Medium-term variability of the UK's combined tidal energy resource for a net-zero carbon grid

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Abstract: The small area of the United Kingdom relative to weather systems makes renewable energy sources variable on short time scales. Short term variability is therefore a growing concern with increasing amounts of renewable energy integration. In this work, we address how tidal energy can contribute to reducing medium-term variability in the future UK energy mix. Two tidal integration scenarios are defined for 2050: for each scenario, a five-minute interval generation profile is calculated using an oceanographic model of UK tides, and the medium-term variability is assessed. Here we show that tidal power shows a lower level of variability compared to other resources. During spring tides, a national network of tidal power stations can produce continuous, although variable, electricity. It is then shown that tidal energy and storage can provide year-round continuous and constant power output, i.e. baseload generation. Therefore, we conclude that tidal energy can provide positive contributions and complement other renewable energy sources.

Keywords: Tidal Energy, Renewable Energy Sources, Grid Integration, Energy Storage.

1. Introduction

Currently, wind and solar are the main renewable energy sources (RES) in the United Kingdom (UK). Driven by 2050 net-zero targets (1-4) further increase in the amount of RESs connected to the UK electricity grid is expected (5). According to the projections of the UK TSO, wind and solar energy will keep growing at a fast rate and they will continue to be the main sources of renewable energy in the future. The continuous growth of wind and solar energy installations is due to a combination of factors, such as their continuously decreasing cost and technology readiness level (6).

In spite of the benefits provided by wind and solar, the variability of natural resources is causing various challenges in the management of the electrical grid: short-term variability (minutes) requires fast adjustment of spinning or non-spinning reserves (i.e. combined cycle gas turbines), thus causing additional costs and emissions. Medium-term (days) and long-term variability (months) pose other challenges in relation to planning and seasonal energy storage (7). As a result, the impact of weather-depend energy sources on electricity supply will keep increasing, as well as impact on demand (8).

Various solutions to mitigate variability are available including: load flexibility, demand-side response, energy storage, interconnectors (9), improved forecasting and planning (10) increasing monitoring and automation. The above solutions require novel approaches to power system management and design, and it is important that they are correctly designed in order to guarantee system stability and security of supply (11).

Energy storage will be an enabling technology to promote the transition to low-carbon electricity. Numerous energy storage technologies are available for addressing the intermittency of VRE and providing flexibility options. Batteries, such as lithium-ion (Li-ion) and sodium-sulfur (NaS) batteries, could contribute to short-term energy storage. As reported in (12) and (13), at extremely high VRE shares over 80%, power-to-gas (PtG) technologies, such as hydrogen and methane storage, could play a major role.

Marine energy technology too in the last few years have shown a significant development, including tidal stream, tidal range and wave generation. Tidal range projects in development in the UK offer an achievable 10 GW installed capacity (14), with energy yield of around 15 TWh/year.

Both tidal and wave generation are attractive for the UK, due to its geographical and oceanographical characteristics. One advantage of tidal energy is the high level of predictability: since tides can be forecasted accurately (15), it is possible to calculate both levels and timings of tidal generation with high resolution for long timescales (decades). A second advantage is that tidal power shows low levels of harmonics and flicker thus ensuring high quality electrical output (16). Previous research addressing the UK tidal resource has aggregated various tidal sites on the power generation curve (17, 18), however, no research work has studied the impact of tidal energy on medium-term variability.

We hypothesise that medium-term variability will be an increasing challenge in the integration of RESs in the UK power grid. This paper will demonstrate that tidal energy can become a valuable complementary RES, thus helping the UK to reach the net-zero target, while guaranteeing diversity and security of supply.

A recent work (7) showed the possibility of large scale integration of ocean energy into the Nordic grid (including Norway, Sweden, Finland and Denmark). In this case, the authors conclude that a fossil and nuclear-free power system is technically feasible, if properly balanced by hydropower. However, the UK is an island nation with a smaller area and three main differences emerge: 1) spatial diversity is less thus increasing the correlation between generation at different sites (19); 2) the UK electrical grid is less resilient than the continental one, i.e. more susceptible to instability and frequency fluctuations (20); 3) hydro resources are not as widely available as in other Northern European countries.

While tidal energy is a growing technology, there is uncertainty in the future installed capacity in the UK and globally. The International Energy Agency forecasts 101 GW of installed tidal stream energy capacity by 2050 (21). The European Ocean Energy Association (2013) predicted 300 MW of tidal stream installed capacity in Europe by 2020 (22), but the number achieved was 10 MW. The UK National Grid published the last version of the Future Energy Scenario (FES) document in July 2020 and significantly increased the forecasts up to 10 GW by 2050 in the UK (5). To mitigate the uncertainty in the forecast, this paper studies two different tidal integration scenarios, based on a conservative and an ambitious acceleration in tidal energy development to 2050. Both scenarios are built from the bottom up, using the authors’ knowledge of the expected sequence of sites to be developed, which is based on the current state of industrial project pipeline, grid constraints and the underlying resource potential.

