stream might be for the UK, the underlying model assumes both domestic and global deployment, which impacts future cost assumptions.

Catapult finds that tidal stream projects create 46 full-time equivalent jobs per year (FTE/year), per MW generated (direct and indirect), which is higher than the estimated 15–25 FTE/year per MW for wind and solar in other studies (ORE Catapult, 2022). At a more local level, Regeneris Consulting and the Welsh Economy Research Unit (2013) estimated that the development and construction of facilities providing 1 GW of tidal stream energy in Wales could generate 17,150 FTE/year along with £611 million GVA for the region.

Evolution of tidal stream energy policy in the UK

Policy support for tidal stream energy in the UK has varied over time (ORE Catapult, 2022). Prior to 2016, several sites for tidal stream deployment were awarded revenue support via the Renewables Obligation (RO) scheme. In 2016, the RO was replaced by the Contracts for Difference (CfD), which has since been the UK's flagship mechanism for supporting low-carbon electricity generation. Tidal stream technologies have initially struggled to secure revenue support from the CfD as they were required to compete under an auction process against more established technologies like offshore wind (P&IG, 2023). This meant that tidal stream deployment was limited to single turbine demonstration projects in the several years that followed (ibid.).

In 2019, the UK legally committed to bringing its greenhouse gas emissions to net zero by 2050, creating an even stronger imperative than before for the country to achieve a low-carbon, diverse and resilient energy mix with a much greater role for renewables. This has contributed to more favourable perceptions of tidal stream energy in recent years, also helped by the successes of some high-profile technology demonstrations as well as the improved coordination of the sector itself (ORE Catapult, 2022). The latter has been enabled by initiatives such as Marine Energy Wales (MEW), the Scottish Marine Energy Industry Working Group (SMEIG) and the Marine Energy Council (MEC), which have acted as a unified voice for the industry in policy engagements (ibid.).

Interest in the tidal stream sector grew further in 2021 due to rising global energy prices and heightened concerns around energy security (ORE Catapult, 2022). In that same year, it was announced that tidal stream energy would for the first time receive a ringfenced budget of £20 million per year under the fourth allocation round (AR4) of the CfD scheme (DESNZ and BEIS, 2021). This was welcomed by industry as a turning point for the tidal stream energy sector in the UK as such subsidy support is thought to have the potential to kickstart a steep cost reduction curve for subsequent projects, such as was achieved in the offshore wind sector. Four projects with a combined capacity of 40.8 MW were awarded contracts in AR4 to come into operation by 2027, which is set to increase the UK's tidal stream capacity almost fivefold from its current level.

In parallel, several key policy documents from the UK Government – including the *Net Zero Strategy* of 2021 and the *British Energy Security Strategy* of 2022 – have acknowledged the untapped potential of tidal stream for both decarbonising and strengthening the UK's national energy mix, although the stated ambition has remained high-level and exploratory. At the start of 2023, the *Independent Review of Net Zero* highlighted tidal stream energy as an area in which the UK is a 'first mover' and, through further investments, could create distinct advantages to lead the global market in the future (Skidmore, 2023). More generally, the Review also called on the Government to "carry out competitiveness analysis for clean technologies setting out the UK's export and import strategies and where it intends to develop leadership" (ibid.). A few months later, it was confirmed that the ringfence for tidal stream energy will continue in the fifth allocation round (AR5) of the CfD scheme, but at a reduced sum of £10 million per year (DESNZ, 2023a). The reduction does not appear to be a decision made specifically for tidal stream energy, as the overall budget of AR5 is lower than that of AR4. Instead, it likely reflects the change in frequency of CfD allocation rounds from every two years to every year, with AR5 being the first allocation round to be run on an annual basis (BEIS, 2022).

In April 2023, the UK Government launched a call for evidence to explore how non-price factors could be introduced into the assessment criteria of the CfD auctions (DESNZ, 2023b). Non-price factors considered include: building capacity (including the necessary manufacturing and infrastructure facilities); innovation (e.g. investment in R&D and use of new technologies); investment in skills needed to strengthen the supply chain; and contribution to energy system flexibility and operability. Tidal stream projects are likely to perform favourably on these criteria given their specific qualities, which we discuss in detail in the following sections. If the considered changes to the CfD are implemented, they might give tidal stream energy projects a competitive edge over other technologies in the bidding, although this is unlikely to significantly impact projects' ability to secure revenue support outside the ringfence. The UK Government remains committed to ensuring value for money, adhering to subsidy control principles[3] and limiting costs for electricity consumers, all of which would reflect on how price and non-price factors are weighted in the assessment criteria (DESNZ, 2023b). In AR4, tidal stream projects cleared at £179 per megawatt hour (/MWh), which is over £90/MWh higher than the clearing price of the next most expensive technology (floating offshore wind) in the group of technologies competing in the same auction 'pot'. The price differential between tidal stream and other technologies currently appears too wide to be bridged by the introduction of non-price factors into the assessment criteria. The ringfence is likely to remain a crucial tool to support the continued deployment of tidal stream energy in the UK in the foreseeable future. The UK marine energy industry itself has also expressed support for the continued use of pot structure (splitting technologies into auction pots based on their level of technological maturity) along with a ringfenced approach to budgeting for specific emerging technologies like tidal stream, considering this important for ensuring a route to market for such technologies within the CfD (MEC, 2023).

The Government has stated a commitment to speeding up the time it takes to bring new renewable generation capacity online, including by creating a more conducive planning environment, reducing network connection timelines and giving Ofgem (the independent regulator of electricity and gas markets in Great Britain) a legal duty to support the delivery of the UK's 2050 net zero target (HM Government, 2023; Ofgem, 2023). A consented tidal stream energy plant can potentially be constructed in less than three years (MEC, 2023). However, the UK's electricity network is currently constrained by a lack of capacity, with some new renewable generation projects having to wait up to 10 to 15 years to get connected and start feeding power into the network (Stallard and Rowlatt, 2023). Implementation of the Government's commitments to shorten the timelines associated with planning and network connection could enable the UK to scale up renewable energy projects, including tidal stream energy, without undue delay.

3 Subsidy control principles mean that any given subsidy would need to be proportionate and limited to the minimum amount necessary to remedy the identified issue or challenge it is designed to address.

3. Tidal stream energy and sustainable growth in the UK

Developing tidal stream energy has the potential to contribute to four strategic objectives relevant for enabling sustainable growth in the UK:

1. Achieving a net zero energy system
2. Ensuring energy security
3. Capturing export opportunities
4. Securing regionally-balanced growth.

This section reviews the existing literature on how tidal stream energy might be able to contribute to meeting these objectives, setting the scene for a deeper exploration in the following sections of how the sector could benefit export opportunities and regionally-balanced growth in particular.

Achieving a net zero energy system

Domestic deployment of tidal stream energy can directly contribute to efforts to reduce emissions from the UK's energy system, in turn helping to unlock growth pathways consistent with net zero for a whole range of sectors. Indeed, tidal stream energy does not directly emit any CO_2, has very low operational CO_2 emissions (associated with operations and maintenance) and is available in abundant quantities in the UK. Every kilowatt hour of power generated by tidal stream energy can save an estimated 394g of CO_2 compared with the same unit of power from a combined cycle gas plant, or 120g of CO_2 compared with that from biomass (ORE Catapult, 2018). Furthermore, the estimated tidal stream resource that the UK could economically capture is enough to meet around 11% of the country's current annual electricity demand (Coles et al., 2021).

Tidal stream energy can also be part of a cost-effective pathway to decarbonise the UK energy system if the industry's stated cost reduction ambitions can be achieved. As the industry is at an early stage, tidal stream energy devices to date have typically been over-engineered to demonstrate proof of concept and ensure operability (ORE Catapult, 2022). As a result, tidal stream energy is currently more expensive than more mature renewables like solar and wind. In the latest CfD allocation round, solar photovoltaics (PV) cleared at a strike price of around £46/MWh (for delivery from 2023) and offshore wind at £37/MWh (for delivery from 2026) (DESNZ and BEIS, 2022). In the same auctions, tidal stream cleared at £179/MWh (for delivery from 2025), but this is already 15% lower than the administrative strike price set for the technology, signalling strong potential for further cost reduction. Indeed, recent analysis has indicated that between 2016 and 2022, the levelised cost of energy (LCOE) from tidal stream energy in the UK fell by over 40% despite receiving little or no revenue support (although it has accessed support in the form of technology-push mechanisms[4]) (ORE Catapult, 2022). And it is estimated that the LCOE could fall to £78/MWh by 2035 under an achievable domestic deployment pathway (ORE Catapult, 2022). For context, offshore wind saw strike prices below £80/MWh for the first time in 2017, 14 years after the UK's first commercial offshore wind farm was installed (BVG Associates, 2019).

Based on the example set by offshore wind, increased deployment of tidal stream energy is expected to drive accelerated learning that will in turn minimise costs of the technology (ORE Catapult, 2022). Key drivers of cost reduction in the near term (up to around 2035) are expected to be economies of scale through devices of larger rotor and higher rated power, economies of

[4] Technology-push mechanisms offer direct support for the innovation of the technology (e.g. R&D grants) as opposed to demand-pull mechanisms, which focus on creating market demand for the technology.

volume from larger farms, and reductions in the cost of capital (ibid.). Further technological innovations such as piled foundations, innovative anchors and mooring system designs, advanced rotors and blades, improved power train and the use of next-generation materials are expected to contribute to cost reductions too (ibid.).

Ensuring energy security

As an ample domestic renewable resource, tidal stream energy can contribute to reducing reliance on energy imports and improving energy security in the UK. Four projects with a combined capacity of 40.8 MW have already been contracted to commence operation from 2025 in the UK, but the tidal stream resource that could be practicably exploited is much greater – estimated to be equivalent to 11.5 GW of generating capacity across the UK and the Channel Islands (Coles et al., 2021). Modelling shows that expanding the capacity of tidal stream energy on the grid could potentially reduce the amount of dispatchable gas (i.e. gas generation that can be turned up and down at the request of grid operators to match demand) needed to balance the electricity system by about 40%, in turn reducing the UK's exposure to volatile gas prices in global markets; a significant finding given that more than half of UK gas is currently imported (Frost, 2022).

Tidal stream energy also has some unique properties that make it well-suited to complement other variable renewables on the grid and help improve the overall resilience of the energy system. Tidal stream energy is driven by the relative movements between the Earth, moon and sun, which is a separate natural phenomenon from weather and solar radiation that drive the more established renewable resources, wind and solar PV. This means the times at which tidal stream generation is available is not affected by the same sources of variation that affect energy generation from wind and solar – thus it is completely decoupled from those sources. Indeed, research has found that a more diverse power generation mix including marine energy sources (i.e. tidal stream and wave) would be consistently more available and better able to meet demand than one that does not include marine energy (Supergen ORE Hub and P&IG, 2023). Furthermore, tidal stream as a form of energy generation is highly predictable far into the future, unlike wind and solar which can only be forecast in the near future. These properties mean that increasing tidal stream energy capacity on the grid could also reduce balancing costs (potentially by up to £1.03 billion per year when coupled with a higher penetration of wave energy) as a result of more efficient use of renewables and reduced need for peaking generation or flexibility (ibid.).

Tidal stream could also offer the UK energy security benefits from a supply chain perspective. Supply chain bottlenecks have affected renewable energy deployment in recent years (as well as infrastructure projects more generally) and have become an important concern for policymakers around the world. Many governments have already introduced major policy measures to onshore the manufacture of products that are of strategic importance to their economies and thereby reduce their exposure to volatile global supply chains. The most prominent example is the Inflation Reduction Act in the US. While the UK has a stated commitment to continue relying on trusted global supply chains and avoid participating in a "discriminatory subsidy race", it also appears to be putting greater focus on developing resilient UK supply chains in support of its net zero transition, as reflected in the language of its *Powering Up Britain* plans and the considered changes to introduce non-price factors into the CfD assessment criteria (HM Government, 2023; DESNZ, 2023b). Against this backdrop, pursuing tidal stream energy may appear particularly favourable. UK tidal stream projects have had a very high domestic content to date – over 80% in some cases – and developers have already stated their desire to keep it high where possible in future projects, potentially even reaching 95% (ORE Catapult, 2022). For comparison, the domestic content of offshore wind projects in the UK over their lifetime is estimated at 48% (BVG Associates, 2019).

Despite the potential benefits of tidal stream for energy security and net zero, the technology was mentioned only briefly in the *British Energy Security Strategy* of April 2022, within the ambition to "aggressively explore renewable opportunities afforded by our geography and geology, including tidal…" (HM Government, 2022). This contrasts with calls from parts of industry and policy circles, for instance from the House of Commons Environmental Audit Committee (2023), for an explicit ambition for the sector, set out in gigawatts of generating capacity. These calls have not materialised to date, with no new announcements on tidal stream energy made in the Government's recently published *Powering Up Britain* plans, which serve as the UK's revised strategy for meeting net zero by 2050 (HM Government, 2023).

Capturing export opportunities

Tidal stream energy has been highlighted in the recently conducted *Independent Review of Net Zero* as an area in which the UK is a first mover and could create distinct advantages in the future (Skidmore, 2023). The UK has some of the best marine energy resource in the world, is home to many of the tidal stream technology concepts that have originated to date and has a strong research base focusing on further developing the technology (ORE Catapult, 2018). In fact, the UK is already exporting its tidal stream technologies abroad (ORE Catapult, 2022). For example, Scotland-based Nova Innovation has secured an export order for 15 tidal turbines and a power purchase agreement from the Canadian province of Nova Scotia (Nova Innovation, 2022). However, the UK's ability to continue to secure export opportunities from the global market if and when it moves from a small number of demonstration projects to mass deployment will heavily depend on whether investments necessary to expand the UK's supply chain are realised and how other countries develop their own markets and supply chains; as discussed in the previous section, this is highly uncertain.

The UK's potential to build a competitive supply chain for tidal stream energy is not in isolation from its industrial capabilities more generally. Countries are competing to capture industrial benefits from the growing demand for clean technologies amid global efforts to move towards net zero emissions. This competition has been fuelled recently by several major economies that have, while not being specific to tidal stream energy, introduced ambitious support packages aiming to make investments in clean technology supply chains more attractive within their own borders. This includes the Inflation Reduction Act of 2022 in the US and the Green Deal Industrial Plan unveiled in response by the European Commission. The UK Government is expected to set out its response to the Inflation Reduction Act in the 2023 Autumn Statement, with Jeremy Hunt, Chancellor of the Exchequer, having committed to "target public funding in a strategic way in the areas where the UK has a clear competitive advantage" (Hunt, 2023). However, there is growing concern that on the global stage the UK is becoming a less attractive place to invest in manufacturing supply chains for clean technologies (Make UK, 2023). Global competition to capture industrial benefits specifically from tidal stream energy is also gaining pace (Renewable UK, n.d.).

Despite the UK's manufacturing supply chains for clean technologies facing increased threat from global competition, the UK might find it easier to secure services-related opportunities from the global market for tidal stream energy as a services-exporting superpower (Curran et al., 2022). The UK has strong existing capabilities in subsea engineering, design and manufacture of offshore foundations and the provision of operations and maintenance in the marine environment underpinned by its well-established offshore industries (e.g. oil and gas and offshore wind) (MEC, 2023; Vivid Economics, 2019e). The UK could build on these capabilities to develop further specialism in services related to tidal stream energy and export these to the global market if and when demand rises.

In the following sections, we provide further evidence on the UK's existing capabilities to export and innovate tidal stream energy technologies to better understand how its ability to capture export opportunities might fare in the context of growing global competition.

Regionally-balanced growth

Tidal stream resource has a good geographical spread and potential project locations across the four nations of the UK (ORE Catapult, 2022). The same applies to the UK's currently small marine energy supply chain. For example, RenewableUK's Supply Chain Map identifies over 230 locations (including offices, manufacturing facilities and R&D centres) across the UK that are engaged in activities related to marine renewables (RenewableUK, 2023). Additionally, the Marine Energy Supply Chain Gateway lists over 850 companies currently active or able to participate in the sector, once again with a decent spread throughout the UK (ORE Catapult, 2018). If underpinned by investments to further develop local supply chains, the deployment of tidal stream energy in the UK could contribute to regionally-balanced growth and support the Government's levelling up agenda.

The ORE Catapult has estimated that 50–60% of the economic benefits from marine energy could be generated in coastal areas, in terms of both GVA and jobs (ORE Catapult, 2018). Many such communities have long been a focus for regional development policies given their higher-than-average unemployment figures and declining traditional industries like shipbuilding and fishing. Some of these communities also rely heavily on oil and gas activities and are set to undergo major economic restructuring in line with net zero pathways. The strong potential for skills transfer between the oil and gas and tidal stream sectors is a silver lining to this concerning picture as both rely heavily on operations in the marine environment. Through developing its tidal stream sector, the UK could create a natural next employment destination for oil and gas workers who might otherwise be at risk of job losses, all while capitalising on its existing capabilities to develop competitive supply chains for an emerging technology. An example can be found in Scotland's Orkney Islands, whose economy has historically relied on oil and gas: in 2020, around 200 people there were employed by businesses that serve the marine energy sector (tidal stream and wave) (Scottish Renewables, 2020).

