Assessment of tidal stream power's ability to enhance energy system resilience

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Abstract—**Results are presented from energy system modelling of the GB grid that investigates the impacts of tidal stream turbine deployment within a future energy scenario. The energy system is stress tested using 2021 as a case study year, when wind resource was lower than average, and gas prices were relatively high. Results show that the inclusion of up to 5 GW of tidal stream capacity, in place of the equivalent offshore wind capacity, results in a 20% reduction in the dispatch of combined cycle gas turbine (CCGT) generation. This is approximately equivalent to a 1 TWh reduction in CCGT dispatch per 1 GW of tidal stream capacity installed. This reduced reliance on CCGT reduces both the total dispatch cost, as well as emissions, by 6.5%. The inclusion of up to 5 GW of tidal stream in place of offshore wind exhibits a reduction in the curtailment of solar PV, offshore wind and tidal stream by 12.5%, 9% and 12.7% respectively. There is also a small but not insignificant uplift in the load factor of all battery storage capacity, of up to 3.5%. These positive system impacts should be balanced against the significant cost premium that tidal stream exhibits relative to offshore wind. Further work is needed to establish the significance of these results in the context of all relevant costs.**

Index Terms—**Dispatch Modelling, Energy System Modelling, Optimisation, Tidal Stream Energy.**

I. Introduction

As energy systems transition from centralised, dispatchable power produced by fossil fuel-based technologies, to de-centralised, intermittent renewables, the need for resilient energy system design is becoming ever-more pertinent. This challenge was brought to the forefront during the energy crisis that started in 2021, when the combination of unseasonal, but not uncommonly low wind resource, and high imported energy prices, resulted in UK Government needing to spend 40 £bn to partially protect UK households and businesses from rising energy costs [1]. This is equivalent to 1.3% of the UK's gross domestic product, and so re-enforces questions over how to ensure energy security and resilience as reliance on weather dependent renewable power increases in the future. In the context of this work energy security is defined as 'the uninterrupted process of securing the amount of energy that is needed to sustain people's lives and daily activities while ensuring its affordability'. Energy resilience is defined as 'the ability of a system to survive strong and unexpected disruptions and to recover quickly afterwards' [2]. Prominent future energy scenarios estimate that by 2050, the UK's solar generation needs to increase by 625%, from its current level, of 16 GWh/year, to 116 GWh/year [3]. Similarly, it is estimated that wind generation needs to increase by 425%, from 96 GWh/year now, to 502 GWh/year in 2050. These increases in annual solar and wind generation would increase the combined contribution of solar and wind to meet total energy supply, from their current level of 7%, to 50% in 2050. Whilst solar and wind are critical as the primary suppliers of renewable energy now, and in the future, the recent energy crisis highlights the potential system security and resilience risks associated with relying so heavily on weather dependent renewable power, even when their contribution to meet demand is relatively modest.

The research presented here investigates system resilience impacts that may arise from the adoption of tidal stream power within the UK's energy system. It is well documented that tidal stream provides a different offering to solar PV and wind [4]–[9]. Firstly, the timing of tidal power is uncorrelated from that of solar and wind. Consequently, diversifying the mix of electricity generation through the adoption of tidal stream alongside wind and solar can enhance supply demand balancing. Secondly, tidal is a predictable source of renewable power, given that the tides are driven by the cyclic motions of the Earth Moon and Sun, which have been well understood for centuries. With this knowledge of semi-diurnal flood-ebb cycles, intra-monthly spring-neap cycles, and interannual lunar nodal cycles [10], [11] tidal power can be accurately predicted over the multi-decadal lifetime of projects. This predictability is beneficial to the energy system because it provides long-term foresight into the intra-day timing of when tidal power will be available, relative to times of high demand. Thirdly, the periodic flood-ebb nature of tidal stream power, with four periods of power generation per day separated by short (ca. 1 hour) slack water periods, is highly compatible with short-duration energy storage [6]. This research explores the utility of tidal stream within NESO's future energy system design to complement prominent solar PV and wind resources.