In this paper, the short-term variability due to wind and solar generation is exemplified through the analysis of historical data provided by the UK TSO. Through the use of an oceanographic model of the UK tides, five-minute data generation profiles for the two tidal energy scenarios described above are provided. The variability in the combined tidal power signal once multiple stream/range schemes are built out is investigated, highlighting the benefit of power smoothing to reduce overall intermittency. The predictable, cyclic nature of the tidal power signals is also demonstrated. Finally, the capacity of battery storage required to achieve baseload power from the combined tidal power signals is quantified.

The Authors acknowledge that the cost of marine energy technologies is not as competitive as other renewable energy sources, and probably won't be by 2050. However, the analysis carried out in (23) indicates that a significant reduction of costs is to be expected, making this technology cost competitive with nuclear power and CCGT. However, with the ambitious emission targets proposed by the UK government as well as the United nations (24), it is likely that solutions that are not the most cost effective will be required.

2. Methods

The approach adopted in this paper is briefly outlined below, and each step will be described in details in the following subsections:

1) Historical wind and solar data are extracted from (25) with 5-minute resolution. An analysis is carried out for this data to exemplify the medium-term variability of wind and solar resources.

2) The most suitable sites for tidal deployment up to 2050 are identified. For each site, an oceanographic model provides tidal heights and velocity, then the annual yield is estimated from a system model with a five-minute resolution.

3) Forecasted levels of tidal energy sources are extracted from (26) and from other sources including (21, 22, 27). Based on these data, two tidal energy scenarios are developed for 2050.

4) Sizing of energy storage is calculated, with the aim of identifying the minimum energy storage required for the tidal sites to provide continuous and constant generation.

2.1 Data collection from online repository

Gridwatch (25) provides open data on the UK electricity generation and demand for the last 10 years. Generation data were retrieved from this source, with two purposes: to assess the existing energy mix in the UK, and to understand the impact of renewable resource variability on a large scale. Gridwatch has been chosen because it provides 5-minute generation data recorded on the UK electricity grid, thus providing reliable data on the energy yield from various plants, and taking into account phenomena such as cloudiness, curtailment and maintenance that would be very difficult to model with the resolution required for this work.

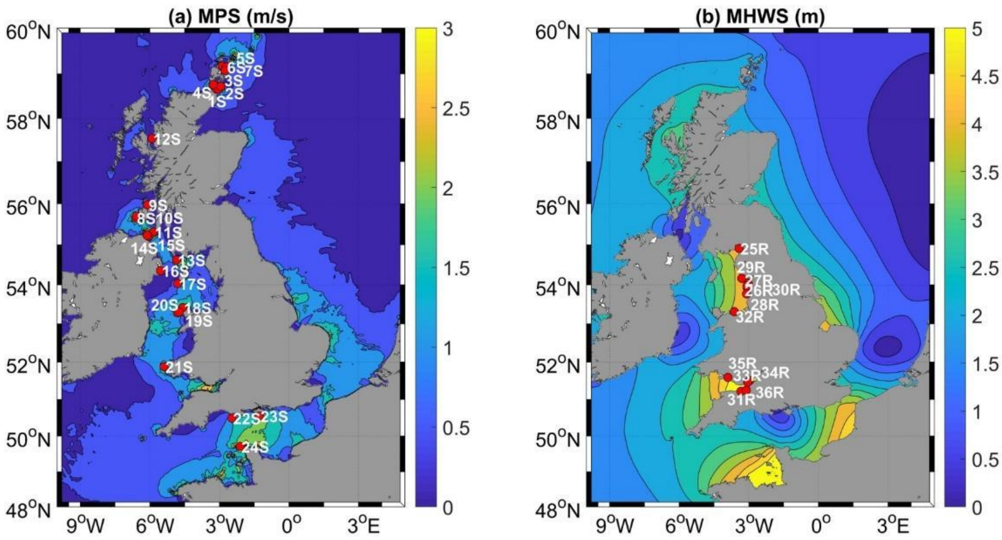
The data analysis was limited to the study of wind and solar data for three years: 2016, 2017 and 2018. Other renewable sources, such as hydro and biomass were not included, as they are less dependent on natural elements and therefore contribute less to variability. Additionally, both hydro energy and biomass are not expected to grow significantly in the near future. Tidal energy data and wave energy data were not available, as they represented only a small portion of the generation for the year considered. Older data sets were not considered because the amount of renewable energy installed was too scarce to allow for a generalisation of the results at the country level.

To accurately represent the variability of different resources, a resolution of 5 minutes was chosen. Interpolation was used to fill in 0.1% of missing data points.

2.2 Tide characterisation and prospective sites

To resolve the tidal energy resource, we use a hydrodynamical model to simulate the phasing (i.e. timing) of potential future developments in tidal power. The hydrodynamical tidal energy modelling is described in Section 2.2.1; however the spatio-temporal variability of the tidal resource resolved by our model is described below as details, important for site selection, are discussed:

The UK astronomical tide progresses from west to east, over Scotland and into the North Sea (17). Spatial tidal elevation differences drive strong currents, and variability in tidal elevation is explained by resonance to bathymetric features (e.g. Bristol Channel) and Kelvin wave processes (e.g. amphidromic points); see (28). The time of High Water (HW) advances by ~50 mins per day because of the 12.42 hour period of the major semi-diurnal lunar tidal constituent ("M2"), which controls the relative phasing of HW around the UK coastline (17, 18). The interaction of M2 tidal constituent with the semi-diurnal solar tide (S2), at a period of 12 hours, results in modulation of the HW magnitude - which describes ~75% of tidal variability (currents and elevation) in UK waters (29) and is phased-locked (largest HWs occurring at the same time of day in the 14.7 day "spring-neap cycle"). Therefore, potential tidal energy sites of Figure 1 are juxtaposed with the typical measure of resource – mean peak spring (MPS) tidal-current speed (sum of M2 and S2 harmonics) and Mean High Water Spring (MHWS) tidal amplitude (i.e. High Water height above MSL).