Arguably, tidal stream energy already appears more prominently in support of economic growth policies at a regional level under devolved administrations than it does at the national level. For example, in January 2023, the Scottish Government published its draft *Energy and Just Transition Plan* in which it outlines its vision for marine energy, underlines the importance of continued funding through the CfD for the development of the sector and seeks views on the priority actions it can take to further advance tidal energy in Scotland (Scottish Government, 2023). Scotland's success in tidal stream energy to date is visible in the outcome of the AR4 in which most of the revenue support for the technology has been secured by companies and project sites based in Scotland (OES, 2023). Scotland is also home to the European Marine Energy Centre (EMEC) where many of the world's leading tidal devices to date have been tested in real sea conditions for the first time.

The Welsh Government also has a strong agenda for tidal stream energy with a stated aim of capturing at least 10% of the potential tidal stream and wave energy off its coastline by 2025 (P&IG, 2023). This is complemented by an ambition to make Wales the location of choice for tidal stream developers and their subsequent supply chains in order for it to emerge as a lead exporter of related technologies and skills (ibid.). It is estimated that tidal stream energy developers including Minesto and Nova Innovation, along with the development of the Morlais demonstration zone, have contributed a total of £67 million of direct investment into the Welsh economy to date (Marine Energy Wales, 2021).

In Northern Ireland, the Department for the Economy in its *Energy Strategy Action Plan* of 2022 acknowledges the potential of tidal stream energy to achieve a more diverse electricity generation mix alongside its wider ambition to ensure that the province can effectively attract investors to benefit from green growth opportunities (P&IG, 2023). Strangford Lough was home to the world's first large-scale commercial tidal stream generator – though this has since been decommissioned, the location remains an important testing and demonstration site.

4. Understanding the UK's relative performance in the exports of tidal stream energy products

Using trade data analysis to inform growth policy

Evidence from the economic geography literature shows that countries and regions more easily develop new competitive advantages in products that are similar to those they already produce competitively (Hidalgo et al., 2007b; Neffke et al., 2011). Furthermore, producing and exporting technologically complex products are associated with greater economic prosperity and growth (Hidalgo et al., 2007a, 2007b; Hausmann et al., 2007). Building on these findings, a quantitative methodology has been developed by Mealy and Teytelboym (2022) which aims to measure countries' current green export capabilities, identify new green export opportunities and predict likely future green export growth.[5]

We apply this methodology to a set of 23 traded products[6] (defined at the 6-digit level in the Harmonised System[7]) that we identify as relevant for tidal stream energy to shed light on the UK's current and future potential export specialism in this area. These products are relevant for, but not exclusive to, tidal stream energy as they include products such as hydraulic turbines, bearings, gears, motors, floating structures and electrical equipment (e.g. transformers and conductors) that are used in a range of activities in energy generation, transport and industry. Measures calculated through this analysis are based on country-level trade data over the period 1995–2020 from CEPII's BACI database (Gaulier and Zignago, 2010).

The key concepts underpinning this analysis are as follows:

- Revealed comparative advantage (RCA): RCA is calculated as a product's share of a country's exports divided by the product's share in global exports. We adjust RCA values so that they lie between -1 and +1,[8] with numbers larger than zero signifying that the country has RCA in a particular product. If a country has RCA in a product, it can be thought of as a specialised exporter of that product. To ensure our analysis is not skewed by short-term fluctuations in trade, we calculate this measure on the basis of five-year rolling averages in annual trade values, starting in 1995–1999 and ending in 2016–2020.
- Product complexity index (PCI): This index ranks products according to the similarity of countries that export them competitively. PCI values are calculated on a relative basis against the universe of all traded products, and standardised to mean set at zero with a standard deviation of 1. Products with higher PCI tend to be more technologically sophisticated and associated with higher growth opportunities.[9]
- Proximity: At the product-to-product level, proximity refers to the probability that a country has RCA in one product given that it has RCA in another. This measure then allows proximity to be defined at the product-to-country level, which represents the average proximity of a product to all the products that a country is specialised in exporting (i.e. has

[5] The methodology is applied to an extensive set of 'green' products in the Green Transition Navigator (Andres and Mealy, 2023) which is an online resource that aims to help countries to better understand their current and future potential competitiveness along the global transition to a green economy. We have previously used this methodology to highlight economic opportunities for the UK across a set of technology areas relevant for net zero (Curran et al., 2022) and in a detailed report on the CCUS sector (Serin et al., 2021).

[6] See Appendix for the full list of products.

[7] The Harmonised System (HS) is a multipurpose international product nomenclature developed by the World Customs Organization (WCO) that comprises more than 5,000 commodity groups, each identified by a six-digit code, arranged in a legal and logical structure and supported by well-defined rules to achieve uniform classification. See the WCO website for further details.

[8] As the ratio of a product's share of a country's exports to the product's share in global exports, RCA can normally take any value between zero and infinity. We transform these raw RCA values so that they lie between -1 and 1 using the following formula: (RCAraw - 1)/(RCAraw +1), where RCAraw refers to the untransformed RCA calculated as described.

[9] For a more detailed discussion of the Product Complexity Index, see Mealy et al. (2019).

RCA in). Proximity values lie between 0 and 1. Countries that have higher proximity to particular products in which they do not yet have an export specialism have been shown to be more likely to develop a specialism in them in the future (Hidalgo et al., 2007b).

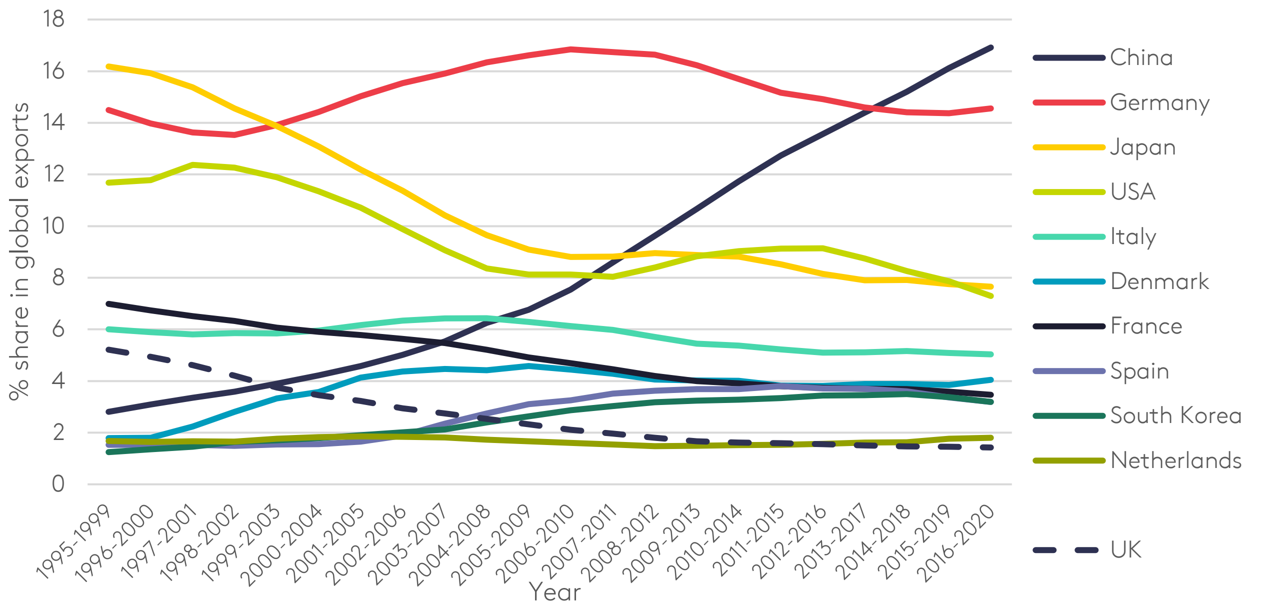
For international comparisons, we calculate our measures (e.g. export shares, RCA) based on all countries, but define the top 10 countries for a given measure only within members of the OECD plus China and Hong Kong, based on the most recent time period in our dataset (i.e. 2016–2020).

The UK's performance in the exports of products relevant for tidal stream energy compared with other countries

Five countries account for over 50% of the global export volume of products relevant for tidal stream energy: China (17%), Germany (15%), Japan (8%), US (7%) and Italy (6%) (see Figure 4.1). China increased its export share drastically from just 3% in the mid-1990s to reach its current position as export leader, while Japan and the US have lost their earlier dominance in this area. Other countries in the top 10 in terms of export share each hold 2–5% of global exports.

Six countries in the top 10 – China, Japan, the US, France, Korea[10] and the Netherlands – all have some tidal stream capacity already installed or under development. These countries could further grow their domestic markets given the tidal resource potential in their waters (see Section 2). However, even if they were to pursue ambitious national deployment programmes for tidal stream energy, they are unlikely to create meaningful export markets for the UK given signs that they already have the manufacturing capacity to meet their own needs. Despite being the global leader on tidal stream energy development to date, the UK does not feature in the top 10 countries in terms of export share, holding less than 2% of the global exports of relevant products in the latest year. This represents a significant fall from a share of over 5% that the UK held in the mid-1990s.

Figure 4.1. Export shares for the aggregate category of products relevant for tidal stream energy of the top 10 countries and the UK (1995–2020)



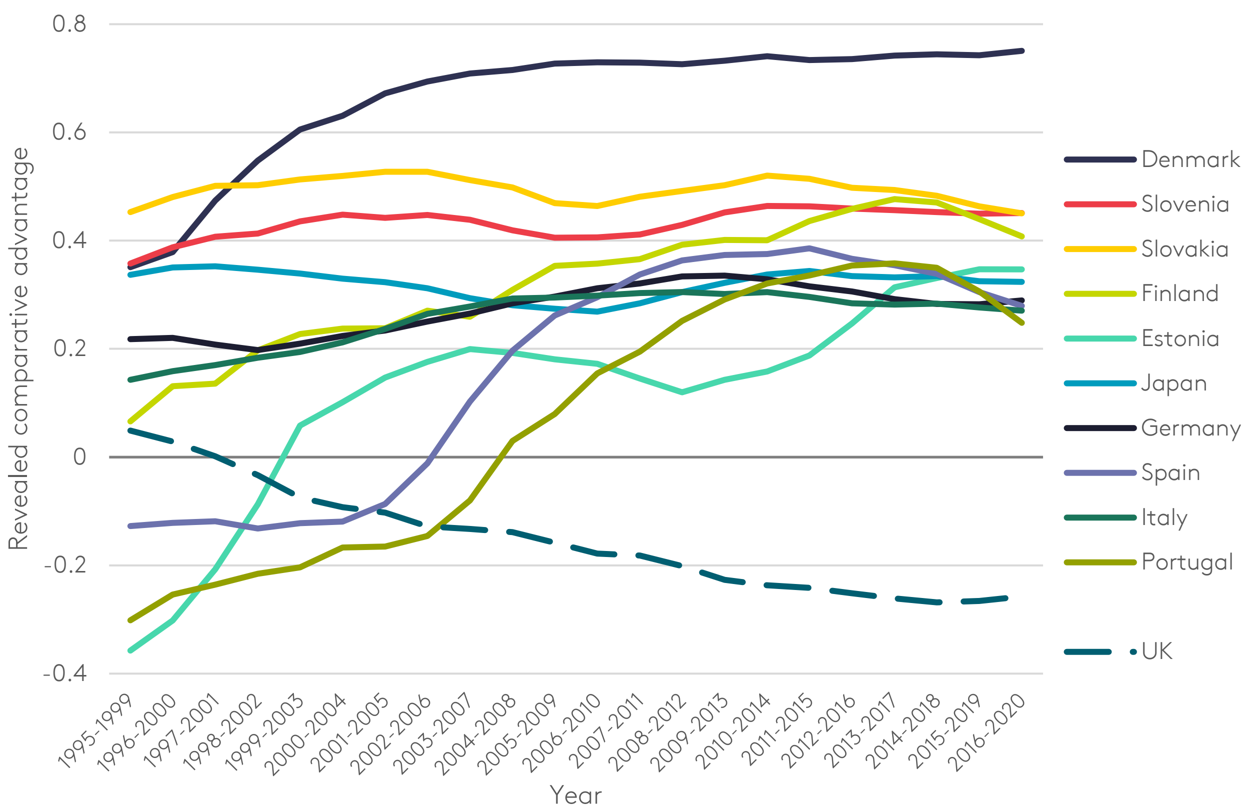
Notes: *Export shares are calculated as five-year rolling averages, starting in 1995–1999 and ending in 2016–2020. The top 10 is defined based on the latest five-year period (2016–2020). The UK is indicated with a dashed line as it is not in the top 10.*

[10] Korea is not included in Table 2.1 of countries active in tidal stream technology as its 0.08 MW installed capacity at the Uldolmok pilot plant is below the inclusion threshold that we set at 0.5 MW.

Looking at the product grouping at an aggregate level, the UK is not a specialised exporter of products relevant to tidal stream energy either, measured by its RCA (see Figure 4.2). While the UK's RCA started from a positive level in the mid-1990s, it has gradually declined since. Denmark is the most specialised exporter of products relevant for tidal stream energy (and is in the top 10 on export share), despite not being a tidal resource hotspot or showing any sign of domestic activity explicitly relating to tidal stream energy (see Section 2). The same is true for five other countries appearing in the global top 10 on RCA – including the landlocked Slovakia. Here it is important to reiterate that the product codes we define as relevant for tidal stream energy are not exclusive to this technology area. Given the nascent state of the tidal stream energy sector, our measures of specialism likely reflect countries' existing capabilities and exports relating to a range of other activities in energy generation, transport and industry which overlap with the tidal stream energy supply chain. For example, Denmark's top-ranking RCA in tidal stream products is likely explained by its success as an exporter of offshore wind products given the large overlap in the supply chains of the two technologies. In fact, eight of the 10 most specialised exporters of wind technologies identified previously (including Denmark) also appear in the current list for tidal stream technologies (Curran et al., 2022).

Notably, neither China nor the US is among the most specialised exporters of products relevant for tidal stream energy, despite the previous analysis showing that they account for some of the highest shares of exports in this area. This reflects the large volumes of exports that China and the US have in other product areas as well, and also appears to be the case for France and the Netherlands. On the other hand, Denmark, Germany, Italy, Japan and Spain feature in the top 10 in terms of both export share and export specialism.