Results are presented from energy system dispatch modelling of Great Britain's (GB's) electrical grid, based on weather and market conditions during the 2021 energy crisis. 2021 was chosen to stress test the energy system model during a period when known

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significant cost impacts were incurred as a result of high imported energy prices and low wind generation. For context, day-ahead electricity prices increased from an average of around 35 £/MWh in 2020, to around 120 £/MWh in 2021. In addition, the annual windiness, which describes the ratio of average wind speed to the long-term average wind speed, was 93% in 2021. There has been only one year (2010, 90%) that has dropped below 93% over the last 27 years.

The ESM simulates the power flows between power generators, energy storage and load, with these system components linked by the transmission grid that connects nine zones across the GB electricity network. Decisions over when and how much power to dispatch from each generator are made based on their availability and dispatch cost, with the objective to minimise the overall system's dispatch cost over the year. A range of tidal stream capacities are investigated, from 0-5 GW, to establish the system impact(s) of replacing relatively small proportions of offshore wind, acknowledging that wind will remain the primary sources of renewable power in the future.

II. Methods

A. Energy system modelling

Energy system modelling is undertaken to identify and quantify the impact(s) from replacing offshore wind capacity with tidal stream capacity on the UK grid. The modelling adopts the framework developed by Pennock et al. (2023) [8]. First, baseline energy system modelling of the UK is undertaken in the absence of contributions from tidal stream energy, based on the National Energy System Operators (NESO's) 'Leading the Way' Future Energy Scenario (FES) for 2030 [12]. NESO's FESs provide a range of scenarios for reaching net zero, with detail on how the evolution of installed capacity of generation, storage and grid develops over time, up to 2050. Portions of offshore wind capacity is then removed from the model and replaced with tidal stream capacity, whilst maintaining the gross annual energy generation of the overall system. This model is referred to as the counterfactual model. The performance of the baseline and counterfactual energy system models are quantified and compared, based on key performance metrics, such as total dispatch cost and carbon emissions.

The open source library Python for Power System Analysis (PyPSA), which is capable of simulating and optimising power systems, has been utilised in this research. The suitability of PyPSA was assessed based on peer reviewed model selection frameworks [13]–[15]. PyPSA is open source, which enables the underlying code to be interrogated and encourages cross-model validation to enhance confidence in the results produced. This transparent approach is necessary to establish the reasons behind modelling results/trends, and holds greater weight when helping to inform network planning, investment decisions and government policy than closed, 'black-box' models. PyPSA also has a track record of influencing policy in other energy related fields (e.g. [16]).

PyPSA dispatch modelling implements linear optimisation to determine the most cost-effective way to dispatch generation and storage within the bounds of domain-specific constraints. Constraints limit the power output/transmission of generators, storage and transmission lines, and storage charging/discharging to user-defined nominal limits, whilst also accounting for the variability in renewable power availability. The objective function is a linear equation that considers the dispatch cost of each technology. The optimisation problem is solved using the Gurobi solver, which iterates through feasible solutions at the vertices of the constraint polytope. Further information on dispatch optimisation within PyPSA can be found in Brown et al. (2018) [17].

Figure 1 shows the UK domain considered in the energy system modelling, which is split into nine zones (Z1-9), based on National Energy System Operator (NESO) transmission boundaries. Bar charts show the make-up of power generation in each zone, in terms of installed capacity, based on NESO's Leading the Way FES [12]. In general, the proportion of generation from renewable sources is high in Scotland (Z1-4), predominately due to contributions from onshore and offshore wind, solar PV, and hydro-electric. There is a small contribution by energy from waste (EfW) in Z4. In Z5 renewable power is complimented with 1 GW of nuclear, along with low levels of biomass, gas, combined heat and power (CHP), and EfW. Z6-9 contain open and combined cycle gas turbines (OCGT and CCGT respectively), with particularly high CCGT capacity in Z8 (10 GW). Offshore wind remains significant in Z5-8 (between 5.8-11.5 GW), as does solar PV, particularly in Z8-9 where resource is greatest (20.5 GW and 9.2 GW respectively). Z2, 5 and 8 have interconnector capacity to Europe, of 1.4 GW, 0.5 GW, 19.7 GW respectively. All zones, with the exception of Z1, have lithium-ion battery storage, with installed power capacity highest in the southern zones, ranging between 0.1 GW in Z3, to 3.5 GW in Z8. Figure 1 also shows the constraints on power transmission across zonal boundaries. Transmission is most constrained in the North, at the boundaries of Z1- 3, where power transmission is limited to 5.3 GW, 10.6 GW and 0.8 GW respectively. The least constrained transmission, of 24.1 GW is between Z7 and Z8. The transmission constraints are kept consistent in the baseline and counterfactual models.

