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UK studies on the wider energy system benefits of tidal stream

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With high predictability and a consistent energy availability profile, Tidal Stream (TS) could play an important part in the optimal future low-carbon energy mix, improving the supply reliability and system resilience through diversification of renewable energy supplementing wind and solar power. This paper summarises key findings from UK studies on the benefits of TS by assessing its impact on the overall energy system. The studies use the Integrated Whole Energy System (IWES) model to minimise the overall cost of the 2050 GB energy system with and without TS under different scenarios while respecting the net-zero emission target and reliability requirement. The results show that TS could displace some capacity of mid-merit or peaking plants, indicating some capacity value of offshore wind and lowering the levelised cost of wind power because of lower system integration costs. Diversifying energy resources and improving flexibility are crucial to coping with low-carbon energy resource variation. The studies also demonstrate that the value of TS by 2050 should be around £50 per MW per h, and this cost target could be achieved if a sufficient learning rate (10–15%) with 10 GW of installed capacity could be obtained in the transition period. Other sensitivity studies provide insight into the impact of location, heat decarbonisation pathways, lower annual wind capacity factor, system flexibility, and interconnection capacity on TS's wider energy system benefits.

A. Introduction

The world's energy system is facing unprecedented challenges over the next few decades. Meeting the carbon emission reduction targets will require intensive expansion of low-carbon electricity generation technologies, such as renewables (wind, PV, marine, biomass), nuclear and Carbon Capture and Storage (CCS) and decarbonisation of heat and transport sectors. While PV and wind power, with a strong emphasis on offshore wind, have had the most capacity installed, these intermittent variable sources have complex system integration challenges, especially due to increased balancing and reserve requirements and long-term reliability, security, and resilience issues against extreme weather conditions.[1] Therefore, diversification of energy resources is crucial while improving system flexibility to cope with variations in low-carbon energy resources.

In this context, Tidal Stream (TS) technologies could be part of the future energy mix, improving its diversity due to the low correlation between the tidal energy profile with PV and the wind profile.[2] Research is emerging that shows the adoption of tidal stream power can enhance supply-demand balancing[3,4] and reduce power variability in the future UK energy mix.[5] TS has predictable daily power output profiles and can be forecasted long-term with high accuracy. This certainty in future supply means tidal stream has the potential to provide energy security benefits by providing a reliable domestic energy source that reduces reliance on volatile energy imports. Optimised design of tidal arrays[6] tend to be close to shore (<5 km), reducing vessel fuel costs and the cost of subsea cables. They have also benefitted from offshore wind innovations and supply chain improvements, and there are conceptual similarities (for example, the horizontal axis turbine and foundations). Whilst these benefits are becoming better understood, it remains unclear how they will impact energy systems, thereby affecting the future viability of tidal stream energy.

TS is yet to break into the mainstream. Across the world, progress to date has largely been individual device deployments to demonstrate proof of concept. Only two TS arrays are deployed in the UK: MeyGen in the Pentland Firth (owned by SIMEC Atlantis Energy) and the Shetland Array (owned by Nova Innovation). As of January 2022, there was only 11.5 MW in the water across Europe.[7] The main reason for low levels of installed capacity to date has been the relatively high costs of the technology, as devices must be designed to survive the harsh tidal currents and wave conditions, which exposes

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devices to high loading. These extreme elements also make installation, operations and maintenance more challenging.