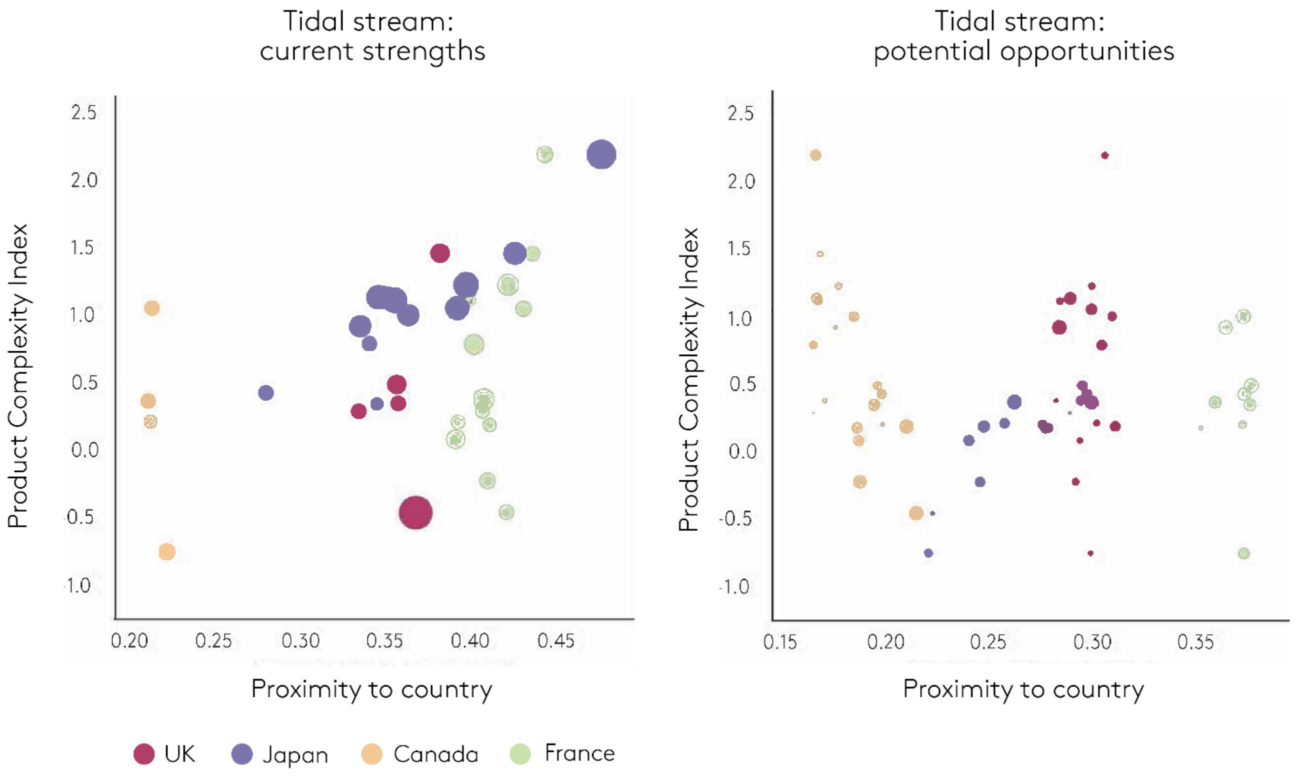
Figure 4.2. Revealed comparative advantage in the aggregate category of products relevant for tidal stream energy of the top 10 countries and the UK (1995–2020)



Notes: *RCA values are calculated as five-year rolling averages, starting in 1995–1999 and ending in 2016–2020, and are adjusted to lie between -1 and 1 where values above 0 indicate specialism. The top 10 is defined based on the latest five-year period (2016-20). The UK is indicated with a dashed line as it is not in the top 10.*

Figure 4.3 maps the strengths and opportunities for the UK, Canada, France and Japan in products relevant for tidal stream energy, along with these products' proximity to a given country's existing productive capabilities on the x-axis, and their product complexity index (PCI) on the y-axis. Canada, France and Japan are chosen as benchmark countries based on the *Energy Innovation Needs Assessment* report on tidal stream (Vivid Economics, 2019e), which, drawing on expert consultation, identifies them as the UK's key competitors in this area. Notably, of these countries, only Japan has emerged as a specialised exporter of tidal stream products in the current analysis. Despite having ambitious domestic programmes to pursue tidal stream energy, Canada and France do not appear in the global top 10 on export specialism, as is also the case for the UK.

Figure 4.3. Existing strengths and new opportunities in tidal stream energy for the UK, Canada, France and Japan (2016–2020)



Notes: *Each bubble corresponds to a product and is sized by the given country's RCA in that product. RCA, PCI and proximity values are calculated based on average trade values for the products between 2016–2020, the latest five-year period available in our dataset.*

The left-hand graph in Figure 4.3 shows the products relevant for tidal stream energy in which the countries already demonstrate specialism (i.e. have an RCA greater than zero). The right-hand graph depicts tidal stream products in which these countries are not currently specialised (i.e. have an RCA below zero) but could build specialisation in the future. Such products can be considered as potential opportunities.

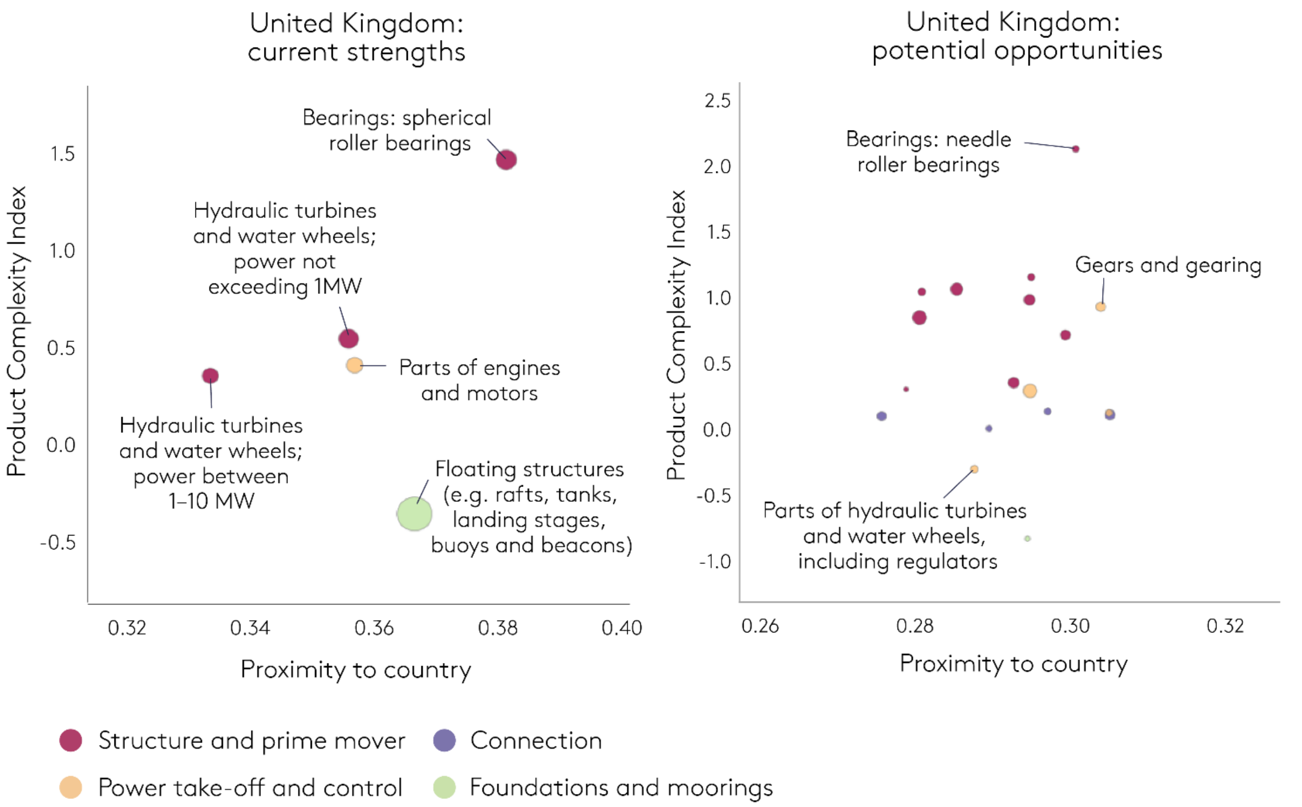
This analysis reveals that the UK has fewer existing strengths in products relevant for tidal stream energy than Japan or France, but slightly more than Canada. The UK's strengths are in products that are lower in complexity and proximity on average than those in which Japan and France have strengths. However, the UK has plenty of potential *opportunities* that are both high in complexity and proximate to its existing productive capabilities. These opportunities could be translated into actual strengths if underpinned by investment to develop relevant supply chain capability. However, while the UK appears to have a greater number of proximate opportunities than Canada or Japan, it is still behind France, whose product opportunities have higher proximity and similar complexity to those of the UK on average.

The UK's performance in the exports of specific products relevant for tidal stream energy

Products that are relevant for the tidal stream energy sector are relatively high in complexity on average when compared with the universe of all traded products (see Figure A1, Appendix). This suggests that tidal stream products tend to be more technologically sophisticated, requiring more knowledge-intensive skills and capabilities in their production. Exports of such products are linked to higher economic prosperity and growth and are also likely to be co-exported with a greater number of other highly complex products.

While the UK has few existing strengths in tidal stream, almost all of these are in complex, high-value products that are core to the technological foundation of a tidal stream energy plant (see Figure 4.4). They include both small (less than 1 MW) and larger (1–10 MW) hydraulic turbines, as well as spherical roller bearings, which is the highest in complexity and closest to the UK's existing production capabilities among UK strengths. There are also many products relating to turbine structure within potential tidal stream opportunities for the UK, alongside some other products relating to the powertrain (e.g. gears and gearing), that are relatively high in both technological complexity and proximity to the UK. However, given the UK's current lack of export specialism in these products, such opportunities are likely being realised elsewhere at the moment. Indeed, according to the ORE Catapult (2022), powertrain components account for most of the non-UK content in tidal stream development in the UK.

Figure 4.4. Existing strengths and new opportunities for the UK in specific products within the tidal stream energy category (2016-2020)



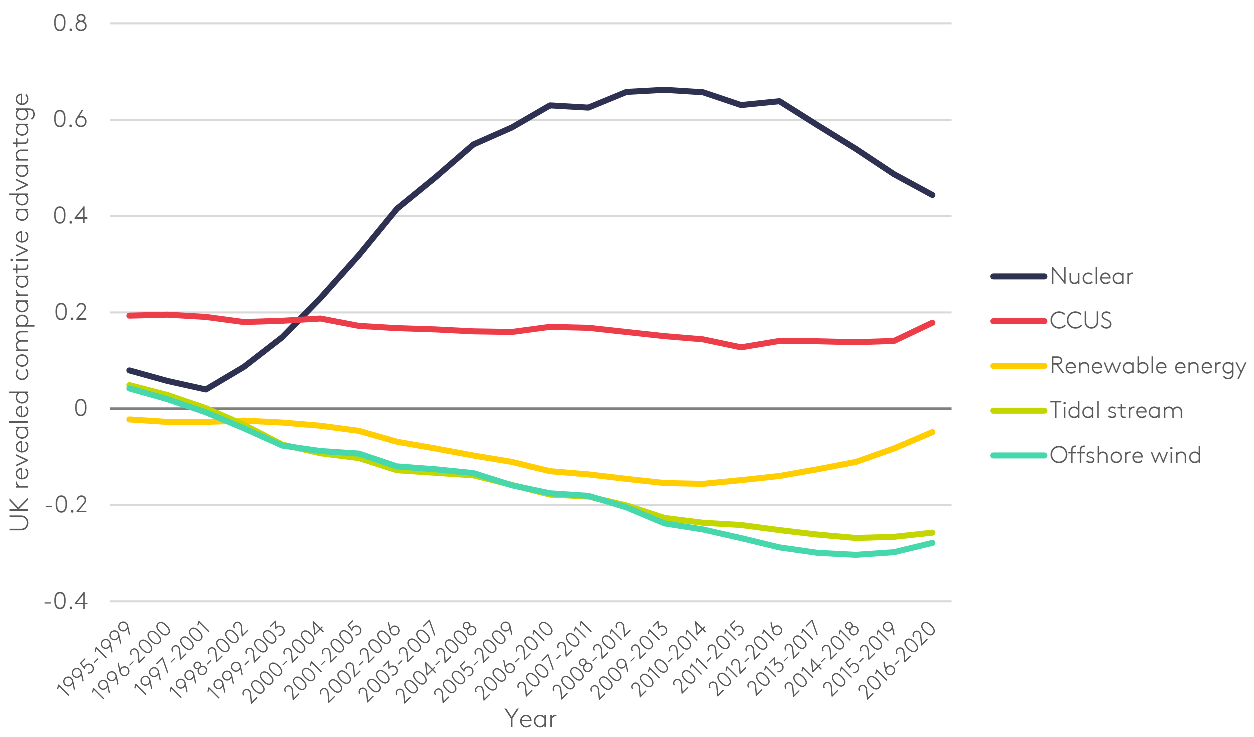
Notes: Each bubble corresponds to a product and is sized by the UK's RCA in that product. RCA, PCI and proximity values are calculated based on average trade values for the products between 2016–2020, the latest five-year period available in our dataset. The products within the overall category defined as relevant for tidal stream energy are broken down into four categories of component types, explained further in Section 2 of the Appendix.

The UK's performance in the exports of products relevant for tidal stream energy compared with other technologies

The UK Government is committed to targeting public funding in areas where the UK has a clear competitive advantage, as previously discussed. In this context, we compare the UK's RCA in products relevant for tidal stream energy as an aggregate category against its RCA in four other technology classes that feature prominently in the UK's strategy for meeting net zero emissions. These include the three specific technology classes (CCUS, nuclear and offshore wind) used previously as comparators on the size of the business opportunity and one more general technology class that represents renewable energy overall (including tidal stream energy, offshore wind, solar PV, etc.).

The UK has a slightly higher RCA in renewable energy technologies overall than in tidal stream specifically, and this has improved slightly in recent years, but its RCA in both areas is negative (see Figure 4.5). Furthermore, the UK's RCA in tidal stream is almost the same as its RCA in offshore wind throughout the analysed period, reflecting the overlap in the products defined as relevant for the two technology areas. In contrast to renewable technologies, the UK has an overall specialism in exporting products for both CCUS and nuclear energy. The UK's RCA on CCUS products has remained almost flat over the entire time period analysed, with an uptick in the most recent years, while its RCA on nuclear energy products increased steeply during the 2000s before taking a sharp decline in the 2010s.

Figure 4.5. Trend of the UK's revealed comparative advantage in the aggregate category of products relevant for tidal stream energy compared to other selected clean technology areas (1995–2020)



Notes: Traded product codes used under the 'renewable energy' category are based on the category of the same name in the Green Transition Navigator (Andres and Mealy, 2023). Traded product codes used under CCUS, nuclear and offshore wind are based on the codes selected for analysis in the Energy Innovation Needs Assessment sub-theme reports for the respective technologies (Vivid Economics, 2019a, 2019b, 2019c).

We also compare the UK's specific strengths and opportunities in tidal stream energy against those it has in CCUS, nuclear and offshore wind (see Figure A2, Appendix). As the total number of products defined as relevant for each technology area is different,[11] we focus our comparisons on PCI and proximity rather than on the number of products across the different technology areas. Broadly speaking, the products across the four technology areas appear similarly proximate to the UK's productive capabilities. Only a few products under nuclear stand out as marginally more proximate. There are, however, greater differences in product complexities. In particular, CCUS products appear more complex overall than the other technology areas within the UK's strengths, while tidal stream and offshore wind products appear more complex than the other two technology areas within the UK's opportunities. This suggests that economic growth opportunities attached to future potential exports (if realised through investments to develop necessary supply chain capability) might be somewhat greater for tidal stream and offshore wind technologies than the other technology areas analysed.

Discussion

The ultimate size that the global market for tidal stream energy will reach is highly uncertain and constrained by the size of the natural resource that can be practicably exploited. However, whatever the ultimate size of the global market, the international competition to capture it will be strong. Our analysis shows that the majority of countries that already have or are looking to deploy tidal stream energy domestically are themselves significant exporters of the relevant products. Exporters may struggle to break into the domestic markets of these countries unless they demonstrate a certain level of export specialism in the relevant products. Interestingly, there are many countries that do not have an explicit link to tidal stream energy yet demonstrate export specialism in products relevant for the sector. If global demand for tidal stream products rises substantially, these countries may decide to apply their existing capabilities to developing dedicated manufacturing capacity for the tidal stream sector, increasing the competitive pressure on the UK. Furthermore, although the UK is currently substantially ahead in sectoral development for tidal stream energy, France could emerge as an increasingly significant competitor as a country that is also looking to expand tidal stream generation domestically and has several tidal stream technology developers of its own.

The UK currently has export specialism in several complex products relevant for tidal stream energy, including hydraulic turbines. However, in the face of strong international competition, the UK's ability to secure export opportunities from the sale of such products as the global market for tidal stream energy grows will be highly conditional on timely efforts to further develop the UK supply chain's capacity. Regardless of the ultimate size of the export opportunity, building a strong domestic supply chain for tidal stream energy is likely to deliver sustainable growth benefits for the UK: namely, enabling the UK to quickly scale-up a low-carbon energy source that can support its net zero transition and energy security, and contributing to regionally-balanced economic growth across the country. Policy support for driving investment into the UK supply chain for tidal stream energy is therefore justified even purely for the opportunities in the domestic market, but it would also be the UK's best chance at maximising the export opportunity it will ultimately be able to capture from the global market. There are many other complex products relevant for tidal stream energy in which the UK does not currently have export specialism, but could develop specialism in the future given its proximate productive capabilities. Developing a strong domestic supply chain for tidal stream energy would give the UK the ability to identify the parts of the supply chain it could most easily develop further specialism to generate export opportunities. Furthermore, while the UK's comparative advantage at the aggregate level in products relevant for tidal stream energy is currently lower than its comparative advantage for those relevant for nuclear and CCUS, some of the products for tidal stream energy are higher in complexity. A targeted approach to developing supply chain capacity and capture export

[11] Namely, we use: 23 product codes under tidal stream; 19 product codes under offshore wind; seven product codes under nuclear energy; and 18 product codes under CCUS.

opportunities specifically from such complex, high-value products could yield important growth opportunities for the UK.