Figure 1 also shows the three locations where tidal stream power capacity (Pt) is introduced in the counterfactual model, at the Pentland Firth in Z1 (Scotland), Morlais in Z7 (Wales) and the Isle of Wight in Z9 (England). The three sites have been chosen since they represent the three leading areas for tidal stream energy development in Scotland, Wales and England. All three sites are currently eligible for subsidy support under the contracts for difference (CfD) scheme. The only other subsidy-ready site is the European Marine Energy Centre site in the Fall of Warness, Scotland. This site has not been included in the energy system modelling at this stage, for the reason that EMEC is a test site. Under the CfD scheme, there is a reported

59 MW scheduled to be installed before 2030 in the Inner Sound of the Pentland Firth, adding to the 6 MW of capacity that is currently installed. No turbines have been installed at Morlais to date, but 3MW of capacity that has recently received subsidy support is expected to be installed before 2030. Finally, no turbines have been installed or won subsidy support at the Isle of Wight site to date. The three sites exhibit different resource magnitudes. In this study, the total tidal stream capacity is increased at 1 GW increments, up to 5 GW. This capacity is distributed proportionately across the three sites, based on practical resource estimates provided in [18], of 11.26 TWh/year (4 GW), 2.41 TWh (0.8 GW) and 0.55 TWh (0.2 GW) at the Pentland Firth, Morlais and Isle of Wight respectively. The installed capacities, and reduction in wind capacities, split by zone, are provided in Table I.

TABLE I
INSTALLED CAPACITY OF OFFSHORE WIND AND TIDAL STREAM IN BASELINE AND COUNTERFACTUAL SCENARIOS.

Zone	Offshore wind	Tidal stream
Baseline		
Z1	1990 MW	0 MW
Z7	11150 MW	0 MW
Z9	1790 MW	0 MW
Counterfactual (1 GW)		
Z1	1854 MW	790 MW
Z7	10387 MW	170 MW
Z9	1668 MW	40 MW
Counterfactual (2 GW)		
Z1	1718 MW	1580 MW
Z7	9624 MW	340 MW
Z9	1545 MW	80 MW
Counterfactual (3 GW)		
Z1	1580 MW	2380 MW
Z7	8853 MW	510 MW
Z9	1421 MW	120 MW
Counterfactual (4 GW)		
Z1	1445 MW	3170 MW
Z7	8098 MW	680 MW
Z9	1300 MW	150 MW
Counterfactual (5 GW)		
Z1	1309 MW	3960 MW
Z7	7335 MW	850 MW
Z9	1178 MW	190 MW

B. Data inputs

The energy system modelling simulates 2021, for the reasons outlined in Section I. Solar PV and onshore/offshore wind power timeseries were obtained from the Renewables.ninja tool [19]. The tool derives solar PV and wind power from resource data made available by the Modern-Era Retrospective analysis for Research and Applications (MERRA-2) project. The solar PV power data was derived based on an azimuth of 180°, 35° panel tilt and no tracking. Onshore wind power data were derived based on the power curve of a Vestas V90 3000, with a hub height of 80 m. Offshore wind power data were derived based on the power curve of a Vestas V164 9500, 9.5 MW device with a rotor diameter of 164 m and hub height of 100 m. These technology specifications are consistent with those chosen by Pennock et al. (2023) [8]. In all cases data was extracted at three locations within each zone, and averaged, to help account for the spatial variability in resource within each zone. Tidal stream power timeseries were obtained from Thetis hydrodynamic modelling [20] of the Pentland Firth, Morlais and Isle of Wight. The model has undergone validation in the main areas of tidal stream energy resource, predominantly in the Pentland Firth [21], with albeit limited validation in the Irish Sea and English Channel proximate to the Morlais and Isle of Wight sites [22]. This is a key area of further work. Power timeseries were derived from the current speeds extracted from the Thetis modelling by allocating turbine specification (i.e., rotor diameter and rated power) to achieve a capacity factor of 0.4, whilst adhering to the site specific constraints on rotor diameter and rated power set by the depth and current speeds at each of the three sites.