In the UK, the tidal stream industry had limited access to revenue support in the past, with developers primarily relying on grant funding, crowdfunding and private investment. This is set to change: with £20 M per annum ringfenced by the UK Government in Contract-for-Difference (CfD) Allocation Round 4 (AR4), 40 MW of new tidal capacity is expected to be commissioned by 2026–27.[8,9] If the industry can show successful tidal projects, following a credible cost reduction pathway and demonstrating reliable operation, this should allow participation in future CfD rounds and unlock further technological innovation and investment from the private sector. It is estimated that after the TS sector has achieved 1 GW of cumulative installed capacity, its LCoE will have dropped from its current level (of about £250–300 per MW per h) to £90 per MW per h.[10]

However, as TS is relatively new, it has been unclear how the penetration of such technology will impact the overall energy system and what is needed to facilitate its cost-effective integration into the incumbent and future systems. The current energy system modelling has often disregarded tidal stream energy completely.[11] Given the nascent nature of the industry, energy system models often are not designed to quantify the benefits that TS may provide. For example, energy system models implementing insufficient spatial and temporal granulation would not capture the benefits of diversifying wind and solar PV with TS in different locations and miss system-defining extreme events, such as unexpected lulls in the wind resource.[12]

A multi-faceted assessment of the practical contribution of TS to the GB future energy mix was reported in ref. 13. While it tried to address the whole-system cost of TS technologies, the studies did not use coherent models to analyse the impact of TS on the investment and operation of the whole-energy systems considering the strong interaction with other infrastructures such as hydrogen and carbon capture and storage (CCS). This paper addresses these shortcomings and aims to evaluate and analyse TS's wider energy system benefits in the UK, considering different future energy system development scenarios. This paper presents the findings from the studies. The contribution of this paper is twofold:

– It provides a framework to analyse the value of tidal stream technology quantitatively using a multi-energy system holistic approach that optimises investment and system operation in electricity, hydrogen, heat and CCS systems simultaneously.

– It summarises the key findings from the related work in the Tidal Stream Industrial Energiser (TIGER) project in the UK context.[14]

B. Analytical approach

TS' system benefits are derived by subtracting the system costs of a system without TS as a counterfactual and with TS. The system implications are determined by comparing the optimal portfolio of energy infrastructure and operation between the two cases. The energy systems are optimised for each case using the Integrated Whole-Energy System (IWES) model. The following provides an overview of the IWES model, but the detailed formulation and description of the model can be found in ref. 15.

IWES is formulated as a large linear-programming-based optimisation problem to minimise the overall system costs (CAPEX and OPEX) of electricity, gas/hydrogen, heating and Carbon Capture and Storage (CCS) systems, as shown in Fig. 1. The model optimises the system's hourly operation across a year and long-term investment decisions concurrently by maximising the synergies across multi-energy systems, respecting the operating, reliability, and carbon emissions constraints. IWES also optimises the technical needs for real-time supply and demand balancing, including frequency regulation and balancing reserve (seconds and minutes timescale), while considering critically essential changes in the system inertia. This aspect is vital for a zero-carbon energy system with a high share of renewables.

The model also includes modelling local district heating systems and national/international energy infrastructure, including energy-flow exchanges with mainland Europe *via* interconnectors. For this study, the GB energy system model is divided into 14 regions following the distribution network[16] to provide sufficient spatial granularity to capture the regional RES, energy demand, distributed flexibility, an energy network characteristics. This modelling approach is essential since those aspects are intertwined and must be analysed simultaneously in the whole-energy system context with sufficient temporal and spatial granularity.

IWES optimises the whole energy supply chain from the supply portfolio, transmission and distribution infrastructure, and energy storage to capture all interactions. The model also considers the dynamic parameters and technical limitations of the selected portfolio of energy sources and flexibility technologies. The benefits of system flexibility provision can be analysed across various energy vectors.

Several UK studies have applied the IWES model to investigate the value of long-duration energy storage,[15] the value of system flexibility and the benefits of hydrogen and electricity integration involving electrolysers and hydrogen-fuelled power generation,[17] to evaluate the performance and system implications of different heat decarbonisation pathways,[18] and identify the system integration cost of renewables.[19]

C. Case studies

Energy system background

The energy system infrastructure and operation in IWES are optimised to meet the 2050 annual energy demand (Fig. 2) and net-zero emissions requirements as described in ref. 20. More detailed information about the approaches, data, and key assumptions can be found in ref. 14.