The UK's long-established offshore wind sector could offer important lessons to inform policy development relating to tidal stream energy. As an aggregate category, the UK's revealed comparative advantage in products relevant for offshore wind is negative and has been declining over time, despite the UK being a global leader in offshore wind deployment. According to an independent review, the UK largely missed the opportunity to develop substantial domestic intellectual property, technology and capability during the early stages of offshore wind deployment, which has meant that the non-UK businesses that led the process have retained supply chain benefits to a large extent (Whitmarsh, 2019). In contrast, Denmark invested early to build a strong domestic supply chain for wind power, in turn delivering domestic projects with high levels of local content and making the sector a key driver of national exports (MEC, 2023). In fact, the UK is currently a net importer of wind technology, principally from Denmark (ibid.). The tidal stream energy sector is very much in its infancy globally, which presents an opportunity for the UK to take a different approach to that of offshore wind from the start, linking deployment of the technology with the development of a domestic supply chain to maximise its chances of securing future export opportunities.

Policy aiming to drive investment into the UK's tidal stream energy supply chain would be most effective if it were designed to provide the long-term certainty to build investor confidence in the sector. The Government currently announces key decisions on the CfD scheme (currently the main route to market for tidal stream energy projects in the UK), such as auction pot budgets and technology ringfencing, only months prior to the closure of each allocation round whereas preparing a project for bidding in the CfD can take multiple years (MEC, 2023). Project developers are therefore required to invest substantial time and resources into project development without the certainty that the necessary budget will be available when they are ultimately ready to place a bid. This kind of disconnect between the policy cycle and the processes that the industry needs to undertake can deter investment (ibid.). Providing greater clarity over intended budgeting for each allocation round multiple years in advance could attract a continuous pipeline of tidal stream projects in the CfD and enable anticipated likely demand from the domestic market to drive investment into the domestic supply chain. Industry has suggested a minimum of three years as an advance notice period that could be considered by Government for this purpose (ibid.).

5. Understanding the UK's relative performance in the innovation of tidal stream energy technologies

Using patents data analysis to inform growth policy

Patents are a key measure of innovation output and can thereby be a good indicator of where future economic value will be generated. While not all innovation is patented – and this is especially true for the services sector, which constitutes a large proportion of the UK economy – data on patents are commonly used by researchers to make comparative analyses of innovation patterns, being internationally available over time and organised under detailed technological classifications. Even though patents data do not fully capture innovations related to services, the transition to net zero will inevitably require further innovation and deployment of physical equipment, for which patents data provide good coverage.

Our patents data come from the 2021 Autumn edition of the Worldwide Patent Statistical Database (PATSTAT Global) published by the European Patent Office (EPO). PATSTAT Global contains information on patent applications filed with patent authorities in various countries. Given that the available data come with lags, the latest complete year in our analysis is 2018. Our analysis of patents data focuses on patent 'families': sets of patents that cover similar technical content or refer to the same invention. Each patent family is referred to as one 'innovation' in the subsequent discussion. The analysis is restricted to patent families consisting of more than one patent application; this serves as a filter so we count higher-quality patents only. We identify the country of origin for these patent families by mapping them to the current country of residence of the corresponding inventors.[12] Patents are categorised into specific technological classifications according to the Cooperative Patent Classification system and we have identified a set of classifications which we define as relevant for tidal stream energy (see Section 3, Appendix). We aggregate innovations that belong to these classifications to describe innovations in tidal stream energy as an overall category in the subsequent discussions. This covers innovations relating to equipment such as blades, stators, rotors, floating structures, submerged foundations and flexible cables.

The key concepts underpinning this analysis are as follows:

- **Revealed technological advantage (RTA).** A country is said to have RTA in a technology area if the area's share of the country's total patenting is larger than the area's share of total global patenting. We adjust RTA values so that they lie between -1 and +1,[13] whereby numbers greater than zero indicate that the given country has innovative specialism in that area.
- **Industrial Strategy Index (IStraX).**[14] The IStraX is based on a model of the innovation process that is fitted to global data on patenting and valuations of companies undertaking innovation. Resulting values therefore reflect the total economic value of an innovation in a certain field calculated as the difference between the expected increase in total value (private value and external values from knowledge spillovers) generated by that innovation and the expected cost of the subsidy, scaled by the expected cost of the subsidy.

  IStraX captures the value of an innovation only to the extent that it translates into profit for some firms. The private value of an innovation is assumed to be captured by the short-term response of the stock market price to innovating companies when a patent is

[12] See Annex 1 in Curran et al. (2022) for further detail on our approach to assigning patent families to geographical locations.

[13] For this we use the same transformation formula as was used for our RCA analysis in the previous section. See Footnote 9.

[14] For further detail on the IStraX methodology, see Guillard et al. (2023).

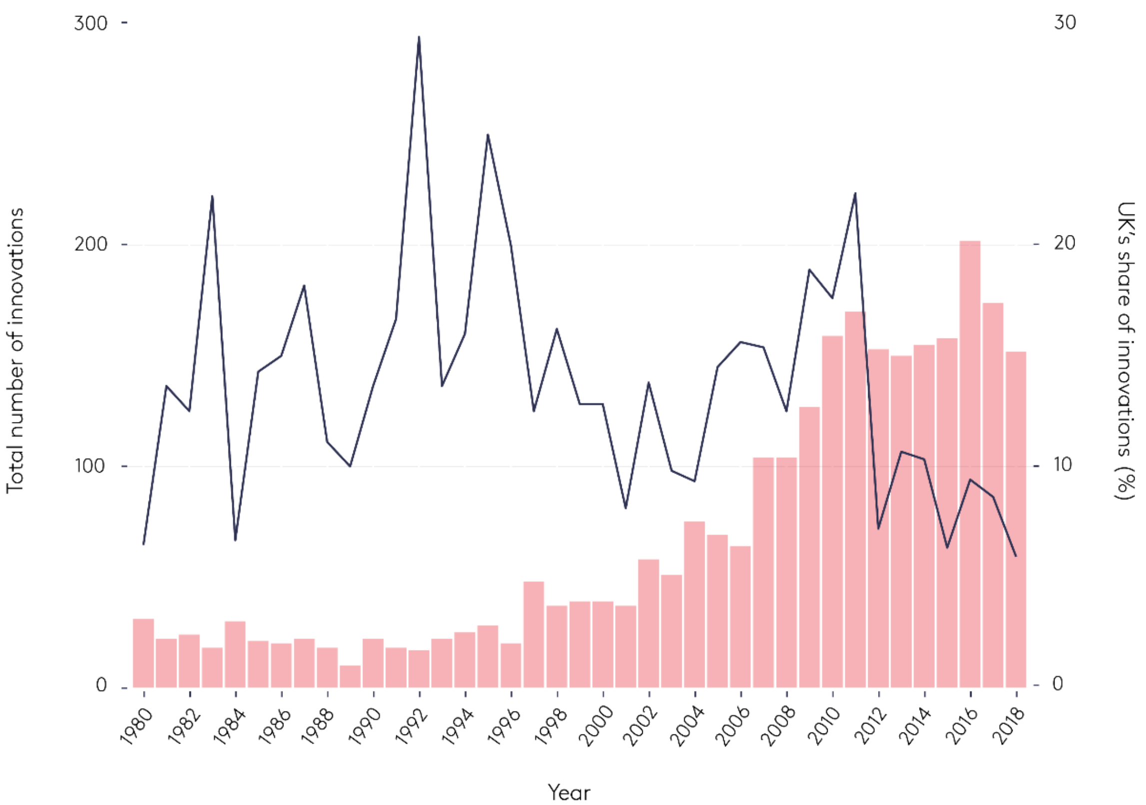
granted (private values of patents for non-stock-listed companies are based on the most similar patents from stock-listed companies). The value of knowledge spillovers created by an innovation is calculated as a proportion of the private value of all innovations that build upon it. Since knowledge spillovers constitute value that is not internalised by the organisation that invests in R&D, they represent an externality that justifies government support for R&D.

We infer the expected cost of the subsidy required to generate an innovation from the observed shape of the private value distribution in a particular technology area. If relatively few low-value innovations are observed, this is a sign that the costs of R&D projects in that area are higher, i.e. innovators will ensure that they can recover those higher costs – on average – by only pursuing the most promising ideas. If average R&D costs in a technology area are high, it will require more government funding to increase innovation.

Evolution of tidal stream energy innovation in the UK and globally

Until the mid-1990s, tidal stream energy remained a small area of innovation on the global scale (see Figure 5.1). Despite significant momentum since then, it remains small compared with much higher patenting activity observed in some other clean technology areas such as low-emissions vehicles, buildings fabric and offshore wind (Curran et al., 2022). The UK's share of annual global patenting in tidal stream has fluctuated over the years and stands at between 5% and 10% in the latest years for which data is available. This is lower than some peaks experienced in the past, including the multiple years before 2000 in which the UK's global share of patenting in tidal stream energy exceeded 20%. However, it should be noted that this was a period when overall patenting in tidal stream was very small, with fewer than 50 patents being processed annually. In this regard, the UK can be considered an early mover in tidal stream energy.

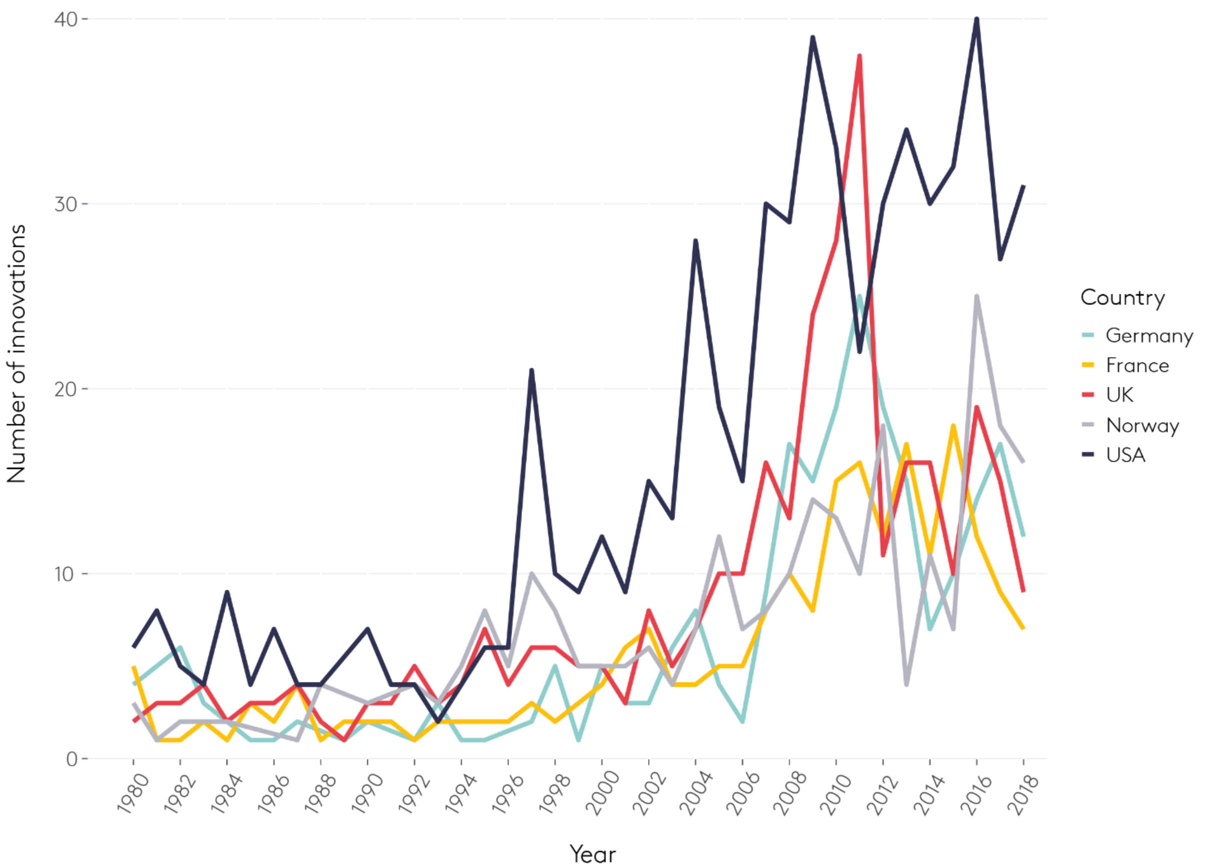
Figure 5.1. Global number of annual innovations in tidal stream energy (left axis; bars) and the UK's share of global annual innovations in tidal stream energy (right axis; line) (1980–2018)



Notes: *The y-axis (left) denotes the total count of global innovations in tidal stream energy over the years (shown in bars). The other y-axis (right) denotes the UK's percentage share of annual global innovations in tidal stream energy over the years (shown with the line).* ***Source:*** *Authors' estimates based on PATSTAT Global 2021 (Autumn edition).*

Building on its early-mover position, the UK has increased its global share in tidal stream patenting even as efforts grew elsewhere in the world during the 2000s. From around 2000 until 2011, the UK's annual patenting in tidal stream increased faster than other top innovators in this area, including France, Germany and Norway. The UK followed a similar trend to that of the US, although lagging a few years behind and remaining at slightly smaller volumes (see Figure 5.2). Tidal stream patenting in the UK then saw a sharp decline after 2011, which is likely explained by the effects of the financial crisis and is observed in patenting for clean technologies more widely (Popp et al., 2022). The UK never fully recovered from this decline in patenting levels for tidal stream, unlike the US which returned to its pre-crisis levels several years later. The UK's annual patenting in tidal stream has continued at similar levels to France, Germany and Norway in the latest years for which data is available, which may be a sign that the UK is starting to lose its competitive edge in this area.

Figure 5.2. Annual number of innovations of the top five innovator countries in tidal stream energy (1980–2018)



Notes: *The y-axis denotes the total count of innovations in tidal stream energy of the five countries over the years.*
Source: *Author's estimates based on PATSTAT Global 2021 (Autumn edition)*

The UK's performance in tidal stream energy innovation compared with other countries

Despite signs of a declining performance on tidal stream innovation in recent years, the UK's total number of patents in this area since 1980 is the second highest globally (see Figure 5.3). The US is by far the leader on this measure, holding almost double the number of patents as the UK over this period. The US does not currently have operational tidal stream facilities[15] but it has some

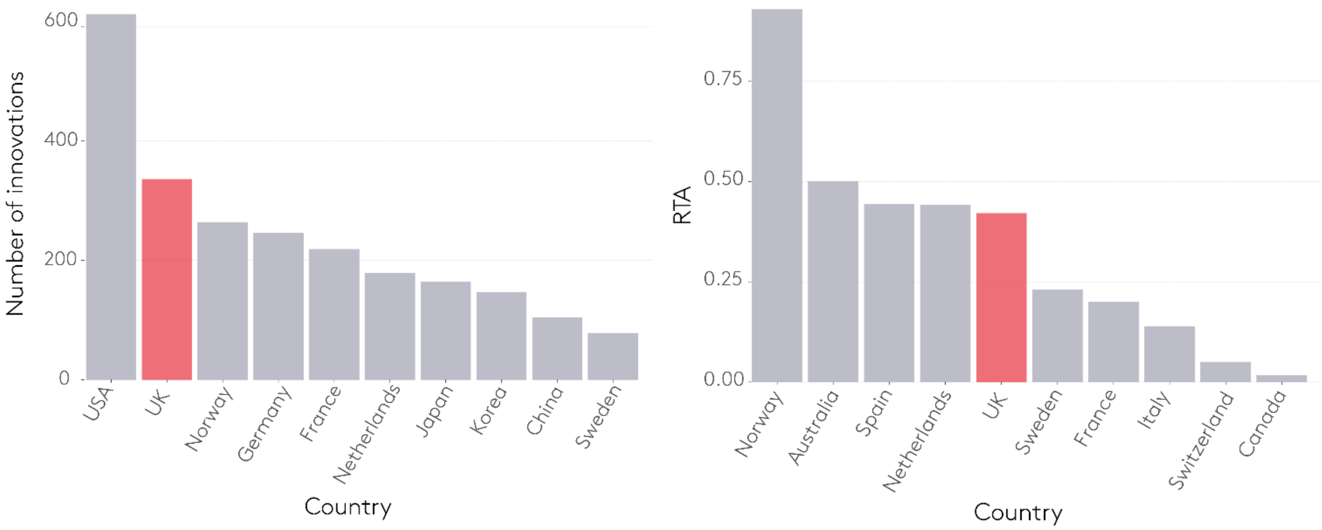
[15] However, the US has a number of operational small-scale demonstration projects for river current energy which involve similar devices to tidal stream energy, although the largest of these, Verdant Power's RITE project with installed capacity of 105 KW, was decommissioned in 2021.

capacity under development, and many tidal stream technology developers. Six of the 10 countries that lead on patenting volume for tidal stream energy – UK, France, the Netherlands, Japan, Korea and China – already have some tidal stream capacity installed.