2021 GB demand data is obtained from NESO's data portal [23]. The demand is split by zone based on sub-national electricity consumption data from the UK Government Department for Business, Energy and Industrial Strategy (BEIS) [24].

The marginal cost of dispatching a unit of electricity from fossil fuel, nuclear and biomass plants is set based on their fuel costs, with the addition of carbon costs for fossil fuel plants, and waste transport and storage for nuclear plants. These fuel based costs are obtained from 2030 electricity generation cost projections for 2030 [25]. A scaling factor of 1.65 is applied to represent 2021 gas prices [26]. Finally hydroelectric and energy from waste are both assumed to have an opportunity cost, as these generators typically only run if they can gain a suitably high electricity price.

III. RESULTS

A. National

National scale results are first presented to comment on broad, GB-wide trends. Figure 2 shows the relationship between the installed capacity of tidal stream, and the annual dispatch of energy from tidal stream, offshore wind, CCGT and EfW. The addition of tidal stream capacity results in an approximately linear reduction in offshore wind dispatch. This is expected since offshore wind capacity is being displaced by tidal stream capacity to maintain overall energy generation. This only holds true if the introduction of tidal stream does not result in changes to the curtailment of offshore wind, which is discussed in due course.

Increasing tidal stream capacity to 5 GW a results in a 21% reduction in the dispatch of energy from CCGT, a 7.8% reduction in hydroelectric dispatch, and a 7.5% reduction in EfW dispatch. Other notable, albeit smaller impacts are a 1.7% increase in nuclear dispatch, 1.6% reduction in biomass dispatch, and a 1.4% increase in solar PV dispatch.

Figure 3 shows the relationship between the installed capacity of tidal stream, and the proportion of available