1S: MeyGen, Pentland Firth, Scotland;
2S: Ness of Duncansby, Pentland Firth, Scotland;
3S: Brough Ness, Pentland Firth, Scotland;
4S: Brims, Pentland Firth, Scotland;

25R: Solway lagoon Irish Sea, England
26R: Duddon Estuary lagoon, Irish Sea, England
27R: Morecombe Bay lagoon, Irish Sea, England
28R: Blackpool lagoon, Irish Sea, England

5S: Westray South, Orkney, Scotland
6S: Lashy Sound, Orkney, Scotland
7S: Stronsay Sound, Orkney, Scotland
8S: Sound of Islay, Western Isles, Scotland
9S: West Islay, Western Isles, Scotland
10S: Islay demo, Western Isles, Scotland
11S: Mull of Kintyre, Western Isles, Scotland
12S: Kyle Rhea, Western Isles, Scotland
13S: Mull of Galloway, Irish Sea, Scotland
14S: Torr Head, County Antrim, Ireland
15S: Fair Head, County Antrim, Ireland
16S: Strangford Lough, Irish Sea, Ireland
17S: Isle of Man, Irish Sea, BCD
18S: Anglesey Skerries, Irish Sea, Wales
19S: Holyhead, Irish Sea, Wales
20S: West Anglesey demo, Irish Sea, Wales
21S: St Davids Head, Pembroke shire, Wales
22S: Portland Bill, English Channel, England
23S: Isle of White, English Channel, England
24S: Alderney Race, English Channel, BCD

29R: Wyre Estuary barrage, Irish Sea, England
30R: Mersey barrage, Irish Sea, England
31R: West Somerset lagoon, Severn Estuary, England
32R: Colwyn Bay lagoon, Irish Sea, Wales
33R: Swansea Lagoon, Bristol Channel, Wales
34R: Newport Lagoon, Bristol Channel, Wales
35R: Cardiff Lagoon, Bristol Channel, Wales

Figure 1: The locations of planned or potential UK tidal energy sites and the hydrodynamic modelled tidal energy resource: currents (a) and range (b). The mean peak spring tidal-stream (MPS) current speed and tidal-stream energy sites is shown in panel a, with mean high water spring tide amplitude (MHWS) and tidal range sites shown in panel b. Planned or potential tidal energy sites were collated from planned and potential developments (31).

All potential tidal range and tidal-stream energy sites considered are shown in Figure 1. The list and magnitude of potential tidal energy sites was based on an exhaustive combination of literature and expert opinion (30). Tidal range energy sites assumed viable if the mean tidal amplitude (i.e. the M2, semi-diurnal major lunar tidal component) is above 2.5 m (15), which restricts potential development to the three main geographic regions where near tidal resonance greatly amplifies tidal elevations: the Bristol Channel, Liverpool Bay, Solway Firth. Tidal-stream energy sites were identified as those under-development or planned in the future – as regions with exceptionally strong tidal currents with resource assessments already undertaken.

Sites where the tidal resource appears large enough, yet no developments are recorded (within the UK renewable energy development database (31,32) – are most likely because of proximity to other industry, distance to a grid-connection or population, or ecologically sensitive areas. For example, in the South-eastern region of the English Channel tidal amplitudes are large enough but the proximity to major ports has resulted in no known tidal range energy developments either listed/planned or under-development.

Based on the uncertainty on the timelines for the installations, the timings of each site are not indicated, however, it is expected that these sites will be operational by 2050 and this is why the Authors chose to carry out the analysis for this year.

2.2.1 Tidal stream energy modelling

To simulate the tidal currents and elevation around the UK (see Figure 1), a successfully developed and accurate ROMS (regional ocean modeling system) tidal model was applied. This model is described in detail in (29). High spatial resolution (for a pan-UK model) of ~1 km was chosen to resolve tidal currents (33), with computed tidal harmonics (both elevation and currents) used to predict (with the t_tide toolbox) high-temporal-resolution tidal time-series (5 min resolution) at each site.

Tidal dynamics were normalised to the mean spring tide amplitude computed by the model (sum of M2 and S2 constituents at tidal energy location of Table 1); hence, the tide time-series, relative to the modelled tidal dynamics, is predicted. This relative predicted tide ensures the tidal power of a site can be scaled for a range of development scenarios, or aggregated to provide a total UK tidal energy power time-series. For tidal stream, because the relative rated and cut-in flow speed allows a normalised power time-series to be predicted (1= at rated array capacity, 0=flow below cut in speed), the normalised power time-series can be applied to a rated array size scenario, and thus the tidal power for any future time-series and development can be predicted for comparison to other renewable energy power time-series at 5 minute resolution retrieved from (25).