Looking now at revealed technological advantage (RTA), the UK ranks fifth on innovative specialism in tidal stream energy globally. This ranking is lower than its ranking on absolute patenting volume, which can be explained by the UK patenting strongly in a range of other areas as well. The US, Germany, Japan and China drop out of the top 10 countries on RTA for the same reason. Meanwhile, Australia, Spain, Italy, Switzerland and Canada appear in the top 10 despite not being among the top innovators in terms of volume.

Similarly to patenting volume, leading on RTA in tidal stream energy also appears somewhat linked to the domestic deployment of the technology. The Netherlands, the UK, France and Canada all have some tidal stream capacity already installed and Australia is identified as a tidal resource hotspot. It is not surprising that countries that have been motivated by the prospect of deploying tidal stream technologies in their own waters have built greater innovative specialism in this area than countries without that motivation. However, the remaining five countries in the top 10 on RTA are not identified as having a substantial tidal resource. Despite this, Norway, Spain and Sweden are home to some tidal stream technology developers.

Figure 5.3. Top 10 innovators in tidal stream energy by total number of innovations (left) and by revealed technological advantage (right) (1980–2018)



Notes: Charts only display countries in the OECD, plus China and Hong Kong. The RTA chart on the right includes a further filter to only display countries that have recorded 50 or more innovations between 1980–2018. RTA values are adjusted to lie between -1 and +1. ***Source:*** *Author's estimates based on PATSTAT Global 2021 (Autumn edition).*

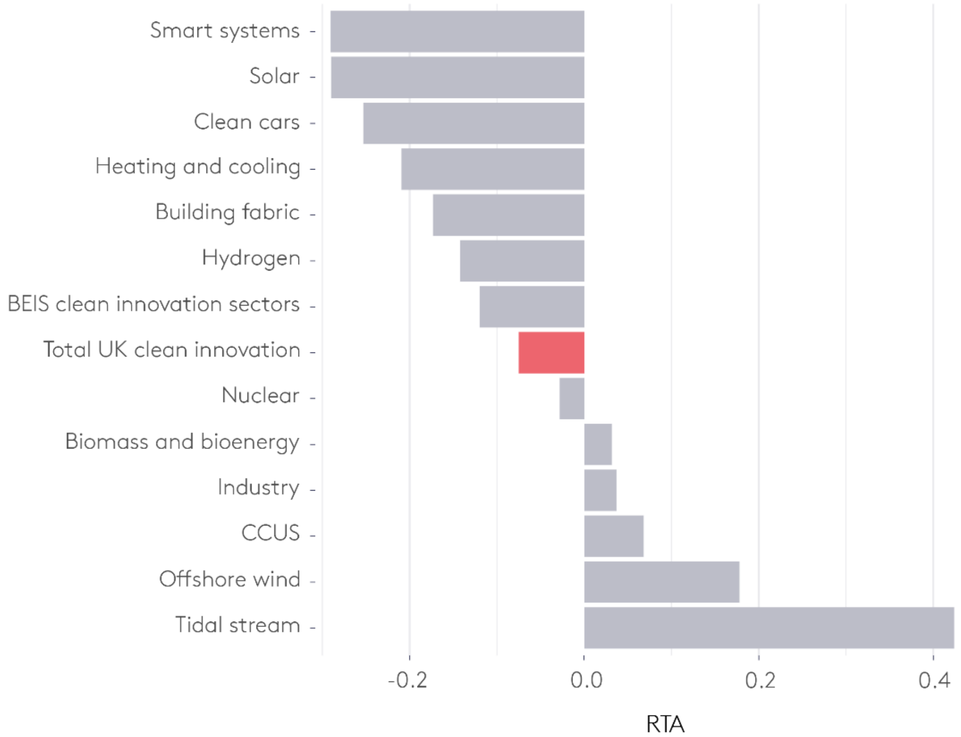
It is clear that plenty of countries that do not necessarily have the natural resource or a significant ambition to deploy tidal stream energy domestically are active innovators of related technologies. Indeed, in recognition of the country's limited potential for tidal energy, a spokesman for the Norway-based Hydra Tidal stated their belief that the best possibilities for Norwegian tidal technology companies like themselves lied in exports including to the UK, rather than in their domestic market (Norway Exports, 2011). The UK is facing competition both from such countries and from those with an explicit ambition to deploy tidal stream energy domestically.

When comparing the top 10 countries on RCA (see Figure 4.2) and RTA (see Figure 5.3),[16] it is apparent that the link between export specialism and innovative specialism is not particularly strong; only Italy and Spain appear in both lists. This may be reflective of the nascent state of the sector. We have already seen that most countries performing highly on export specialism in products relevant for tidal stream energy do not actually have a domestic sector for the technology. Instead, their specialism is likely driven by manufacturing and trading activities relating to other similar technologies like offshore wind. It is also possible that countries with innovative specialism in tidal stream may not have yet translated this into a domestic supply chain of related technologies.

The UK's performance in and estimated returns from tidal stream energy innovation compared with other technologies

Of all the clean technology areas analysed,[17] the UK is most specialised in the innovation of technologies relevant for tidal stream energy (see Figure 5.4). The UK is also a specialised innovator of biomass and bioenergy technologies, industrial decarbonisation, CCUS and offshore wind, but does not demonstrate RTA in clean technologies overall due to its poorer performance in areas like solar energy and low-emissions vehicles ('clean cars').

Figure 5.4. The UK's revealed technological advantage in tidal stream energy and other selected clean technology areas (1980–2018)



Notes: *Patent codes underpinning the clean technology categories on the y-axis are based on Martin and Verhoeven (2022), with the 'clean cars' category added based on Curran et al. (2022). Total UK Clean Innovation refers to all UK innovations under the 'Y02' class from the Cooperative Patent Classification system, which corresponds to technologies or applications for mitigation or adaptation against climate change. RTA values are adjusted to lie between -1 and +1.*
Source: *Author's estimates based on PATSTAT Global 2021 (Autumn edition).*

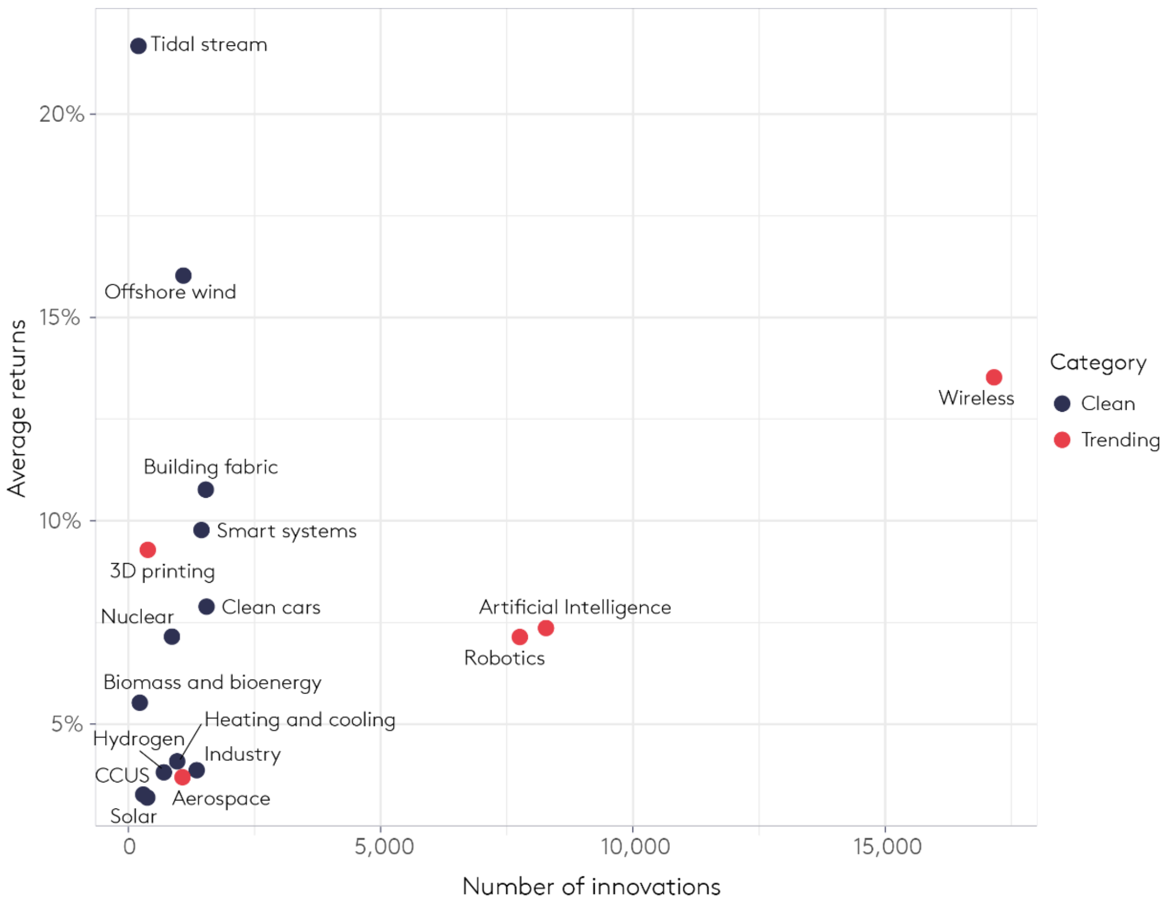
[16] Note that different time periods are used to define the top 10 countries for the two measures, i.e. 2016–2020 for RCA and 1980–2018 for RTA. Since tidal stream energy is a small area of innovation overall, looking at a longer time period since 1980 provides a clearer idea of a country's innovative specialism in this area and prevents the analysis from being skewed by short-term fluctuations in the number of innovations produced. Forexport specialism, on the other hand, it is more relevant to assess a country based on the latest available evidence on its trading activities.

[17] Set of technology areas analysed is based on Martin and Verhoeven (2022) and were selected and designed in collaboration with the (then) Department for Business Energy and Industrial Strategy. See Appendix 2 in Martin and Verhoeven (2022) for further detail.

The UK's specialism in tidal stream innovation can also be explored at the more detailed level of technological classification (see Figure A3, Appendix). Nine of the top 10 technologies in which the UK has RTA relate to foundations and moorings. Examples include: submerged foundations which can be relevant for tidal stream devices fixed on the seabed; and floating structures that could have applications for floating tidal stream devices. The remaining technology in the top 10 relates to controlling the powertrain. Technologies relating to the structure of the generation device or electrical connection aspects do not appear in the UK's top 10 specialisms.

Tidal stream energy demonstrates potential to yield relatively high returns to public investments in innovation in the UK (see Figure 5.5). In fact, it has the highest estimated average returns of the set of technology areas analysed. Looking at the more detailed level of technological classifications within tidal stream, innovations in 'tide or wave power plants' make up the biggest single driver of returns (see Figure A4, Appendix). These specific innovations relate to the main structure of the plant (as opposed to supporting equipment like electrical cables), which is estimated to represent almost half the capital expenditure related to a tidal stream project (Supergen ORE Hub and P&IG, 2021). This suggests that if the UK continues to invest in innovating these technologies, it could drive important cost reductions while accessing strong returns.

Figure 5.5. UK returns to additional public investments in innovation for tidal stream energy and other selected clean and trending technology areas



*Notes: The y-axis indicates the estimated returns (as a percentage) for the UK to an additional £1 R&D subsidy in a given technology area. The x-axis indicates the total number of innovations in a given technology area. Analysis is based on innovations between 2009–2018. Indigo bubbles are clean technology areas and red bubbles are technology areas within the 'trending' category. **Source:** Author's estimates based on PATSTAT Global 2021 (Autumn edition).*

Overall, tidal stream energy represents a relatively nascent area of innovation for the UK. If the UK invests to grow tidal stream to a similar size as some of the more established technology areas like clean cars or offshore wind (currently representing over twice the number of innovations as tidal stream), it could further increase its returns. Interestingly, some trending technologies from the broader economy including wireless, artificial intelligence and robotics represent higher innovation volumes than all the clean technology areas analysed, but are far behind a number of these clean technology areas in terms of average returns.

The UK's level of innovative specialism and returns to investment in innovation vary across the different clean technology areas, and tidal stream energy appears to be a promising area in both respects. However, while this analysis can inform the UK's strategy to capture innovation-led growth opportunities in its transition to net zero, progress will need to be made on deploying all these clean technologies – including those in which it may not be able to establish a specialism in the global market – if the UK is to transform its energy system in line with net zero emissions.

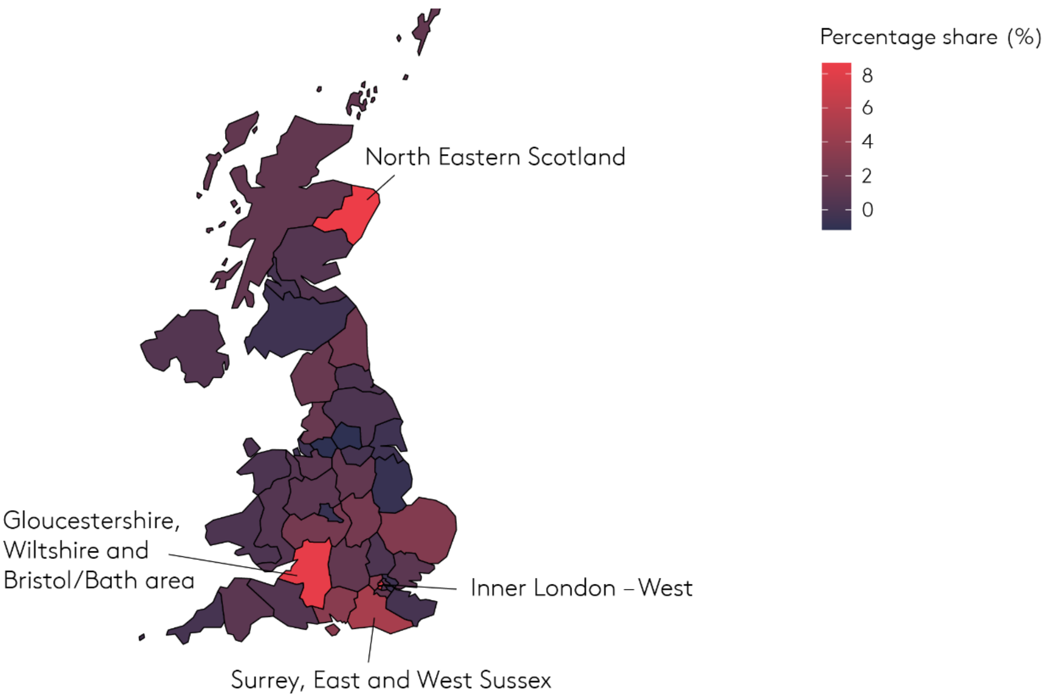
Regional dimensions of tidal stream energy innovation in the UK

The preceding analyses suggest that, at the national level, the UK has comparative strengths in technologies relevant for tidal stream energy and the potential to extract high returns from related innovations relative to other technology areas. However, in the context of generally uneven economic performance across the UK, it is important to understand where technological strengths are located and the extent to which investments to build on such strengths could support economic growth in different regions in the coming years. Of course, as with any technology, the knowledge generated from innovations in tidal stream energy will not automatically translate into local growth and jobs; the extent to which that happens will depend on the timely development of relevant supply chains and the skills base in an area.

Regional share of patenting

Two regions stand out as having a particularly high share of the UK's total patents relevant for tidal stream energy: North Eastern Scotland; and the Gloucestershire, Wiltshire and Bristol/Bath area of South West England (see Figure 5.6 below). The former region is home to the University of Aberdeen and Robert Gordon University, which focus heavily on marine energy research (MEC, 2019), while the latter has fairly close proximity to marine energy research facilities in Wales and has a high share of UK clean patents overall (Curran et al., 2022). Surrey, East and West Sussex, and inner-west London – areas that patent heavily on clean technologies generally – also hold high shares of tidal stream patenting. Inner-west London is home to Imperial College London, which conducts marine energy research (MEC, 2019).

Figure 5.6. Regional share of total UK innovations in tidal stream energy (1980–2018)



Notes: *Percentage share represents the proportion of total UK innovations in tidal stream energy between 1980-2018 held by each NUTS 2 region.* ***Source:*** *Author's estimates based on PATSTAT Global 2021 (Autumn edition).*

Regional patenting intensity

Next we consider how patenting intensity varies around the country, a measure that expresses patenting in tidal stream energy as a share of overall patenting in a given region (see Figure 5.7). If a region holds a very high volume of UK patenting in general, it would be unsurprising if a considerable amount of these patents relate to technologies relevant for tidal stream energy. This appears to be the case for the regions of London and the South East, which do not show high patenting intensity despite holding a large volume of the UK's patents in tidal stream energy.