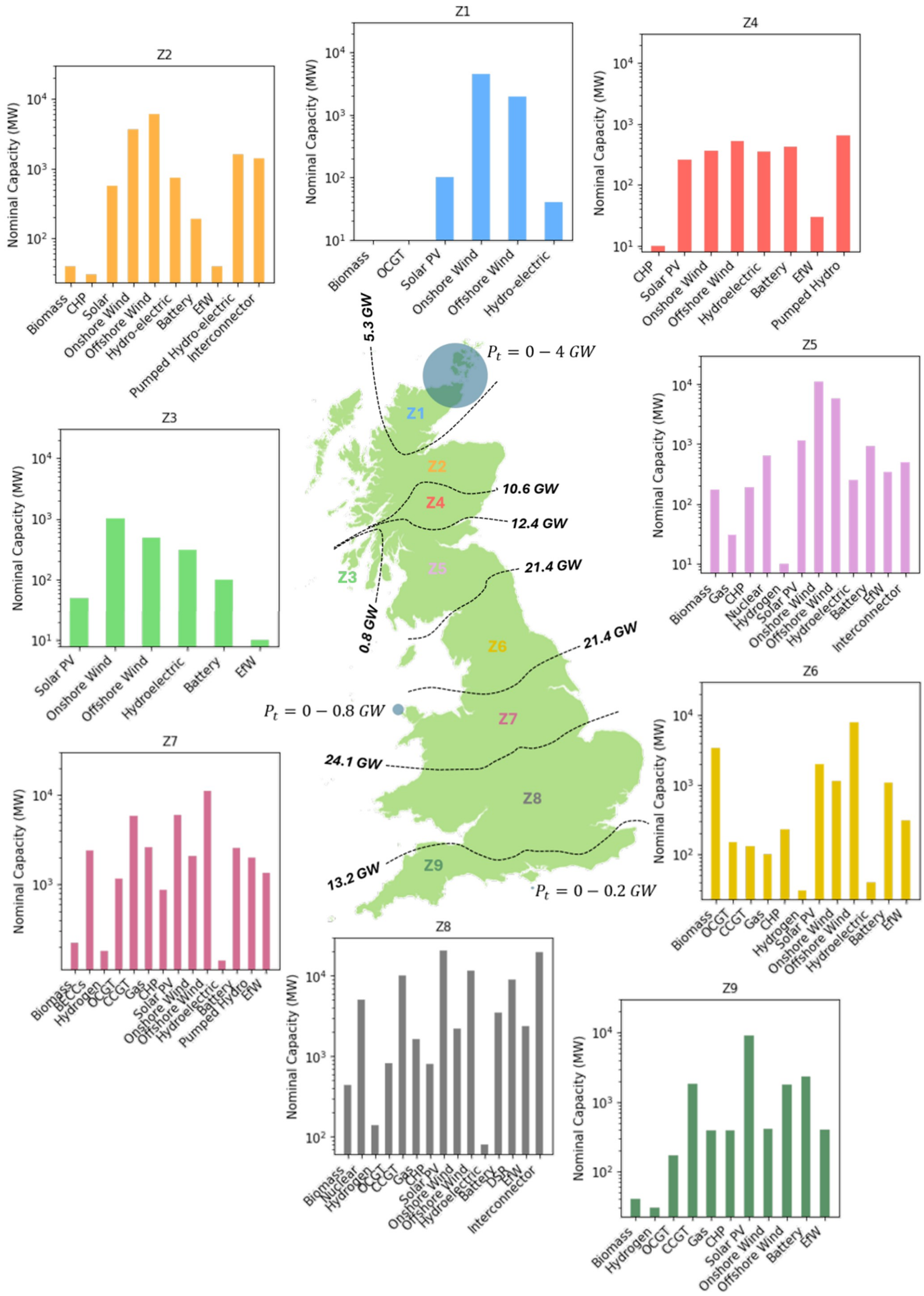

Fig. 1. Summary of UK domain used in energy system modelling, including the (i) zones along with transmission boundaries and crosszone transmission constraints, (ii) installed capacities in each zone of the baseline model, (iii) locations and capacity ranges of tidal stream deployment in the counterfactual model.

solar PV, offshore wind and tidal stream energy (E_a) that is curtailed (E_c) over the year. Results show a noticeable reduction in the proportion of available power that is curtailed with the introduction of tidal stream. This is particularly significant in the case of solar PV, which shows a 12.5% reduction in the proportion of energy that is curtailed instead of being dispatched in the counterfactual case with 5 GW of tidal stream, relative to the baseline model without tidal stream. Offshore wind shows a 9% reduction in the proportion of available energy that is curtailed. The introduction of tidal stream also results in a decrease in the proportion of available tidal stream energy that is curtailed, of 12.7%, with the increase in its installed capacity from 1 to 5 GW. This is not a linear trend, with the proportion of available power that is curtailed levelling out at around 7% by the point that 3 GW of tidal stream is installed.

The introduction of 5 GW of tidal stream capacity results in a 6.5% reduction in overall (a) annual cost of dispatch, and (b) carbon emissions. This is the result of tidal stream reducing the dispatch of CCGT generation, which is one of the main contributors to both dispatch cost and emissions. In general dispatch

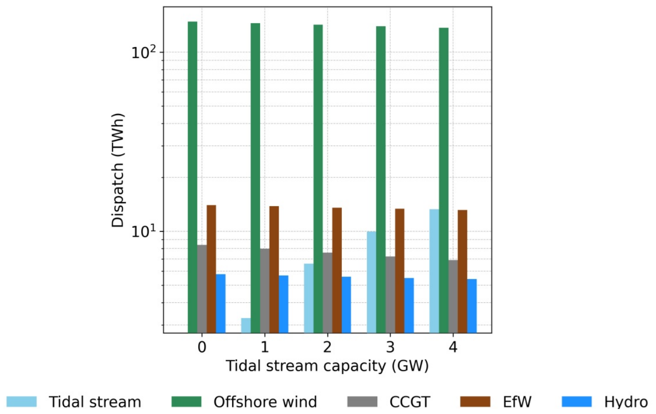

Fig. 2. Relationship between tidal stream the installed capacity, and the annual dispatch of tidal stream, offshore wind and combined cycle gas turbine (CCGT) energy across GB.