The ROMS tidal model was validated previously in (29): using 20 “A-class” tide gauges available through British Oceanographic Data Centre (32), with a Root Mean Squared Error (RMSE) of 15 cm and 12° for the M2 harmonic, and 5 cm and 10° for the S2 harmonic; whilst tidal current validation using 15 depth-averaged current meters gave an RMSE of 0.05 m/s and 0.02 m/s for M2 and S2 current harmonics respectively (with 12° RMSE of phase for both constituents). However, to ensure the tidal resource was predicted accurately, additional model validation was performed in this paper - using observations of tidal dynamics close to proposed tidal energy schemes (see Figure 1). Six tide-gauge records in the NTSLF (national tide and sea level facility) were used, and the most complete data series within a 12-month record of the pure “tide-only” series within the BODC record was compared to the tidal model (see Table 1). Six ADCP (Acoustic doppler current profile) records from deployments near proposed tidal-stream energy schemes were also collated in Table 1 for model validation with Root-Mean-Squared-Error (RMSE), normalised-RMSE, and the linear regression score (RSQ) shown in Table 1. The last two columns show the validation against phase and magnitude of the two main tidal constituents (M2 and S2) in terms of phase angle and magnitude.

The additional validation shown in Table 1 allows us to have confidence in the prediction of tidal phase; the key component for the aim of this paper (to resolve the impact of any tidal energy development scenario to the balance of supply-demand at a national scale). The relatively poorer validation of tidal magnitude in Table 2 (as opposed to phase), is likely due to the 1 km resolution not resolving complex bathymetric features likely to enhance the flow and thus resource (33)– and can be negated by normalising the tidal signal relative to the spring tidal dynamics (which our method is based on); hence we conclude the predicted tidal energy scenarios power time-series is accurate, as the relative temporal variability in the tidal energy resource tidal phase (compared to other renewable energy supply and demand) was accurately simulated.

Table 1: Validation statistics for both elevation (tide gauges) and currents (Acoustic Doppler Current Profile: ADCP), where the hydrodynamic model is compared to observations of amplitude (amp) and phase (pha) for two major constituents (M2 and S2), alongside Root-Mean-Squared-Error (RMSE), normalised-RMSE, and the linear regression score (RSQ).

Latitude °N	Longitude °W	Time-series validation data	Time-series validation			Harmonics difference			
			RMSE	NRMSE	RSQ	Absolute diff. M2 harmonic		Absolute diff. S2 harmonic	
						δ (amp)	δ (pha)	Δ (amp)	Δ (pha)
58.67	-3.13	(ADCP) 08/2017	0.32 m/s	14%	73%	-0.48 m/s	-15°	-0.39 m/s	-15°
53.32	-4.79	(ADCP) 08/2013-09/2013	0.66 m/s	10%	85%	-0.54 m/s	-2°	-0.04 m/s	-10°
53.44	-4.3	(ADCP) 02/2014-03/2014	0.37 m/s	16%	61%	-0.33 m/s	4°	0.06 m/s	-1°
53.24	-4.73	(ADCP) 09/14-11/14 (12)	0.59 m/s	12%	78%	-0.16 m/s	-5°	0.05 m/s	3°
59.14	-2.81	(ADCP) 10/2014	0.86 m/s	47%	89%	n/a: record too short for accurate calculation of harmonics			
59.14	-2.81	(ADCP) 11/2014 (12)	0.92 m/s	48%	81%	n/a: record too short for accurate calculation of harmonics			
51.51° N	2.72°W	(NTSLF) 2012	2.01 m/s	0.14	0.74	0.71 m	4°	0.55 m	-14°

		100% record							
51.21° N	3.13°W	(NTSLF) 2001 100% record	1.32 m	0.1	0.86	0.60 m	13°	0.44 m	-3°
51.57° N	3.98°W	(NTSLF) 2004 100% record	1.23 m	0.13	0.79	0.41 m	6°	0.32 m	-10°
53.45° N	3.02°W	(NTSLF) 2001 92% record	1.18 m	0.12	0.78	0.20 m	-2°	0.21 m	-22°
53.33° N	3.82°W	(NTSLF) 2009 85% record	0.64 m	0.07	0.91	0.15 m	2°	0.16 m	-16°
54.65	3.57	(NTSLF) 2003 100% record	0.53 m	0.06	0.95	0.25 m	8°	0.20 m	-8°

2.2.2 Tidal range energy modelling

A simple practical approach is used to simulate tidal range power plants at regions where the tidal range resource around the UK coast allows it. The subtlety that makes the representation of tidal range power plants challenging is the adequate treatment of the varying modes of operation of any tidal range energy system and the efficiency losses of tidal range turbines under varying heads of operation. This is accomplished using the application of a 0-D model (26) under a set of assumptions that generalise the method across all areas of interest.