If tidal stream energy has a higher-than-average share of a region's overall patenting, this could imply that the region has a particular specialism for tidal stream innovation. In that regard, North Eastern Scotland as well as the Highlands and Islands perform very highly on patenting intensity. The latter region consists of Pentland Firth (home to MeyGen which is the world's largest tidal stream project in planning), the European Marine Energy Centre (EMEC) in Orkney (a world-leading test and demonstration centre for tidal stream and wave devices), and the world's first tidal stream array, installed by Nova Innovation off the Shetland Islands (P&IG, 2023). Central and Southern parts of Scotland also demonstrate patenting intensities above the UK average. With various sites specialising in tidal stream energy research and demonstration, Scotland as a whole demonstrates leadership in tidal stream innovation in the UK. However, even in regions with some of the highest patenting intensities, tidal stream energy represents only about 0.6% of all regional patenting. Tidal stream energy therefore remains a niche area of innovation with strong growth potential.

Other regions with high patenting intensity for tidal stream energy include Northern Ireland, Cumbria, Devon, and Cornwall and the Isles of Scilly. These are currently among the relatively less productive regions of the UK overall, therefore capitalising on their innovative specialisms in the emerging tidal stream energy industry could generate local benefits and contribute to regionally-balanced growth (Curran et al., 2022).

Figure 5.7. Tidal stream energy innovations as a share of total region innovations (1980–2018)

*Notes: Percentage share represents tidal stream energy innovations as a share of total innovations within NUTS 2 regions between 1980–2018, and is used as a measure of patenting intensity in tidal stream energy at the regional level. **Source:** Author's estimates based on PATSTAT Global 2021 (Autumn edition).*

Regional spillover effects

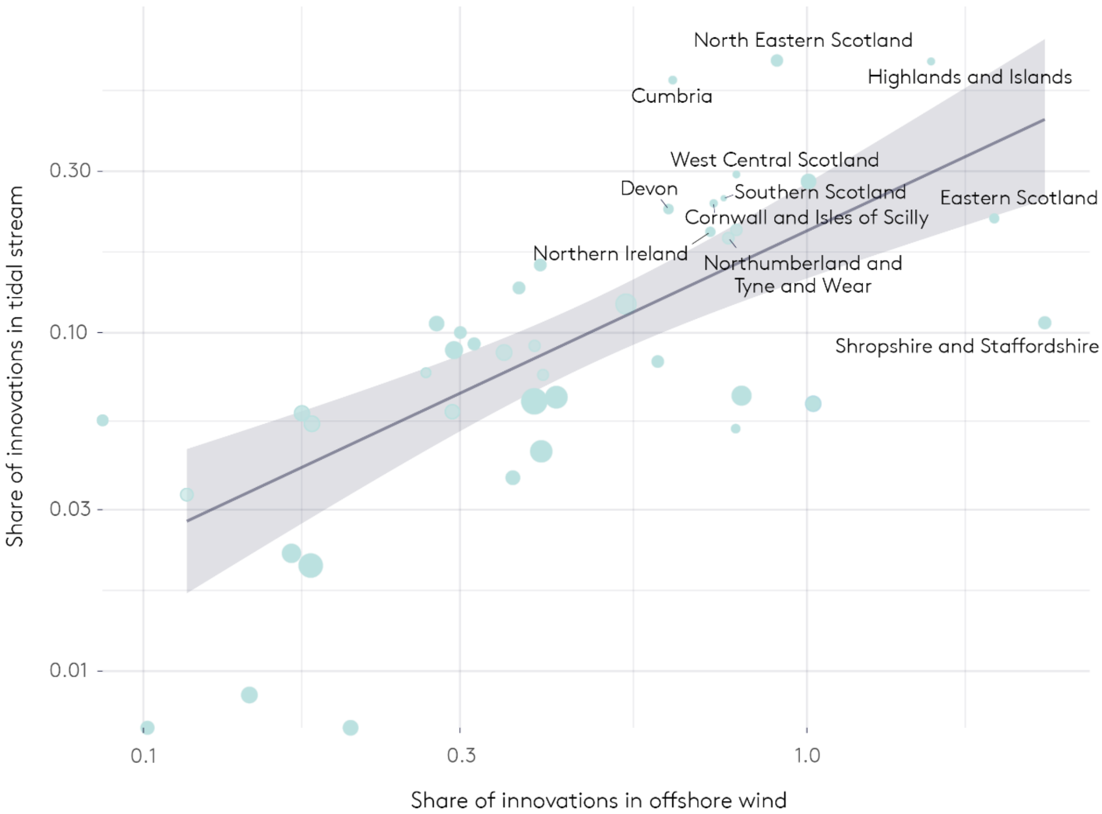
We next turn to the regional patterns in returns to investments in tidal stream innovation. This draws on work that uses the IStraX methodology to divide the UK into two broad regions: the 'golden triangle' (consisting of London, Oxford and Cambridge and which historically holds a disproportionate share of the UK's R&D activity overall); and the rest of the country (Curran et al., 2022). Investments in tidal stream innovation made in the rest of the country (excluding the golden triangle) were seen to generate particularly high returns in the same regions that received investment, with little spillover (see Curran et al., 2022). This suggests that policies to stimulate tidal stream innovation in less innovation-intensive regions in the UK are likely to generate returns that will actually be retained in these regions in support of addressing economic disparities.

On the other hand, investments in tidal stream innovation within the golden triangle do not appear to generate particularly high returns in these regions themselves (see Curran et al., 2022). But tidal stream investment does stand out in terms of spillovers to the rest of the country: returns for other regions from investments in tidal stream innovation in the golden triangle are around 20 times the returns from those investments for the golden triangle itself. This is the highest level seen out of all the technology areas analysed. By exploring the potential local benefits and broader spillover effects across technology types, this analysis finds that investments in innovation in tidal stream energy both within and outside the golden triangle can play an important role in enhancing economic growth across the UK.

Regional innovation across sectors

Finally, we compare regional patterns of innovations in tidal stream energy and offshore wind and oil and gas extraction: two areas that hold strong potential for knowledge and skills transfer for the tidal stream sector. We find a positive correlation between high-innovation locations in tidal stream energy and offshore wind, with Eastern Scotland and the Highlands and Islands standing out as having a particularly high volume of patenting in both (see Figure 5.8).

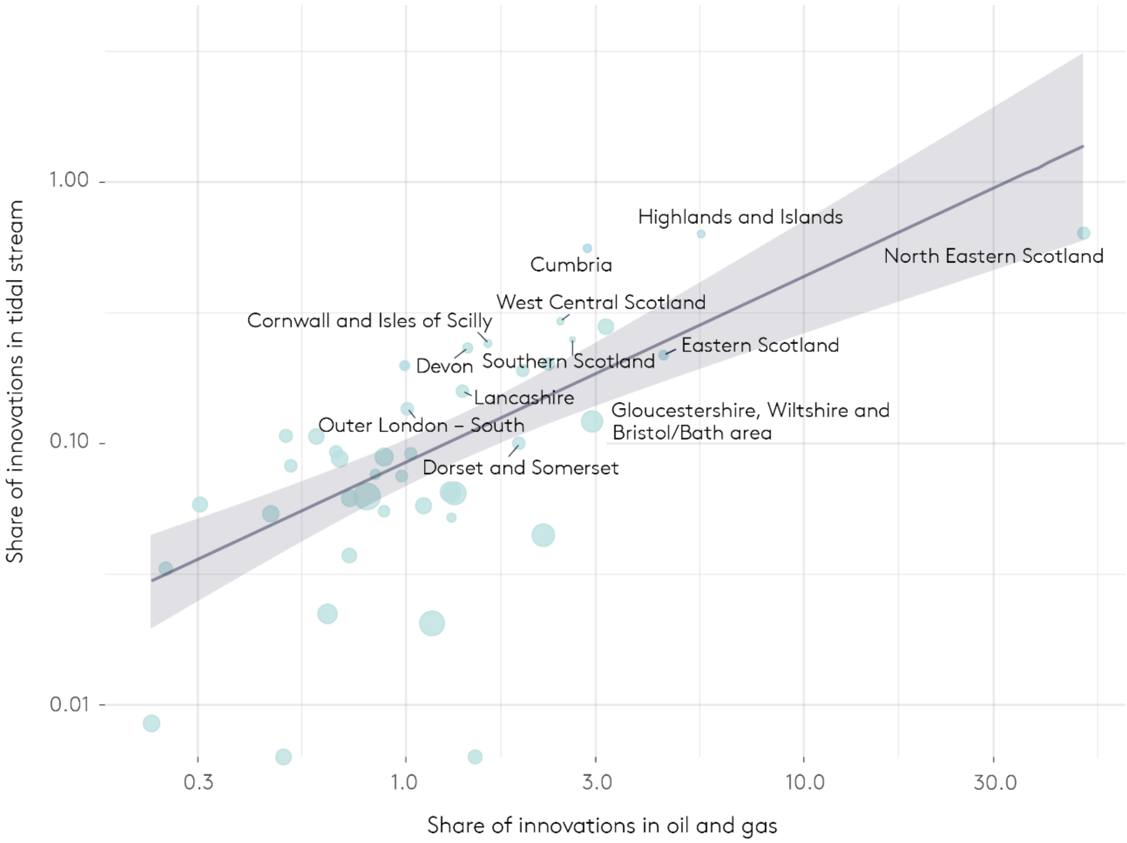
Figure 5.8. Innovations in tidal stream energy versus innovations in offshore wind by UK regions (1980–2018)



Notes: The chart plots the log transformed share of tidal stream energy innovations to all innovations against the log transformed share of offshore wind innovations to all innovations, at the NUTS 2 regional level.

Tidal stream innovation also has a positive correlation with areas that have traditionally patented intensively in oil and gas extraction technologies. For example, North Eastern Scotland stands out with its strong patenting in both (see Figure 5.9 below). Additionally, Serin et al. (2021) found a positive correlation in areas patenting in CCUS and oil and gas extraction.

Figure 5.9. Innovations in tidal stream energy versus innovations in oil and gas by UK regions (1980–2018)



Notes: The chart plots the log transformed share of tidal stream energy innovations to all innovations against the log transformed share of innovations in oil and gas extraction to all innovations, at the NUTS 2 regional level.

Discussion

The UK is a highly specialised innovator in tidal stream energy globally and its specialism in tidal stream energy exceeds its specialism in all the other clean technology areas analysed. The UK could build on its existing specialism by investing further in innovations to drive down the cost of existing tidal stream technologies. This would position the UK to deploy tidal stream technologies cost-effectively and at scale in its own waters. Public investments in tidal stream innovation have also been shown to deliver higher estimated returns than other clean technologies analysed, creating a strong case for continued public support for these innovations, including to encourage the development of even newer tidal stream generation concepts. While the CfD mechanism can continue to be utilised as a route to market for relatively established tidal stream technologies, direct support for innovation via technology-push mechanisms (e.g. R&D grants) will be important to support the development and commercialisation of new technologies.

We have found that the UK already has export specialism in several complex products including turbines which are relevant for tidal stream energy, and productive capabilities proximate to some other complex products in which it could develop specialism in the future. By positioning itself at the forefront of technological development through continued investment in innovation, the UK would maximise its chances to unlock opportunities to export such technologically complex and high-value products alongside its knowledge, engineering expertise and services relating to tidal stream energy development, when the global market picks up. The installation of tidal arrays has been found to require technical skills that are closely linked to the technology being deployed, signalling the opportunity for the UK to export installation-related services, along with UK-developed tidal stream devices themselves (Vivid Economics, 2019e).

There is further evidence that tidal stream energy has the potential to support regionally-balanced growth, with related innovative activity spread across various UK regions and investments in related innovations seen to deliver strong regional spillovers. There is also scope for capability transfer from oil and gas, offshore wind and CCUS to tidal stream energy at the regional level. Indeed, offshore wind, CCUS and tidal stream are the three areas of all the clean technology areas analysed in which the UK has the highest innovative specialism. There is good reason to believe that pursuing the development of all three of these technologies under a holistic strategy for the offshore economy – as opposed to pursuing any one sector alone – could enable effective skills transfer, support a just transition for declining industries in coastal areas, unlock mutually reinforcing opportunities and yield greater economic benefits.

6. Conclusion and recommendations

The assessment in this report of the potential of tidal stream energy to support sustainable growth in the UK has concluded that this form of energy can serve as an effective complement to wider efforts on both net zero and energy security. Developing the UK's tidal stream energy sector can also support regionally-balanced growth across the country.

We argue that the UK should pursue tidal stream energy underpinned by a strong domestic supply chain to maximise sustainable growth opportunities from this emerging technology. This would require rapidly developing the UK supply chain's capacity to deliver domestic projects cost-effectively and at scale, while continuing to invest in technological innovations to drive further cost reductions. This would be a low-regrets approach for the UK, regardless of how the global market and supply chains elsewhere for tidal stream energy may pan out. While the global market for tidal stream energy remains small, the UK would have built capacity to quickly expand a domestic source of low-carbon energy supply, with significant benefits for the energy system and strong potential to support growth across its regions. In a future where the global market picks up, the UK, having positioned itself at the forefront of technological development, would readily be able to export some complex products in which it has specialism alongside its knowledge and services underpinned by its innovative strengths abroad. This approach would also mean the UK retains and strengthens a holistic supply chain for tidal stream energy, revealing further areas in which it might be able to develop international competitiveness, which could be scaled up if meaningful demand emerges from the global market. Given the patterns in its current productive specialisms and innovative strengths, the UK is especially well-positioned to create export opportunities from some specific high-value products such as turbines relevant for tidal stream energy.

In light of a domestic market constrained by the size of the natural resource that can be practicably exploited, an export opportunity set to remain limited in the short term and competitive pressures presented by other countries, there is limited imperative for the private sector to invest in growing the UK supply chain for tidal stream energy without explicit support from policy. Such support could come first and foremost in the form of an overarching ambition for the tidal stream energy sector set by the Government, specifying a capacity target and timeline to inform private sector investment. As with any technology, specific mechanisms underpinning that ambition would be most effective if tailored to support tidal stream technologies at different levels of development through to commercialisation. The CfD mechanism could support the deployment of relatively established tidal stream technologies at scale in UK waters, unlocking cost reductions from economies of scale and volume, technological refinements and savings on the cost of capital. However, especially in light of the relatively high returns to investment that tidal stream innovations have generated to date, economic opportunities for the UK could also lie in developing newer concepts for generating tidal stream energy. Further work could explore which types of mechanisms would most effectively carry such early-stage tidal stream technologies to commercialisation.

Recommendations for policymakers

- **An explicit statement of government ambition in tidal stream energy would help to drive private sector investment into the domestic supply chain and the delivery of the technology at scale in UK waters.** This stated ambition could be in the form of a domestic deployment target in gigawatt terms, as already advocated by industry.
- **The Contracts for Difference (CfD) scheme can continue to be utilised to scale up relatively established tidal stream technologies in the UK.** A continued ringfencing approach for tidal stream energy, with greater clarity over budgeting given multiple years in advance for each successive allocation round, can accelerate deployment and catalyse drivers of cost reduction for the technology, as previously seen in offshore wind.

- **Government can maximise sustainable growth opportunities from tidal stream energy by coordinating policy across deployment and supply chain development**. In particular, proactive coordination across the Department for Energy Security and Net Zero, the Department for Business and Trade and the Department for Science, Innovation and Technology is needed on this agenda, which could be complemented by introducing non-price factors in the CfD assessment criteria in a way that rewards supply chain development – although this cannot substitute for price-based support.
- **Government should consult with industry to explore which mechanisms can most effectively carry early-stage tidal stream concepts to commercialisation,** building on the UK's innovative strengths in tidal stream technology to create economic benefits.
- **A holistic strategy for the offshore economy that includes tidal stream alongside CCUS and offshore wind is likely to yield greater economic benefits than pursuing any single area alone**. The UK demonstrates complementary specialisms for these three technologies at both a national and regional level.