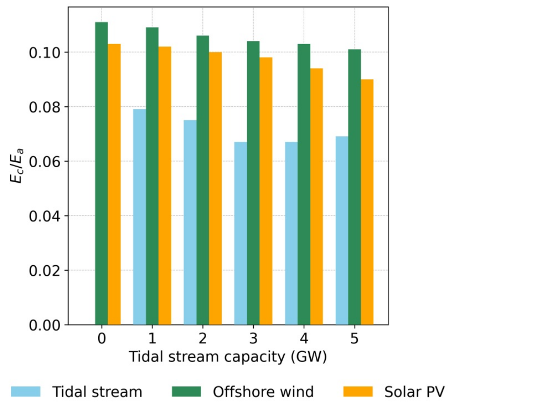

Fig. 3. Relationship between tidal stream installed capacity, and curtailment of tidal stream, offshore wind and solar PV energy, as a proportion of their available energy.

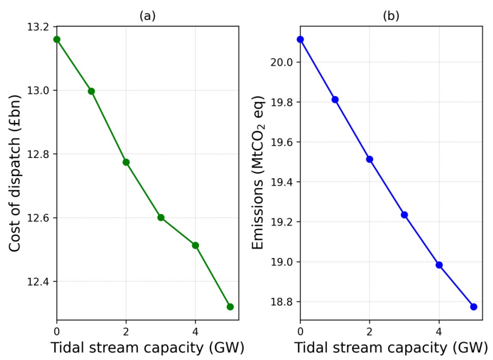

Fig. 4. Relationship between tidal stream installed capacity, and (a) system cost of dispatch, and (b) carbon emissions.

cost and emissions reduce approximately linearly with the introduction of tidal stream, as shown in Figure 4. The relationship between tidal stream capacity and cost of dispatch exhibits discrepancies to this, which is attributed to the fact that whilst fossil fuel dispatch reduces linearly with tidal stream capacity being introduced, this reduction in fossil fuel dispatch only impacts upon the dispatch cost in time steps when fossil fuel generators are no longer the marginal generator, which is not necessarily linear.

B. Regional

Figure 5 shows the change is dispatch by zone, as tidal stream capacity is added to the system. The dispatch results are normalised by the baseline dispatch in each zone. Results show a 40% increase in Z1 dispatch once 5 GW of tidal stream capacity is introduced, with 4 GW in Z1. This arises as a result of tidal stream capacity replacing offshore wind capacity in Z1, and the timeliness of this added tidal generation being more aligned with demand and storage charging capacity than that of the offshore wind energy it has replaced.

Dispatch in Z2, 3, 5, 6 and 8 remain relatively unaffected by the addition of tidal stream capacity. Z4 shows an initial reduction in dispatch as 1-2 GW of tidal stream capacity is added, then an increase and then subsequent plateauing of dispatch as 4-5 GW of tidal stream capacity is reached, to a level that is 15% greater than its baseline dispatch.

Z7 and 9 show a reduction in dispatch, even though both zones include tidal stream capacity in the counterfactual model. This is because they contain significant levels of CCGT capacity, which is often displaced by tidal stream dispatch from Z1.

Figure 6 shows the relationship between tidal stream installed capacity and the percentage change in battery load factor as a result of introducing 5 GW of tidal stream capacity, split out by zone. Results show a small but not insignificant improvement in the load factor of all batteries. This is particularly the case in Z2- 4 and Z7 where load factor improvement is between 2-3.5%. There are several reasons why battery load factor shows greatest improvement in these zones. The first is that they are proximate to the most significant levels of tidal stream energy generation. Tidal stream has been shown to be highly complimentary to short duration energy storage due to its high frequency power cycling (4 periods of power generation per day) and the relatively short slack periods between power generation [9] that batteries need to discharge over to maintain power supply to the system. Another, particularly in Z3, is that in regions with relatively low levels of power generation and storage, small changes to the supply profile that arise from introducing tidal stream capacity can have a significant impact on the performance of the energy system. A third is that in zones with significant fossil fuel generated power, power from battery storage is more likely to be favoured, thereby increasing the cycling of the battery and hence improving its load factor. Load factor is a primary driver for the economic feasibility of battery storage projects [27], and these improvements are not anticipated to be insignificant in the economic viability of battery projects.