For simplicity, we consider that all tidal range schemes will operate under a two-way generation strategy and a "fixed control" (35), meaning that the operation is not optimised to exploit the energy of individual tidal cycles, but instead generic scheduling parameters are imposed. This assumption can deliver conservative estimates given the inherent flexibility of tidal range power plants which can lead to further gains through an optimised operation featuring pumping intervals (36), while recent studies (37) demonstrate the potential to support a more continuous generation profile by combining multiple schemes in some of the sites considered herein. Generic assumptions for the tidal range power plant specifications are also imposed as per (38) where the installed capacity is determined by an empirical function of the mean tidal range and the impounded surface area. The surface area of the power plants herein is also assumed to remain constant, an assumption that presents limitations in estuarine regions that feature extensive intertidal regions. However, this can be justified if it is assumed that the area imposed is an effective impounding area that is representative of the mean surface area during the plant operation.

The 0-D model requires a free surface elevation time series at the sites of interest which was drawn from the ROMS hydrodynamic model discussed previously. Given the primary focus of that model on capturing the tidal stream phasing, the elevation time series were scaled by a correction factor based on observed data from UKHO tide gauge network. The time series were then fed to the 0-D model for all sites and instantaneous Power per Capacity (*P/C*) time series were produced that were used for each of the different scenarios.

A summary of the normalised results for the performance is included in Table 2 demonstrating how the study acknowledges that for the same energy output, a significantly different area *A* may be required based on the mean tidal range. For some of the projects listed in this table, the same location is used as they are in close proximity (i.e. 27R and 28R; 34R and 35R).

Table 2: Tidal range energy characteristics at sites of interest for the year 2018. $|H|$ is the mean annual tidal range, E_{max} is the annual theoretical potential energy (38), E is the annual energy output predicted from the 0-D model, A is the power plant impounded surface area and C is the installed capacity. η_{ext} represents the extraction efficiency relative to the theoretical potential energy. The location of each site (25R to 35R) is shown in Figure 1b.

ID	|H| (m)	E_{max}/ A (KWh/m^2)	*E/A* (KWh/m^2)	C/A (MW/km^2)	η_{ext} (%)
25R	5.35	60.26	19.14	16.09	32
26R	5.77	70.17	24.90	18.71	35
27R 28R	5.97	75.12	27.84	20.03	37
29R	5.37	60.73	19.40	16.21	32
30R	5.82	71.39	25.64	19.04	36
31R	7.07	106.51	44.26	28.09	42
32R	5.36	60.52	19.27	16.15	32
33R	6.37	86.45	33.58	22.81	39
34R 35R	7.42	117.49	49.60	30.95	42

2.3 Tidal energy scenarios

Two different tidal energy scenarios are built for 2050, using the sites listed above.

2.3.1 First scenario: FES50

The FES document provides a detailed analysis of the expected energy mix in the UK up to 2050 (26). It is based on complex assumptions in relation to: policy support, economic growth, consumer engagement and energy efficiency. Based on these five assumptions, the document provides four 'future scenarios' that highlight the possible developments of the UK energy mix. The assumptions underlying each scenario, and other resources, such as the data workbook and the modelling methods are available for free access at (26). The database is updated annually.

For each year, and each scenario, the document provides a projection of the installed capacity and generation, broken down for different energy sources. For one of the four scenarios (named ‘leading the way’) the total installed capacity of tidal energy schemes in the UK could be up to 10 GW (26). Based on this forecast, the first scenario, named FES50 is built considering fourteen tidal stream schemes (1.4 GW) and seven tidal range schemes (8.6 GW), as shown in Table 3. The table also shows the tidal resource phase: the relative timing of the tidal resource for each site is given relative to High Water at Dover. Absolute timing of peak tidal-resource, within the dominant fortnightly “spring-neap” tidal cycle of the UK, given as time of Mean High Water Spring (MHWS) for elevation, or Mean Spring Tide peak (flood tide) current, in UTC.

Table 3: List of the schemes considered for the FES50 and Max50 scenarios, with temporal variability and phase diversity in UK tidal resource described using timing difference of peak resource.

ID	Site	Installed capacity (MW) per scenario		Tidal resource phase	
		FES50	Max50	Relative peak output (HH)	Absolute time of Mean Spring (HH:MM UTC)
1S	MeyGen	400	400	-5	01:30
2S	Ness of Duncansby	100	100	-3	02:30
3S	Brough Ness	100	100	-4	01:30
4S	Brims	200	200	-2	02:30
5S	Westray South	0	200	-3	02:30
6S	Lashy Sound	0	30	-4	07:45
7S	Stronsay Sound	0	100	-3	02:45
8S	Sound of Islay	12	12	+3	14:30
9S	West Islay	0	30	-5	09:45
10S	Islay demo	100	100	-3	14:00
11S	Mull of Kintyre	30	30	-2	13:45
12S	Kyle Rhea	8	8	-6	10:45
13S	Mull of Galloway	30	30	-3	15:00
14S	Torr Head	0	100	-4	07:30
15S	Fair Head	0	100	-6	18:30
16S	Strangford Lough	0	20	-5	10:30
17S	Isle of Man	0	210	-3	14:45
18S	Anglesey Skerries	10	10	-4	02:30
19S	Holyhead	80	80	-3	03:30