The UK is assumed to be energy positive at the annual level (total annual demand is less or equal to annual production), and the interconnectors are used for short-term energy/power

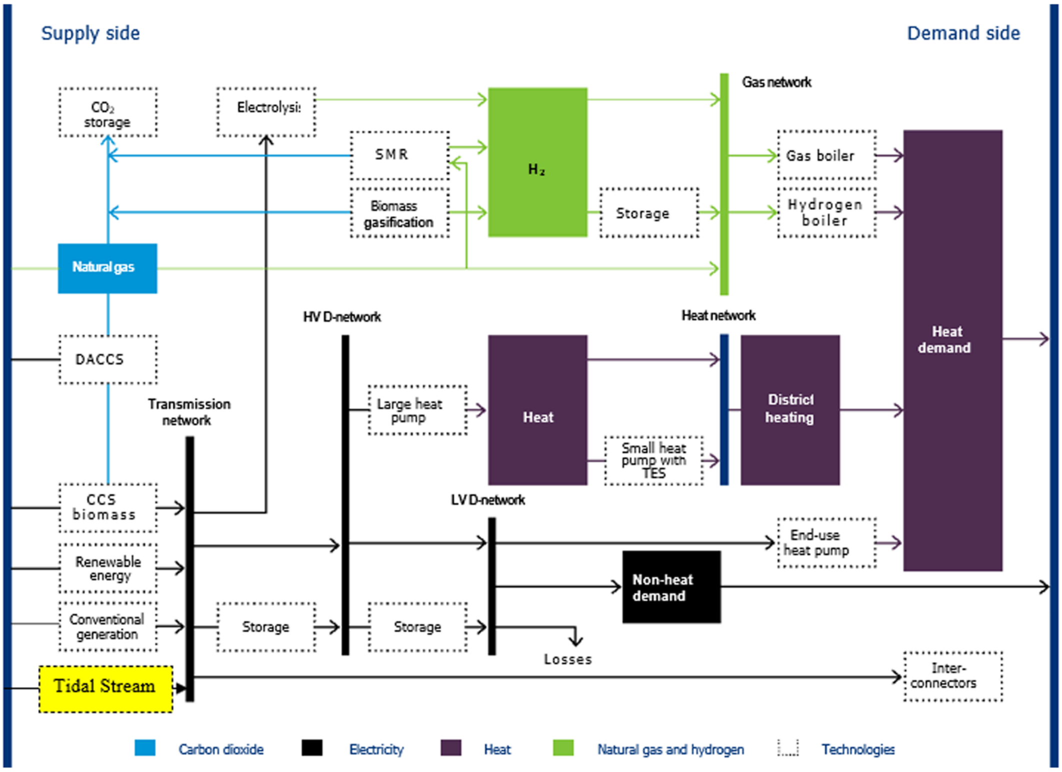

Fig. 1 The Integrated Whole Energy System (IWES) Model. Notes: SMR: Steam Methane Reformer; CCS: Carbon Capture and Storage; DACCS: Direct Air CCS, TES: Thermal Energy Storage; HV/LV: High voltage, Low Voltage; D-Networks: Distribution networks. Renewable energy includes wind, PV, hydro, and Tidal Stream technologies.

exchanges with adjacent countries. IWES also contains the simplified modelling of continental Europe and Ireland, so the power exchanges depend on dynamically changing operational requirements in those systems. It implies that different system needs may trigger export and import constraints. The study also assumes heat and transport will be decarbonised through electrification and hydrogen for fuel and heating.