Figure 7 shows the relationship between tidal stream capacity, and the load factors of batteries in Z2 and 3, and the load factor of a pumped hydro plant in Z7. Whilst in general the increase in tidal stream capacity results in an increase in load factor across all three technologies, results show exceptions to this trend, where load factor drops as a result of installing tidal stream capacity, only to increase again as tidal stream

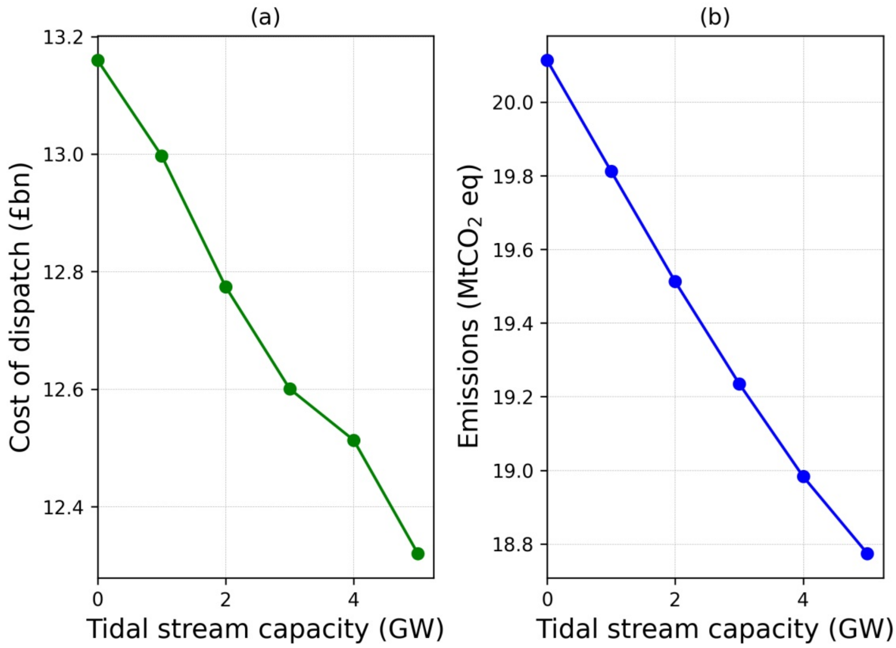

Fig. 5. Relationship between tidal stream installed capacity, and the change in dispatch, when normalised by baseline dispatch, across zones 1-9.

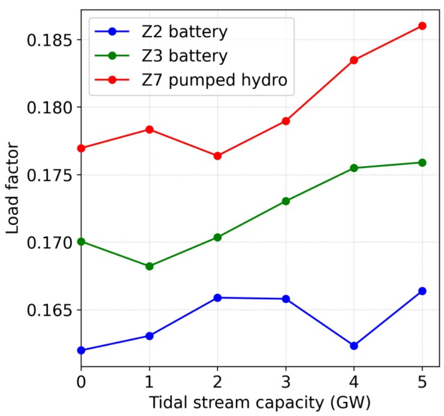

Fig. 6. Percentage change in load factor of battery stoarge in Z2-9 as a result of introducing 5 GW of tidal stream capacity across Z1, 7 and 9.

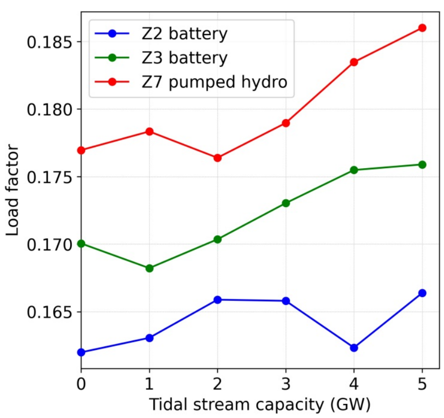

Fig. 7. Relationship between tidal stream capacity, and the load factors of batteries in Z2 and 3, and the load factor of a pumped hydro plant in Z7.

capacity is increased further.