20S	West Anglesey demo.	240	240	-3	03:00
21S	St Davids Head	10	10	-4	19:45
22S	Portland Bill	30	30	-6	00:00
23S	Isle of White	30	30	-3	09:15
24S	Alderney Race	0	1400	-3	09:00
25R	Solway lagoon	0	3000	+0.08	12:05
26R	Duddon Estuary lagoon	2500	2500	-0.58	11:30
27R	Morecombe Bay lagoon	0	2500	-0.5	11:35
28R	Blackpool lagoon	1000	1000	-0.58	11:25
29R	Wyre Estuary barrage	160	160	-0.33	11:40
30R	Mersey barrage	700	700	-0.5	11:30
31R	West Somerset lagoon	0	3000	-4.92	7:05
32R	Colwyn Bay lagoon	1500	1500	-0.92	11:05
33R	Swansea lagoon	0	320	-5.33	06:20
34R	Newport lagoon	750	750	-4.58	08:45
35R	Cardiff lagoon	0	2400	-4.58	08:45
36R	Bridgewater lagoon	2000	2000	-4.83	08:10
Total capacity per scenario (GW)		**10 (S:1.4+ R:8.6)**	**23.4 (S:3.6+ R:19.8)**		

2.3.2 Second scenario: Max50

In contrast to the low levels of tidal energy capacity considered in the FES analysis, the estimated installed capacity potential of tidal stream and tidal range projects is as high as 15 GW (27) and 37 GW (40), respectively. In the literature, the contributions of tidal stream and tidal range projects to the UK energy mix can vary greatly, indicating high levels of uncertainty around the long term contributions of all technologies (41).

The second scenario considered has high levels of tidal energy penetration and the total installed capacity is 23.4 GW. This ambitious scenario is considered to improve the understanding of the benefits that tidal energy projects can offer when built out at scale. Some sites are clustered in ‘hubs’ of known high energy resource. For example, four sites are located in the Pentland Firth, three around Islay and two close to Anglesey. Co-locating projects at these hubs can bring practical benefits, as site developers may be able to share infrastructure costs, such as any necessary improvements to roads/harbours/ports/grid. It also enables dedicated supply chains to emerge to reduce cost and generate jobs.

The installed capacity of tidal stream projects is 3.6 GW and 24 projects are considered, as shown in Table 3. This installed capacity could be achieved with a build out rate of approximately 100 MW/year, which has been adopted in literature by the Offshore Renewable Energy Catapult (27). The tidal range installed capacity is 19.8 GW in 2050. This is achieved by 12 projects, with installed capacities informed by the Hendry Review (40).

2.4 Energy yield and energy storage calculation

The combination of the power outputs from all sites allowed calculating the five-minute tidal energy profiles for each scenario. The final step of this work consisted in sizing the energy storage required to achieve constant power output from all sites and equal to the average power output. This design choice was made because even in Max50 scenario, tidal energy will be only a small portion of the total energy installed and will contribute only minimally to supply the forecasted energy demand. Therefore, it is hypothesized that other technologies, such as energy storage, hydrogen and flexibility services will be used to meet the rapid demand, while tidal energy will supply baseload generation as currently done by nuclear energy (5, 25).

For each data point, the difference between 'average' power output (i.e. the objective value) and 'actual' power output was calculated. A positive difference meant that power was absorbed by the energy storage unit; a negative difference meant that power was absorbed by the energy storage unit. The maximum value of this difference led to calculating the power rating (MW) of the energy storage unit.

It was assumed that the difference calculated above was constant for each five-minute interval between two data points, thus leading to determining the energy rating in GWh.

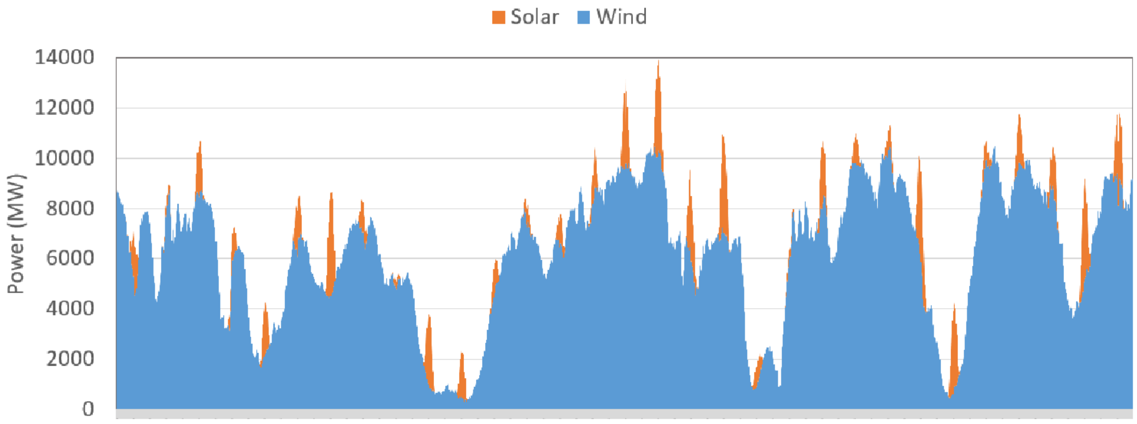
A round trip efficiency of 85% for the energy storage units was assumed to provide a conservative, result, although energy storage technologies are evolving rapidly and the expected efficiency in 2050 may be higher. Additionally, active management of the tidal range holding period and the use of pumping at slack tide can provide a different type of storage mechanism, reducing the energy storage power and rating.