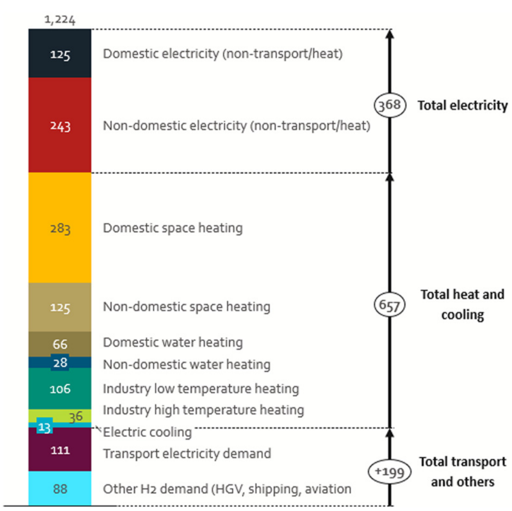

Fig. 2 2050 GB annual energy demand (TW h year^{-1}).[17]

Tidal stream potential locations and capacities

TS's potential locations and capacities were selected according to 22 sites considered in ref. 21. The location of the sites, alongside an additional 22 sites identified as potentially suitable for TS energy extraction,[13] are shown in Fig. 3. Whilst it is acknowledged that the additional 22 sites will augment the total TS energy resource, the focus of this paper is on the 22 sites originally considered by the Carbon Trust[21] because the additional 22 sites tend to have a smaller energy resource that is more uncertain at this stage of their development. The study provides locations and annual production estimates for sites across the UK, subject to environmental constraints. Potential installed capacities (Table 1) and the locations (Fig. 3) are inferred from the reported annual energy yield by assuming projects are deployed to operate with an average capacity factor of 40% following the design of MeyGen's turbine.[22] A higher capacity factor (50%) could be achieved, as reported in ref. 23.

Depth-averaged tidal flow speed data with a duration of 1 month was obtained for each site from regional-scale hydrodynamic models, locally refined to a resolution of *circa* 50 m within prospective tidal array sites.[2] Harmonic extrapolation was implemented to extend the data sets to 1 year at a 30 minute resolution. The annual flow speed data sets were used to derive the power time series for each farm. The rated power of each farm dictated its maximum power output. A turbine cut-in speed of 1 m s^{-1} was implemented. These constraints amount to a baseline installed capacity of 11.8 GW aligned to.[21] Based on