C. Discussion

It is important to acknowledge that marginal cost is one of many economic considerations when planning future power generation. For this reason the dispatch cost results presented in this paper must be contextualised with respect to other relevant costs. For example, the estimated difference in capital cost between a tidal stream turbine project and offshore wind farm is around 4 £m/MW, or 4000 £m/GW. This is based on the reported capital cost of the 6 MW MeyGen Phase 1A tidal stream turbine array, of 8.5 £m/MW [28], and the reported capital cost for offshore wind, of 4.5 £m/MW. Clearly the capital cost premium associated with tidal stream capacity far outweighs the annual dispatch cost reduction arising from installing tidal stream capacity. Whilst out of the scope of this work, further interrogation of all additional cost considerations is needed to provide a fuller appreciation of developing one technology over another. An example of this is the potential cost benefit of minimising grid upgrades as a result of introducing tidal stream energy to the system in place of some offshore wind. It will also be prudent to consider future cost projections out to 2050, since the UK Government Department for Energy Security Net Zero estimate that the 203 levelized cost of tidal stream energy will be 180% greater than fixed offshore wind, but that gap will reduce to 30% in 2050 [**?**].

The viability of tidal stream will also be dependent on dispatch costs over the duration of the projects in question (generally expected to be 25 years), the capital cost, along with a wide range of other factors such as operating costs, and costs associated with wider system impacts from installing tidal stream capacity that are not considered in this work.

Results presented in this paper show that the introduction of 1 GW of tidal stream results in a 1.2% reduction in total annual dispatch cost, which is equivalent to 0.16 £bn, based on a low wind year. For comparison, energy system modelling carried out by Pennock et al. (2023) [8] found that for an average wind year, the replacement of offshore wind capacity with 1 GW of tidal stream capacity resulted in a 0.5% reduction in total dispatch cost (0.07 £bn). Further work is needed to determine energy system performance with/without tidal stream over the wide range of weather conditions expected during the full duration of the renewable power projects.

IV. Conclusions

This research investigates the system resilience impacts of replacing planned offshore wind with tidal stream capacity on the GB energy system, based on a low wind year in 2030. Results show that the inclusion of 5 GW of tidal stream capacity reduces the dispatch of CCGT, EfW, hydroelectric and biomass by 21%, 7.8%, 7.5% and 1.6% respectively. There are also modest increases in the dispatch of nuclear and solar PV, of 1.7% and 1.4% respectively. Further, the inclusion of tidal stream results in a modest improvement in the load factor of battery storage across GB, particularly those in close proximity to tidal stream installations. Once 5 GW of tidal stream capacity is installed, there is a 6.5% reduction in total dispatch cost and carbon emissions, which mainly arise due to a reduction in CCGT dispatch.

Results presented in this paper show that the introduction of 1 GW of tidal stream results in a 1.2% reduction in total dispatch cost, which is equivalent to 0.16 £bn, based on a low wind year. For comparison, energy system modelling carried out by Pennock et al. (2023) [8] found that for an average wind year, the replacement of offshore wind capacity with an equivalent 1 GW of tidal stream capacity resulted in a 0.5% reduction in total dispatch cost (0.07 £bn). Further work is needed to determine energy system performance with/without tidal stream over the wide range of weather conditions expected during the full duration of the renewable power projects.

Results highlight that the introduction of tidal stream energy has varying impacts across different regions. In North Scotland, there is a significant increase in renewable dispatch due to the replacement of offshore wind with tidal stream, with the timeliness of tidal power showing greater alignment with demand than the wind energy that it has replaced. Other regions in the midlands and south coast of England show a reduction in dispatch due to the displacement of CCGT generation by tidal power.

Despite these benefits, determining the economic feasibility of tidal stream remains a key challenge. While dispatch cost reductions are observed, they are relatively small compared to the high capital costs associated with tidal stream projects currently. A comprehensive analysis incorporating long-term capital/operational costs and broader system impacts is essential to fully understanding its viability in the future given that the capital cost premium of tidal stream energy is projected to reduce significantly.

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