3. Results

3.1 Analysis of historical data

Solar and wind generation data are plotted in Figure 2 for January 2018 and July 2018. These two months exemplify the behaviour of these two sources for the UK, in the winter and in the summer. In winter months wind generation is more prominent than in the summer, when solar generation provides a greater contribution. The maximum power output of solar power in January 2018 was approximately 4 GW, while average solar generation was less than 1 GW. Wind generation provided up to 10 GW peak and approximately 6 GW average. In July 2018, solar energy provided up to 8 GW maximum power while wind is generally below 2 GW (except for a few days at the end of July).

Similar behaviours are observed for other months in 2018. Data for 2016, 2017 and 2019 were also analysed, leading to similar conclusions (25). The detailed analysis of interannual variability is out of the scope of this paper, although it is a very important topic as described in (42).



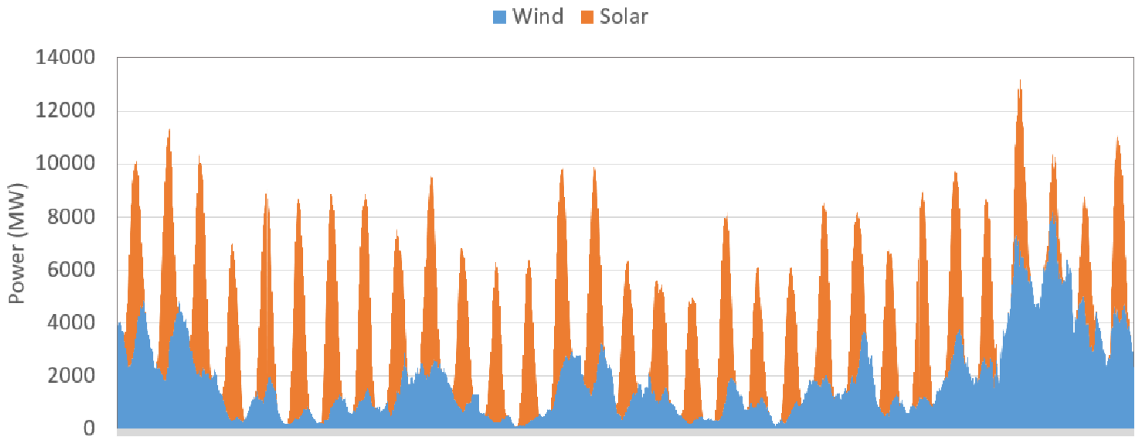


Figure 2: Wind and solar generation for January 2018 (top) and July 2018 (bottom). The data is cumulative with solar added to wind. Data from (18).

Wind generation shows significant medium-term variability caused by weather systems that typically affect the entire UK (19, 43). Since large wind plants are currently located in close proximity (onshore in Scotland, offshore in the east coast), spatial diversity is further reduced (31). For the future, it can be expected that further penetration of wind generation is likely to exacerbate this condition, although some spatial variability may be introduced by resources installed further offshore, where the wind resource is also more consistent.

Solar generation presents repeated patterns, however, significant day-to-day variation in the summer are evident, to be attributed to clouds variability. In the winter, the levels of solar energy generation are low due to short days and low levels of irradiance.

The combination of wind lulls and low irradiance in the winter leads to overall lower levels of renewable generation. This phenomenon is typical of other north European countries, and is defined by the term ‘dark doldrums’ (44). Currently, these shortcomings in energy generation are met through thermal plants, while heat storage is used in some countries.

While the more regular energy generation due to solar energy may allow for sizing energy storage units to mitigate day-to-day variability in the summer months, this approach may be more challenging in the winter months (45). However, with new energy storage technologies being developed, this concern may be mitigated in the future, for example by deployment of thermal energy storage (46), and hybrid electrical and thermal energy storage solutions (47).

The installed capacity of wind and solar energy in 2018 was 20.9 GW and 12.7 GW respectively (26), however, the actual installed capacity per month is not known. Additionally, the levels of curtailments and outages of wind and solar plants are not known. In spite of these limitations, however, further insights can be extracted from the data.

Eight shortfall events (where power output falls below 10% of 33.6 GW for three days) were counted in 2018. This metric has been chosen because it is a typical event reported elsewhere, and represents the worst case scenario for system planning in the UK (45). The total occurrence of generation below 10% takes place for approximately 28% of the time. This result is important for two reasons: firstly, it exemplifies the low capacity factor of RESs and it shows some short-fall events present a long duration and pose challenges for the transmission system operator. Given the low spatial diversity and the high proportion of wind and solar plants in the UK, it can be expected that variability of these resources will be exacerbated (48) for the foreseeable future. Predicting the variability of renewable energy generation in the future is an important research question that will require significant investments to develop not only accurate weather models, but also site-specific models.

3.2 Scenario FES2050

Figure 3 shows the forecast power generation time series from tidal stream schemes, tidal range schemes and their combination for the first scenario (FES50). The 10 GW generation assumed for this scenario is made up of 1.4 GW of tidal stream capacity and 8.6 GW of tidal range capacity according to (5).