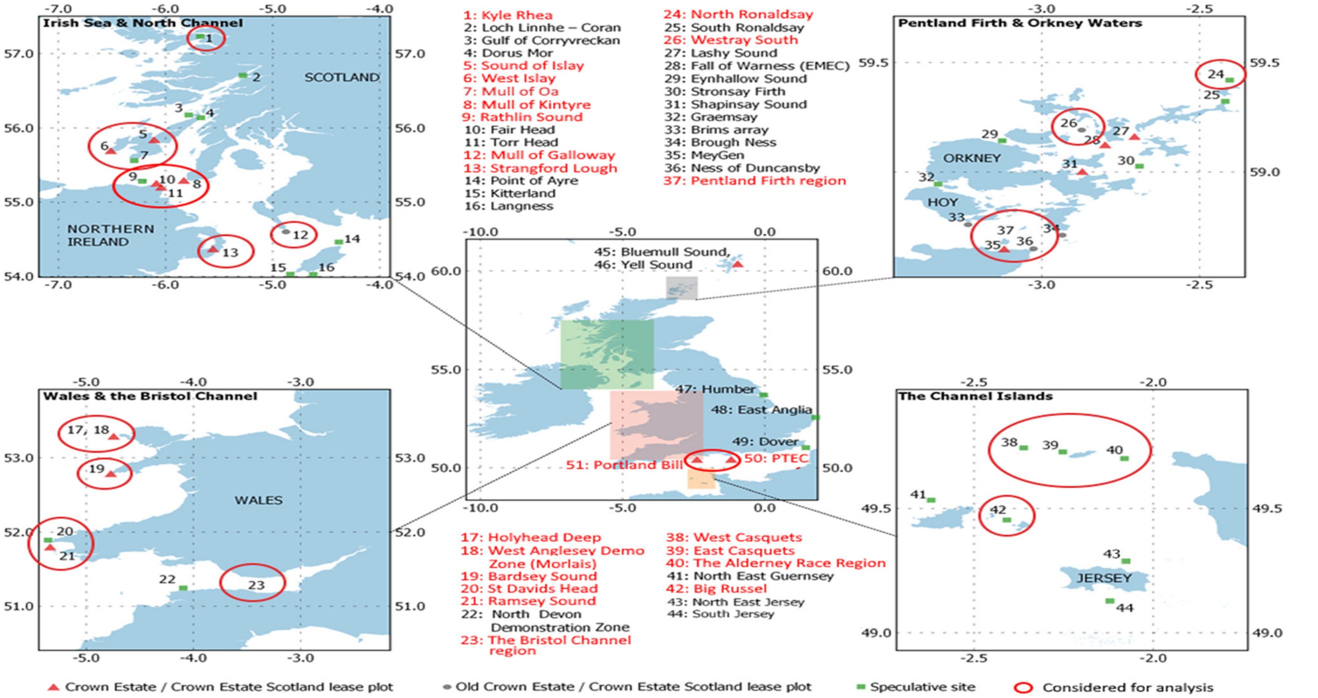

Fig. 3 Installed capacity and locations of Tidal Stream. Originally published by Coles *et al.*,[13] modified to show the specific sites considered for this study in red.

those data, The University of Plymouth generated a set of power time series for farms at each site.

Impact on energy system costs

The studies consider three TS deployment scenarios (Low: 5.9 W, Core: 11.8 GW, and high: 17 GW) by uniformly scaling the tidal capacities in Table 1 to reach the total capacity target. The impact of TS on the system costs is shown in Fig. 4. In each scenario, the impact of TS on different system component costs is quantified and analysed. All cost figures were expressed in the real value of GBP(£) in 2020. The positive changes in Fig. 4 mean additional system costs and the negative changes mean cost savings due to TS. It is worth highlighting that TS CAPEX is not considered in this study as it aims to identify the gross benefits of TS and the range of its LCOE target.

The modelling results demonstrate that TS reduces:

– The total generation CAPEX (both low and non-low carbon technologies) by 0.6 – 1.7 £ bn per year depending on low/core/high scenarios.

– Electricity OPEX due to less gas and biomass fuel usage in the electricity sector.

– CAPEX of carbon removal technologies such as DACCS and CAPEX of carbon storage – the results indicate that the indirect impact of TS in these cases is to reduce residual emissions and sequestered Carbon; therefore, the cost of offsetting emissions and storing Carbon becomes lower.

In addition, TS also increases the revenue from exporting electricity from GB to Europe.

On the other hand, some system costs increase, for example:

– CAPEX of transmission by around £0.1 bn per year due to the locations of TS.

– CAPEX and OPEX of hydrogen production technologies from gas and biomass due to a shift from biomass for electricity to hydrogen production; this will be discussed in the next section.

The analyses above indicate the system components affected by TS. It is worth highlighting that most of the TS impacts are related to savings in energy infrastructure investment costs (CAPEX-related), indicating the long-term value of TS. Savings in OPEX are between 13% and 22% of the total TS energy system benefits. The results imply that the TS CAPEX should be below the gross system benefits for the investment to be justified.

Impact on the power generation mix

As shown in the previous figure, the largest impact of TS is on electricity generation costs, indicating some changes in the optimal generation mix proposed by the model. The changes in the power generation portfolio due to TS are depicted in Fig. 5.

The modelling results suggest the following:

– TS can substitute a mix of generation technologies such as offshore wind (the most affected), PV, biomass CCS, hydrogen CCGT (H2 CCGT) and conventional CCGT using natural gas (NG CCGT). Since TS can displace dispatchable generation capacity (CCGT), the model indicates that TS has a 20–30% capacity value, *i.e.* the ratio of firm generation capacity (*e.g.* controllable plants such as CCGT and biomass) that can be displaced and TS installed capacity. The result should be taken cautiously because the core study assumes certain flexibility from demand response and distributed storage, which helps improve the capacity credit of variable renewable generation.