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Appendix

1. Potential economic benefits from tidal stream energy in the UK

Table A1. Review of existing studies

Title	Publishing organisation	Scope	Key finding	Key assumptions
Cost reduction pathway of tidal stream energy in the UK and France (October 2022)	Offshore Renewable Energy (ORE) Catapult	Jobs quantified at national level from the domestic deployment of 20 MW tidal stream energy farm	46 FTE-year per MW (direct and indirect) created	Calculated by scaling up the estimated GVA (at £10.6m) and FTE/year jobs created (at 49 direct and 45 indirect FTE/years) from the Orbital O2 device manufacture, assembly and deployment in 2021, assuming a 13% learning rate in the cost of subsequent units.
What is the value of innovative offshore renewable energy deployment to the UK economy? (September 2021)	Supergen Offshore Renewable Energy Hub, and the Policy and Innovation Group at the University of Edinburgh	Economic benefits quantified at national level from the domestic and export markets for tidal stream energy (impacts of wave energy and floating offshore wind separately quantified)	Cumulative GVA by 2050 between £5bn (under a 'low ambition' scenario, of which £2.45bn is from the domestic market) and £17bn (under a High Ambition scenario, of which £4.46bn is from the domestic market)	Deployment assumptions at the UK level are based on Energy Systems Catapult's ESME (6 GW of tidal stream by 2050) and at the global level are based on International Energy Agency TIMES modelling (71 GW of tidal stream by 2050). For deployment costs, it is assumed that cost targets from the EU Strategic Energy Technology Plans for ocean technologies are met. Results are presented across two levels of local content ambition: a 'Low Ambition' scenario assuming 5% retention of UK content in the domestic and international supply chains for tidal stream and a 'High Ambition' scenario assuming 25% retention of UK content in domestic and international supply chains.
Energy Innovation Needs Assessment sub-theme report: tidal stream (October 2019)	Led by Vivid Economics (commissioned by the former Department for Business, Energy and Industrial Strategy)	Economic benefits quantified at national level from only the export market for tidal stream energy (domestic business opportunities were not sized)	£540m annual GVA and nearly 5,000 direct jobs supported p.a. by 2050. Additionally, annual GVA by 2030 is estimated at £35m	UK deployment and technology cost assumptions are based on ESME modelling. This suggests 16 GW of UK deployment by 2050 under a high innovation scenario and around 40% capital cost reductions from innovation between 2020–2050. Global deployment assumptions are based on International Energy Agency forecasts suggesting around 50 GW of the 150 GW of global ocean energy deployment by 2050 will be in tidal stream technologies.
Wave and Tidal Energy: The Potential Economic Value (April 2019)	Policy and Innovation Group at the University of Edinburgh and Energy Systems Catapult, supported by Wave Energy Scotland	Economic benefits quantified at national level from the domestic and export markets for tidal stream energy (wave energy	£41.5bn net GVA (almost half coming from export markets) and a 7:1 ratio of benefit to industry support (CfD-	Assumes a hypothetical scenario that represents if the UK "gets everything right". Under this scenario, tidal (and wave) generation reach cost parity with other sources of generation by 2030, resulting in an LCOE of £90/MWh. UK content assumed at 80% in domestic projects and at 15% in 2030 (reducing to 5% by 2050) in

		impacts separately quantified)	type) between 2030–2050.	global projects. For wave and tidal stream combined, 37.7 GW UK deployment and 337 GW global deployment by 2050 is assumed.
Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit (May 2018)	ORE Catapult	Economic benefits quantified at national level from the domestic and export markets for tidal stream energy (wave energy impacts separately quantified)	Net cumulative benefit by 2030 of £1.4bn (or £95m per year on average) – consisting of £1.6bn GVA from the domestic market and £1.1bn GVA from exports, offset by £1.3bn of CfD-type revenue support Almost 4,000 direct jobs supported by 2030 and 14,500 by 2040	Assuming 100 MW UK deployment per year from 2021/22, up to 3 GW deployment per year in the rest of the world (with UK capturing a realistic share of the growing global market) and a cost reduction trajectory that sees a LCOE of £150/MWh by 100 MW installed, £130/MWh by 200 MW installed and £90/MWh by 1 GW installed.
The Economic Impact of the Development of Marine Energy in Wales (July 2013)	Regeneris Consulting and the Welsh Economy Research Unit at Cardiff Business School (commissioned by the Welsh Government)	Economic benefits quantified for Wales from the development and construction of tidal stream energy in Wales (wave energy impacts separately quantified)	£38m GVA and 1,060 FTE/year from 30 MW tidal deployment (Scenario 1); £241m GVA and 6,740 FTE/year from 240 MW tidal deployment (Scenario 2); £611m GVA and 17,150 FTE/year from 1 GW (Scenario 3)	Three marine energy deployment scenarios are considered: 1) 60 MW (consisting of 30 MW wave and 30 MW tidal stream); 2) 300 MW (consisting of 60 MW wave and 240 MW tidal stream); 3) 1 GW (consisting of 250 MW wave and 750 MW tidal stream). For each scenario, impacts arising from direct employment and expenditure, indirect expenditure via supply chains sourced within Wales as well as induced expenditure by employees supported through direct and indirect effects are considered. Spending assumptions based on estimates of actual installations at the time. Impact from exports is outside of the scope.

2. List of product codes used in the analysis of trade data

Section 4 sets out our analysis of global trade data to shed light on the UK's relative performance in exports relating to the tidal stream energy sector. This analysis is based on a set of 23 traded product codes (defined at the 6-digit level in the Harmonised System [HS]) that we identify as being relevant for tidal stream energy. The HS is a multipurpose international nomenclature developed by the World Customs Organization for the classification of products, commonly used by participating countries for customs purposes. It comprises more than 5,000 product descriptions identified by a six-digit code. The codes are organised in a hierarchical way where the first two digits of a six-digit code identify the chapter the product type is classified in, the middle two digits identify the grouping within that chapter, and the last two digits provide a more specific description of the type of product.

The Energy Innovation Needs Assessments (EINAs) are a series of reports commissioned by BEIS and conducted by a consortium of organisations led by Vivid Economics to provide evidence and analysis on the role of different technologies, one of which being tidal stream energy, in the UK's future energy system. EINAs include analysis of trade data underpinned by a selected set of HS codes for each technology provided in the footnotes of the sub-theme report of the respective technology. We draw the list of products we define as being relevant for tidal stream energy for the purposes of this report by taking all of the codes used in the EINA sub-theme report on tidal stream (Vivid Economics, 2019e), and combining them with certain codes found in the EINA sub-theme report on offshore wind (Vivid Economics, 2019c) in recognition of certain similarities in the physical layout of the two technologies and to achieve a more comprehensive list overall. We also include a code in our list which corresponds to floating structures in order to cover tidal stream generator designs consisting of floating foundations. Our proposed additions to the original list in the EINA tidal stream sub-theme report have been reviewed and finalised with expert consultation. It is important to note that the resulting list is one of product codes that are relevant for, but not exclusive to, tidal stream energy as the HS codes do not come at the level of granularity that would have made that possible. For example, a six-digit code that we define as relevant for tidal stream energy is 841011 which corresponds to 'turbines; hydraulic turbines and water wheels, of a power not exceeding 1000kW'; which could describe a turbine used not only in tidal stream energy generation but also in a conventional hydroelectric power plant.

We work with the 1992 version of the HS and convert codes drawn from any external sources based on future revisions of the HS into their 1992 equivalents before starting our analysis. We do this based on the Conversion and Correlation Tables provided by the World Customs Organization. The EINA reports do not specify which revision of the HS the selected codes originate from, but we assume it is HS 2017 based on our previous observation in Serin et al. (2021) that some codes used in the CCUS sub-theme report only exist beyond the 2007 revision of the HS and as it would be expectable for the latest available revision of the HS to have been used in the EINA reports at the time they were conducted (as they were published in 2019). Only a few product codes are affected by the conversion and these are detailed in the following footnotes; all other codes remain unchanged as a result of the conversion. We take an exhaustive approach for the conversion between revisions whereby if a code in the future revision corresponds to multiple codes in HS 1992 (i.e. 1:n correlation), we include any additional corresponding code(s) as well.

Below is the list of product codes we define as relevant for tidal stream energy where the codes drawn from the EINA tidal stream sub-theme report are indicated in indigo, those drawn from the EINA offshore wind sub-theme report indicated in red and the authors' addition of the code relating to floating structures indicated in blue. The list is broken into four component categories: 1) Structure and Prime Mover; 2) Power Take Off and Control; 3) Foundations and Moorings; and 4) Connection, in order to roughly match the component categories under which our patent codes are given in the source report we draw them from (Martin and Verhoeven, 2022; further detail is provided in the next section of the Appendix). This list of product codes relevant for tidal stream energy underpins our analyses in Section 4 where the codes feature individually in certain charts and as an aggregate category in the others.

Tidal stream energy

Structure and prime mover

- **841011:** Turbines; hydraulic turbines and water wheels, of a power not exceeding 1000kW
- **841012:** Turbines; hydraulic turbines and water wheels, of a power exceeding 1000kW but not exceeding 10000kW
- **841013:** Turbines; hydraulic turbines and water wheels, of a power exceeding 10000kW
- 850300: Parts suitable for use solely or principally with the machines of heading 8501 or 8502 *(covers components like stators, rotors, rotor housing)*
- 848210[18]: Ball bearings
- 848220: Bearings; tapered roller bearings, including cone and tapered roller assemblies
- 848230: Bearings; spherical roller bearings
- 848240: Bearings; needle roller bearings
- 848250: Bearings; cylindrical roller bearings n.e.s. in heading no. 8482
- 848280: Bearings; n.e.s. in heading no. 8482, including combined ball/roller
- 848291: Bearings; parts, balls, needles and rollers
- 848299: Bearings; parts, (other than balls, needles and rollers)

Power take-off and control

- **841090:** Turbines; parts of hydraulic turbines and water wheels, including regulators
- **850230[19]:** Electric generating sets (excl. wind-powered and powered by spark-ignition internal combustion piston engine)
- 848340: Gears and gearing; ball or roller screws; gear boxes and other speed changers, including torque converters
- 841280: Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof; Other engines and motors; Other[20]
- 841290: Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof; Other engines and motors; Parts[21]

Foundations and moorings

- **252390:** Cement; hydraulic kinds n.e.s. in heading no. 2523
- 890790: Other floating structures (for example, rafts, tanks, coffer-dams, landing stages, buoys and beacons); Other

Connection

- **854460:** Insulated electric conductors; for a voltage exceeding 1000 volts

[18] This code is originally provided at the 4-digit level in the EINA sub-theme report on offshore wind. We have included all 6-digit codes that fall under 8482 in our list; this explains the inclusion of the following seven codes in our list as well.

[19] Originally 850231 in the EINA offshore wind sub-theme report, converted to its HS 1992 equivalent given here.

[20] While this exists under the same category as 'nuclear reactors' at the highest hierarchical level in the coding system, its relevance for tidal stream energy lies in the description 'other engines and motors' at the lower hierarchical level and is unrelated to nuclear reactors.

[21] As above, while this exists under the same category as 'nuclear reactors' at the highest hierarchical level in the coding system, its relevance for tidal stream energy lies in the description 'parts of other engines and motors' at the lower hierarchical level and is unrelated to nuclear reactors.

- **850423:** Electrical transformers; liquid dielectric, having a power handling capacity exceeding 10,000kVA
- **850434:** Transformers; n.e.s. in item no. 8504.2, having a power handling capacity exceeding 500kVA
- **853720:** Boards, panels, consoles, desks, cabinets and other bases ... for electric control or the distribution of electricity

HS codes used in Section 4 for comparative analyses with other sectors are also set out below:

CCUS

281121, 381400, 730410, 730410[22], 730511, 730512, 731100, 841480, 841490, 842139, 842199, 890520, 901580, 902610, 902620, 902690, 850880[23], 850890[24] (based on Vivid Economics, 2019a).

Nuclear

840110, 840120, 840130, 840140, 284420, 284510, 284590 (based on Vivid Economics, 2019b).

Offshore wind

730820, 730890, 841280, 841290, 848210, 848220, 848230, 848240, 848250, 848280, 848291, 848299, 848340, 850230[25], 850300, 853720, 854460, 850423[26], 850434[27] (based on Vivid Economics, 2019c).

Renewable energy

220710, 290511, 392510, 700991, 700992, 730820, 730890, 732113, 732183, 761090, 761100, 830630, 840619, 840690, 841011, 841012, 841013, 841090, 841181, 841182, 841199, 841280, 841290, 841581, 841861, 841869, 841911, 841919, 841950, 841989, 841990, 847989, 848340, 848360, 850161, 850162, 850163, 850164, 850230, 850300, 850421, 850422, 850423, 850431, 850432, 850433, 850434, 850440, 850490, 850619, 850720, 853710, 853720, 854140, 870290, 870390, 890790, 900190, 900290, 901380, 901390, 903289 (based on the Green Transition Navigator; Andres and Mealy, 2023).

22 Originally 730411 and 730419 in the EINA CCUS sub-theme report, converted to their HS 1992 equivalent given here. The given code covers both codes from the EINA as there is a n:1 correlation between HS 2017 and HS 1992 for the two codes concerned.

23 Originally 841480 in the EINA CCUS sub-theme report, converted to its HS 1992 equivalent given here (note the 1:n correlation, with the original code also staying in the list).

24 Originally 841490 in the EINA CCUS sub-theme report, converted to its HS 1992 equivalent given here (note the 1:n correlation, with the original code also staying in the list).

25 Originally 850231 in the EINA offshore wind sub-theme report, converted to its HS 1992 equivalent given here.

26 Originally provided as 850400 in the EINA offshore wind sub-theme report which could not be located in the database. This code was therefore assumed to be referring to 850423 based on similar analysis in the EINA tidal stream sub-theme report.

27 Above assumption also applies here.

3. List of patent classifications used in the analysis of patents data

Section 5 sets out our analysis of global patents data to shed light on the UK's relative performance in innovations relating to tidal stream energy technologies. Our patents data come from the 2021 Autumn edition of the Worldwide Patent Statistical Database (PATSTAT Global) published by the European Patent Office (EPO). There are several limitations associated with PATSTAT which we describe in detail in Annex 1 in Curran et al. (2022), along with a discussion of certain measures we take to mitigate them where possible.

PATSTAT classifies patents into technological groupings according to the Cooperative Patent Classification system (CPC). The CPC system is a result of a joint effort between the United States Patent and Trademark Office (USPTO) and the EPO. Its objective is to harmonise the European Classification system (ECLA) and the United States Patent Classification (USPC) while being compliant with the International Patent Classification system (IPC). The CPC system follows a hierarchical structure and is divided into nine sections (human necessities, textiles, physics, electricity, etc.), which in turn are divided into classes, sub-classes, groups and sub-groups (in that order). A patent can be assigned to more than one classification under the CPC system if the innovation is pertinent in more than one technological context. The lower the hierarchical level in the classification system (where sub-groups make up the lowest level), the more detailed the technological description attached to the classification is; this enables a granular understanding of the potential applications of a given patent classified according to the CPC system.

Provided below is the list of patent classifications (containing a mix of sub-classes, groups and sub-groups) we define as being relevant for tidal stream energy based on the 'Knowledge spillovers from clean and emerging technologies in the UK' report (Martin and Verhoeven, 2022). We have taken the list of patent classifications under 'tidal stream' from the source report almost as is for the purposes of the current report, with the exception of the following amendments: Y02E10/20 class has been replaced with Y02E10/28; and classifications of Y02E10/30, F03B3/02, F03B3/10 and H01B7/12 have been removed. These amendments have been decided upon expert consultation to keep the list in the current report as specific as possible to tidal stream energy, in recognition of the removed classes demonstrating greater relevance for other types of hydro energy such as tidal range, wave and salinity gradient.

The list is broken into four component categories as found in Martin and Verhoeven (2022): 1) Structure & Prime Mover, 2) Power Take Off & Control, 3) Foundations & Moorings and 4) Connection. The majority of our analyses in Section 5 use this list of patent classifications as an aggregate category to describe innovations in tidal stream energy as a whole. We also have supplementary analyses in Figures A3 and A4 disaggregating the overall category into specific classifications at the lower levels of the classification hierarchy.