Table 1 List of potential TS capacities

Project name	Country	Array power capacity (MW)
Orkney		
Westray Firth	Scotland	260
North Ronaldsay Firth	Scotland	70
Pentland Firth		
Pentland Firth Shallow	Scotland	352
Pentland Firth Deep	Scotland	4700
Northern Ireland		
Strangford Lough	Northern Ireland	40
East Raithlin Sound	Northern Ireland	35
Raithlin Island	Northern Ireland	62
West Coast		
West Islay + Islay	Scotland	690
Kyle Rhea	Scotland	20
Mull of Kintyre	Scotland	120
Mull of Galloway	Scotland	100
Wales		
Holyhead (Morlais)	Wales	560
Ramsey Island	Wales	130
Uwchmynydd (Bardsey)	Wales	6
England		
Bristol Channel – Minehead	England	125
Bristol Channel – Barry & Mackenzie Shoal	England	65
English Channel		
Portland Bill	England	30
Isle of Wight	England	300
Alderney Race	Channel Islands	3600
Big Russel	Channel Islands	11
East Casquets	Channel Islands	425
West Casquets	Channel Islands	140
Total (all projects)		11 841

– There is also a reduction in NG CCGT capacity leading to less electricity OPEX and the cost of storing Carbon from Carbon Capture and Storage units and offsetting residual emissions by using DACCS, as shown in Fig. 4.

– TS is not a substitute for nuclear power generation. Even with a high TS penetration (17 GW), the reduction in nuclear capacity is very modest, *i.e.* around 0.2 GW. The results indicate that the model does not suggest that TS displace nuclear's role as a baseload low-carbon generation and firm capacity.

Most of the benefits are CAPEX related, indicating the long-term value of TS supported by the long-term predictability of TS energy with high accuracy. This contrasts with other renewable technologies, such as wind and solar PV, whose annual energy outputs vary substantially.

Optimised tidal stream capacity as a function of its LCOE

There is still uncertainty about the future cost of TS as it continues to be developed and is yet to be deployed on a mass

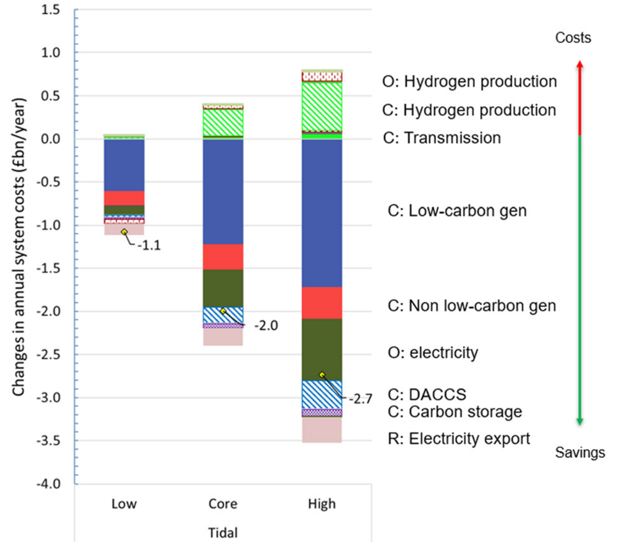

Fig. 4 The changes in annual system costs attributed to TS (notes: C = CAPEX, O = OPEX, R = Revenue).