<u>Tidal stream energy</u>

Structure and prime mover

- **Y02E10/28:** Tidal stream or damless hydropower, e.g. sea flood and ebb, river, stream
- **F03B3/00:** Machines or engines of reaction type; Parts or details peculiar thereto (breaks into the below classifications, some of which contain further classifications within them)
    - F03B3/04: with substantially axial flow throughout rotors, e.g. propeller turbines (rotors per se F03B3/126)
    - F03B3/08: with pressure-velocity transformation exclusively in rotors
    - F03B3/12: Blades; Blade-carrying rotors
    - F03B3/16: Stators

Power take-off and control

- **F03B15/00:** Controlling (controlling in general **G05** ; regulation of plants characterised by the use of siphons **F03B13/086**) (breaks into the below classifications, some of which contain further classifications within them)
    - F03B15/005: Starting, also of pump-turbines
    - F03B15/02: by varying liquid flow
- **E02B9/08:** Layout, construction or equipment, methods of, or apparatus for, making tide or wave power plants (water-pressure machines, tide or wave motors F03B)

Foundations and moorings

- **B63B2035/4466:** Floating structures carrying electric power plants for converting water energy into electric energy, e.g. from tidal flows, waves or currents
- **E02D27/52:** Submerged foundations, i.e. submerged in open water
- **B63B21/00:** Tying-up; Shifting, towing, or pushing equipment; Anchoring (breaks into the below classifications, some of which contain further classifications within them)
    - B63B2021/001: Mooring bars, yokes, or the like, e.g. comprising articulations on both ends
    - B63B2021/003: Mooring or anchoring equipment, not otherwise provided for
    - B63B21/02: Magnetic mooring equipment
    - B63B21/04: Fastening or guiding equipment for chains, ropes, hawsers, or the like (means for fastening cables or ropes in general F16G11/00)
    - B63B21/16: using winches (winches per se B66D)
    - B63B21/18: Stoppers for anchor chains (anchor capstans B66D1/72)
    - B63B21/20: Adaptations of chains, ropes, hawsers, or the like, or of parts thereof
    - B63B21/22: Handling or lashing of anchors
    - B63B21/24: Anchors
    - B63B21/50: Anchoring arrangements or methods for special vessels, e.g. for floating drilling platforms or dredgers
    - B63B21/54: Boat-hooks or the like, e.g. hooks detachably mounted to a pole
    - B63B21/56: Towing or pushing equipment (tugs B63B35/66; towing arrangements for water sports use B63B34/60)

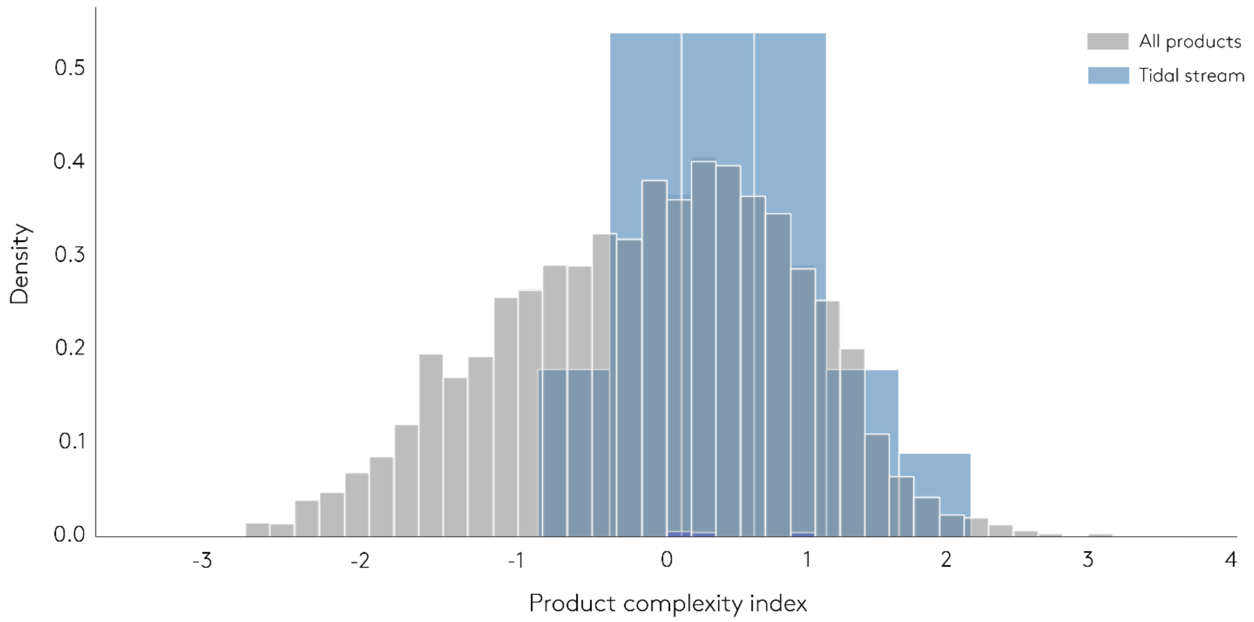
Connection

- **H01B7/045:** Flexible cables, conductors, or cords, attached to marine objects, e.g. buoys, diving equipment, aquatic probes, marine towline

Patent classifications underpinning other clean and emerging technology areas used in comparative analyses in Section 5 are also drawn from Martin and Verhoeven (2022) and were defined in collaboration with BEIS, with the authors' addition of the 'clean cars' category based on Curran et al. (2022). The oil and gas extraction technologies category used in Figure 5.9 is based on the subclass E21B in the CPC system which corresponds to 'Earth drilling, e.g. deep drilling; obtaining oil, gas, water, soluble or meltable materials or a slurry of minerals from wells'.

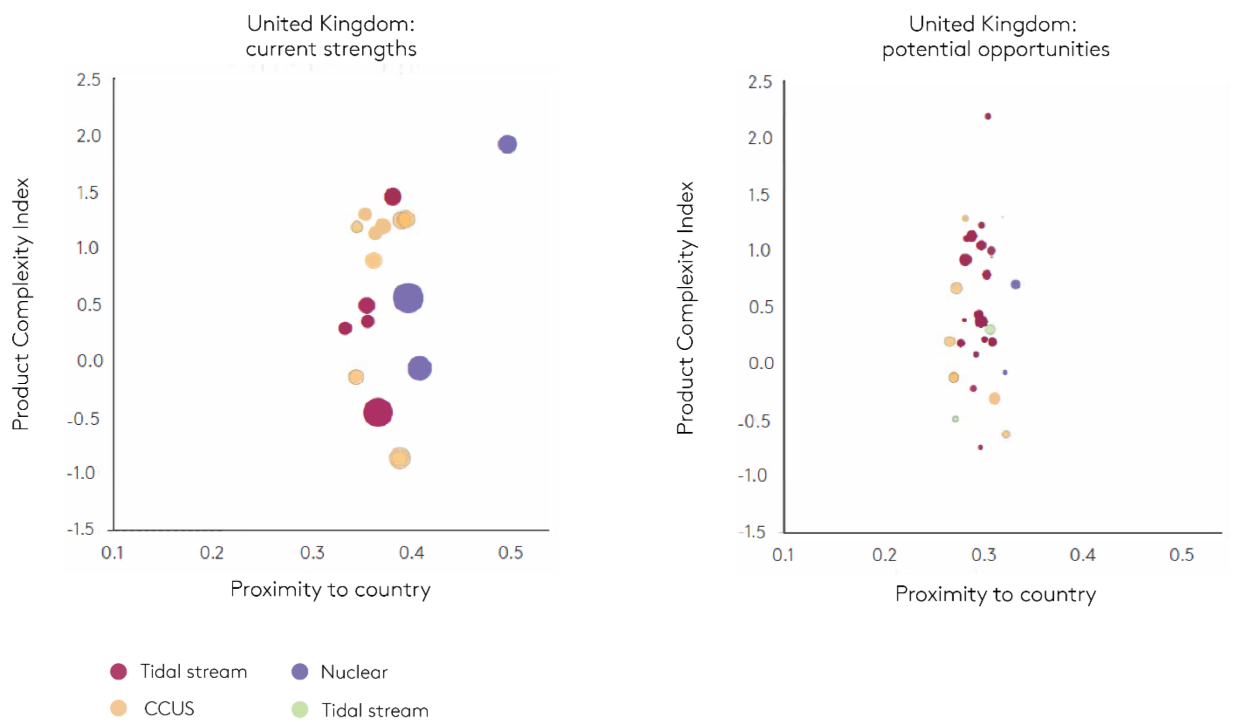
4. Supplementary charts

Figure A1. Distribution of Product Complexity Index of products relevant for tidal stream energy relative to all traded products



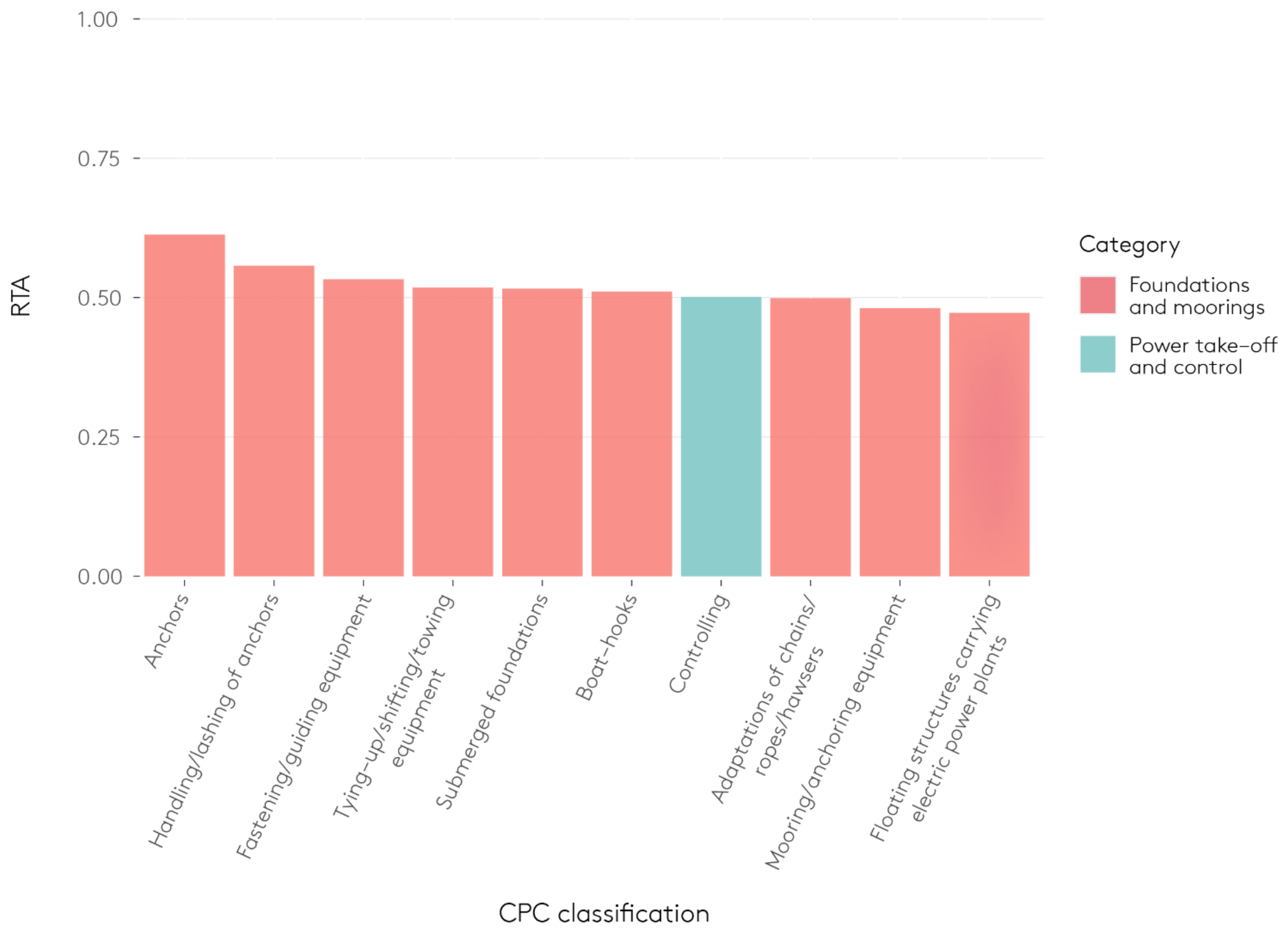
Notes: PCI values are calculated for each product on a relative basis against the universe of all traded products, and standardised to mean set at zero with a standard deviation of 1. PCI calculations are based on the latest five-year period available in our dataset (i.e. 2016–2020).

Figure A2. Existing strengths and new opportunities for the UK in tidal stream energy, CCUS, offshore wind and nuclear energy (2016–2020)



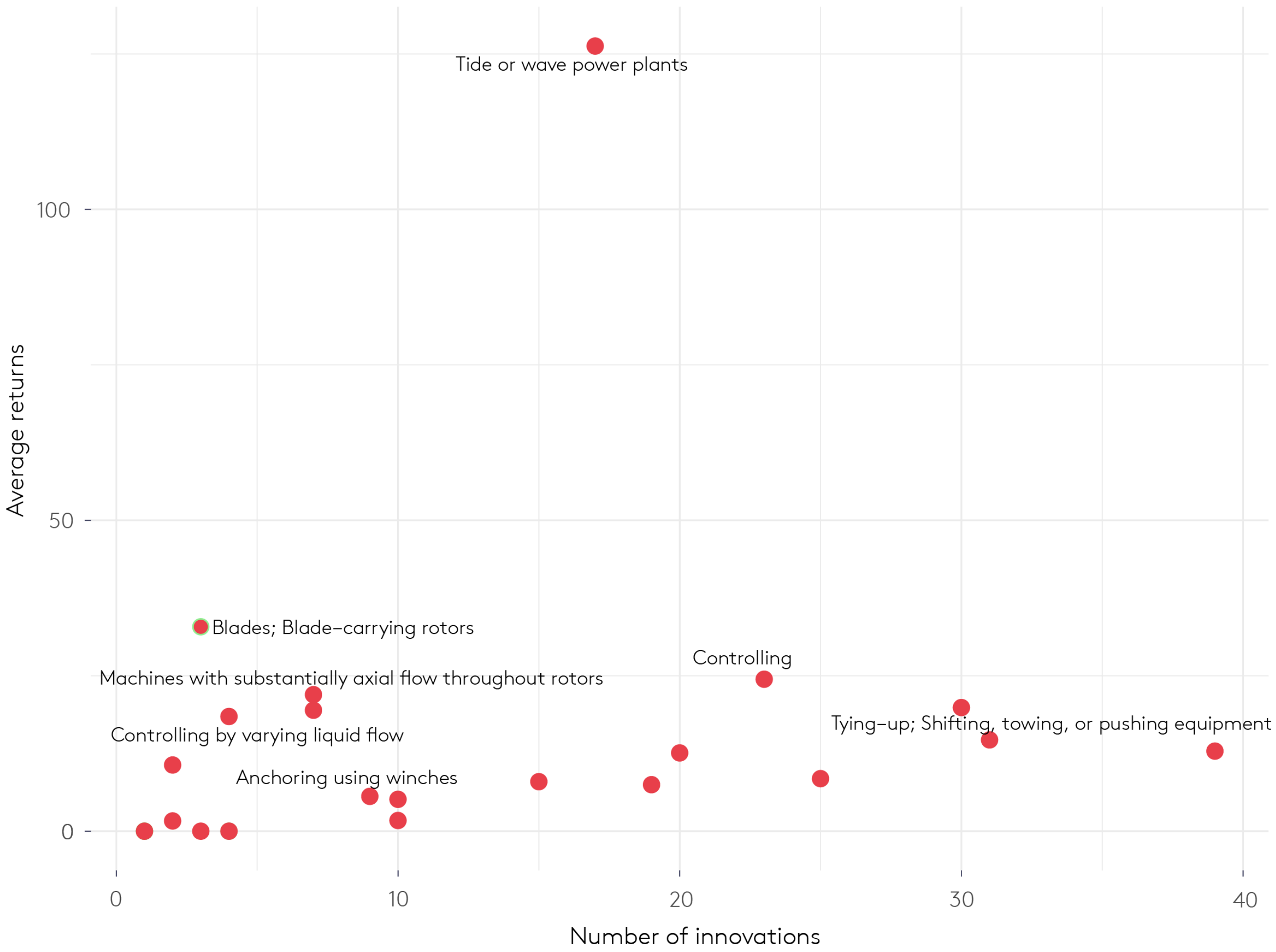
Notes: Each bubble corresponds to a product and is sized by the UK's RCA in that product. RCA, PCI and proximity values are calculated based on average trade values for the products between 2016–2020, the latest five-year period available in our dataset. Due to a large overlap between tidal stream and offshore wind products, many green bubbles that represent offshore wind are obscured by the red bubbles of tidal stream.

Figure A3. UK's revealed technological advantage for the top ten detailed technology classifications within tidal stream energy (1980-2018)



Notes: Chart displays the top ten detailed classifications of innovation in which the UK has RTA. These classifications of innovation correspond to individual patent codes within the overall group of patent codes defined as relevant for tidal stream energy innovation, as listed in Section 3 of the Appendix. The innovation classifications are colour-coded by the same four categories used to break down the list in Section 2 of the Appendix, but only classifications found in 'Foundations and moorings' and 'Power take-off and control' appear in the top 10.

Figure A4. UK returns to additional public investments in innovation for detailed technology classifications within tidal stream energy



Notes: The y-axis indicates the estimated returns (as a percentage) for the UK to an additional £1 R&D subsidy in a given technology classification within tidal stream energy. The x-axis indicates the total number of innovations in a given technology classification. Analysis is based on innovations between 2009–2018. The data point with the highest average returns that reads 'tide or wave power plants' corresponds to the patent classification E02B 9/08 in the Cooperative Patent Classification System.

Source: Author's estimates based on PATSTAT Global 2021 (Autumn edition)