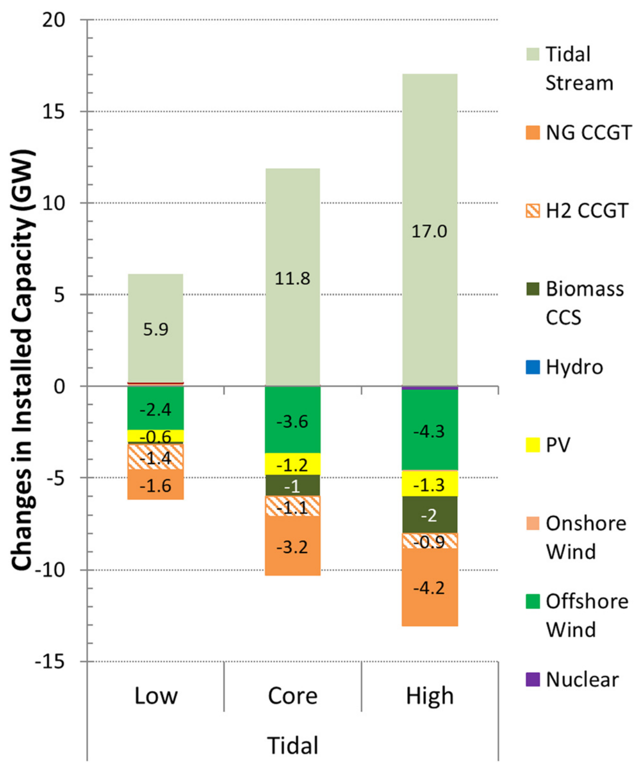

Fig. 5 Changes in power generation capacity due to TS.

scale. In this context, various sensitivity studies are carried out to understand the impact of various TS Levelised Cost of Energy values (LCOE) on its deployment and energy system costs. Earlier, the per-unit energy of TS gross system benefits (excluding the TS costs) was calculated at around 48.88–55.27 £ per MW per h, with the range of capacity installed between 5.9 GW and 17 GW. In this study, the optimisation model was run considering the

Table 2 Locations of TS deployment

Location	LCOE of TS	
	£40 per MW per h	£50 per MW per h
Scotland and Northern Island	5678	23
Wales	2088	401
England and Channel Islands	13 051	2663
Total (MW)	20 816	3088

levelized cost of TS. Three LCOE figures are used: £40 per MW per h, £50 per MW per h, and £75 per MW per h, and the model proposes 20.8 GW, 3.1 GW, and no TS capacity, respectively. The locations of TS proposed by the model are summarised in Table 2.

The results align with the previous analyses as they indicate that the range of TS LCOE should be between £40 per MW per h and £50 per MW per h to compete against other technologies. It is worth highlighting that even at £50 per MW per h, which is around £15 per MW per h (43%) higher than the LCOE of offshore wind assumed in the study (*i.e.* £35 per MW per h), the model still proposes 3.1 GW of TS. It demonstrates that TS will have more benefit to the system than installing additional wind as it improves diversity in renewable outputs. The model considers the system integration cost of technologies, including TS and wind. As the system integration cost increases with higher renewable penetration, TS becomes competitive against the additional renewable capacity at a certain point.

How does this align with cost projections?

Arguably the main finding from the study was the establishment of a £50 per MW per h breakeven tidal stream LCOE by 2050. While certain aspects of the tidal technology could warrant a cost premium (for example, the high predictability), from a purely economic perspective, this is the level that the tidal technology must reach to reduce the overall energy system costs.

The current LCOE of the tidal stream is generally considered to be between 150 and 200 £ per MW per h, depending on the technology and site conditions.[24] This is reflected by the administrative strike price for AR4 at £179 per MW per h. It is worth noting that the strike price is expected to be higher than LCoE because the subsidy is designed for 15 years, not the 25 year project life that is usually assumed for tidal stream projects. The sector has seen a rapid cost decrease in the last five years, even without revenue support. LCOE in 2015 was estimated at $440 per MW per h by Bloomberg New Energy Finance (BNEF),[9] equivalent to £380 per MW per h in 2021 currency. From 2015 to 2022, this implies a significant 53% LCOE reduction, despite only a handful of turbine installations. Coles *et al.* state that the industry has achieved a learning rate of 26% during the early phases of development and that TS could dip below £150 per MW per h by 2030, based on a mid-range learning rate of 17%).[7] Projections by the Offshore Renewable Energy Catapult estimated that tidal stream LCOE could reach £90 per MW per h by the time 1 GW has been installed, which could be achieved by the early 2030 s if upcoming projects can capitalise on the strong sector headwinds at present. A 10–15% learning rate would be enough to achieve an LCOE of £50 per MW per h by 2050 (assuming 10 GW installed), which compares favourably to learning rates seen for more established technologies. A similar conclusion was obtained in the feasibility study and cost-benefit analysis of tidal energy for Ireland.[25]

Sensitivity studies

Various sensitivity studies have been performed and analysed to identify and understand the key drivers influencing the value of TS from the energy system perspective. Given the space limitation, the key findings of the sensitivity analyses are extracted and summarised in this paper. More detailed information about the results of sensitivity studies can be found in[26] and in our report on TIGER's project website.[14] The key findings are as follows.

– The gross system benefits of TS are location specific. TS in England and Wales has around 2.5–4% higher value than TS in Scotland. The TS value of Scotland is slightly lower due to transmission investment requirements to transport power from Scotland to England, where the bulk of demand is located.

– The gross system benefits of TS will also depend on how the heat demand will be decarbonised. The benefits of TS in the pathways with high electricity demand, such as deep electrification and hybrid heating, are ∼50% higher than in the hydrogen pathway.

– A lower annual offshore wind capacity factor intensifies the system benefits of TS and *vice versa*. The gross system benefits of TS with a 52% offshore wind capacity factor obtained from a low wind year are 40% higher than those in a system with the median wind (60% average). On the other hand, having a 64% wind capacity factor in a high wind year will reduce the system benefits of TS by 20%.

– The gross system benefit of TS is higher when the energy system flexibility is low. The results also suggest that the storage requirements to maximise the value of TS is relatively small from the system perspective.

– Increasing interconnection capacity will reduce the gross system benefits of TS from £2 bn per year to £1.7 bn per year as the system flexibility increases.

Conclusions

Tidal Stream (TS) technologies provide alternative low-carbon energy sources that seamlessly integrate with other low-carbon technologies in net-zero emission systems. While TS can be operated in synergy with other technologies, it also competes and could displace a mix of generation technologies such as offshore wind, biomass with CCS, gas and hydrogen power generation. The predictability and consistent output profiles of TS improve the capacity value of TS. TS variability could be firmed with energy storage, but its portfolio should be optimised from the whole-energy system perspective.

The study has established a 2050 cost target of £50 per MW per h for TS. The figures are system-specific and depend on the assumptions of other technologies. This could be achieved by

2050, subject to a 10–15% learning rate and 10 GW of TS installed capacity, assuming further support and deployment of this technology. Most of the benefits are CAPEX related, indicating the long-term value of TS supported by the long-term predictability of TS energy with high accuracy. This contrasts with other renewable technologies, such as wind and solar PV, whose annual energy outputs vary substantially. While TS mostly affects the electricity system, where most system benefits are derived, the studies also demonstrate and quantify the indirect impact of TS technologies on the hydrogen system, gas usage, and carbon removal and storage requirements. TS reduces residual emissions and the volume of sequestered carbon; therefore, the costs of offsetting emissions and storing carbon become less. The results highlight the sector coupling between electricity and other system components, and therefore, the value of TS (or any new) technologies should be assessed in a holistic manner considering its impact on the whole energy system.

Author contributions

D. Pudjianto is the main and corresponding author. He performed the studies and the analyses. C. Frost administered the research work, while the TS scenario and data were provided by D. Coles and A. Angeloudis. G. Smart and G. Strbac contributed to the policy discussion and findings.

Conflicts of interest

There are no conflicts to declare.

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