Timeseries data is included for periods of (a-c) 1 year and (d-f) 15 days, covering a spring neap cycle. The annual power time series show high levels of power generated during spring tides, and lower levels of power generation during neap tides. Highest spring tides occur during the spring and vernal equinox’s, around the 21st March and 23rd September respectively, resulting in slightly higher levels of power generation than that around the summer and winter solstices. Both tidal stream and tidal range schemes generate power cyclically, with power generation peaking four times a day, as a result of the semi-diurnal tides in the UK.

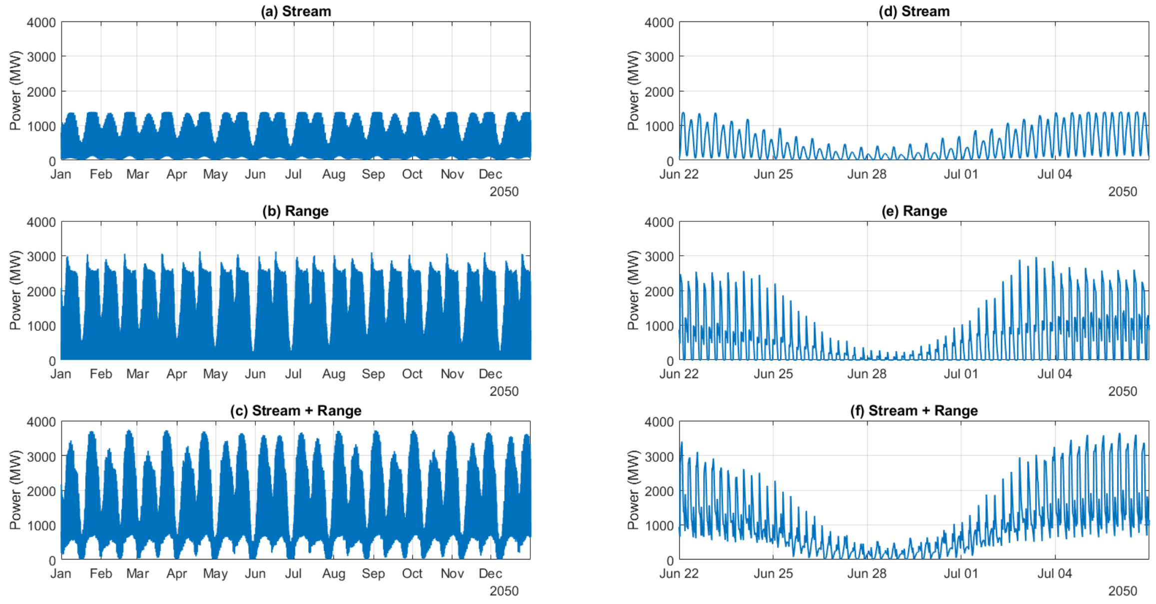


Figure 3: FES50 scenario - Forecast power generation time series from tidal stream and tidal range schemes over (a-c) 2050 and (d-f) a spring neap cycle.

The maximum total instantaneous power generated by the tidal stream schemes is 1.4 GW (Figure 3a), i.e. the same as the installed capacity. This demonstrates close alignment in the phasing of tidal stream power generation, since all sixteen tidal stream schemes generate maximum power at the same time. Close phase alignment in the tidal stream sites also results in slack tide occurring around the same times, resulting in generation falling below 10% of installed capacity 21% of the time.

The maximum total instantaneous power generated by the tidal range schemes is 3.13 GW (Figure 2b), 64% lower than the total installed capacity of the range schemes (8.6 GW). This demonstrates a level of generation phase difference between tidal range schemes. However, even with this generation phase difference, generation below 10% of the range installed capacity occurs 64% of the time, over three times the period of the tidal stream schemes. This is because (a) the capacity factor of the tidal range schemes is relatively low, (b) the operation of the tidal range schemes is such that they generate at high power levels for short periods of time, and (c) the phase diversity of tidal power plants is limited among schemes in the Irish Sea, and for schemes within the Bristol Channel. While schemes in the Bristol Channel complement ones in the Irish Sea, if they are operated to maximise yield, there are gaps that remain.

Figure 3c shows that when the tidal stream and tidal range schemes are combined, the phase difference between the technologies is beneficial and periods with low generation are reduced significantly. Generation below 10% of the overall installed capacity occurs just 10% of the time, less than the analysis of solar and wind data. Furthermore, low generation takes place only for a few hours rather than for days as shown for wind generation.

The maximum combined generation varies significantly in a month, from 500 MW during neap tides to 3.6 GW during spring tides. During spring tides the combined power is maintained above c. 650 MW for periods of c. 6 days, because of differences in phasing of generation from tidal stream and tidal range projects.

3.4 Scenario Max50

In the larger Max50 scenario (Figure 4), the total installed stream power is 3.57 GW and the total installed tidal power is 19.83 GW. As with the FES50 case, close phase alignment results in slack tide occurring around the same times at the location of the tidal stream sites, resulting in periods with zero generation. This is illustrated in Figure 4d, which shows the forecast power generation time series of the tidal stream schemes over a spring neap cycle in 2050. This phenomenon confirms the conclusions included in (45) about the lack of spatial diversity in tidal generation, and by considering Figure 4f, tidal stream and tidal range generation appears to be broadly in phase.

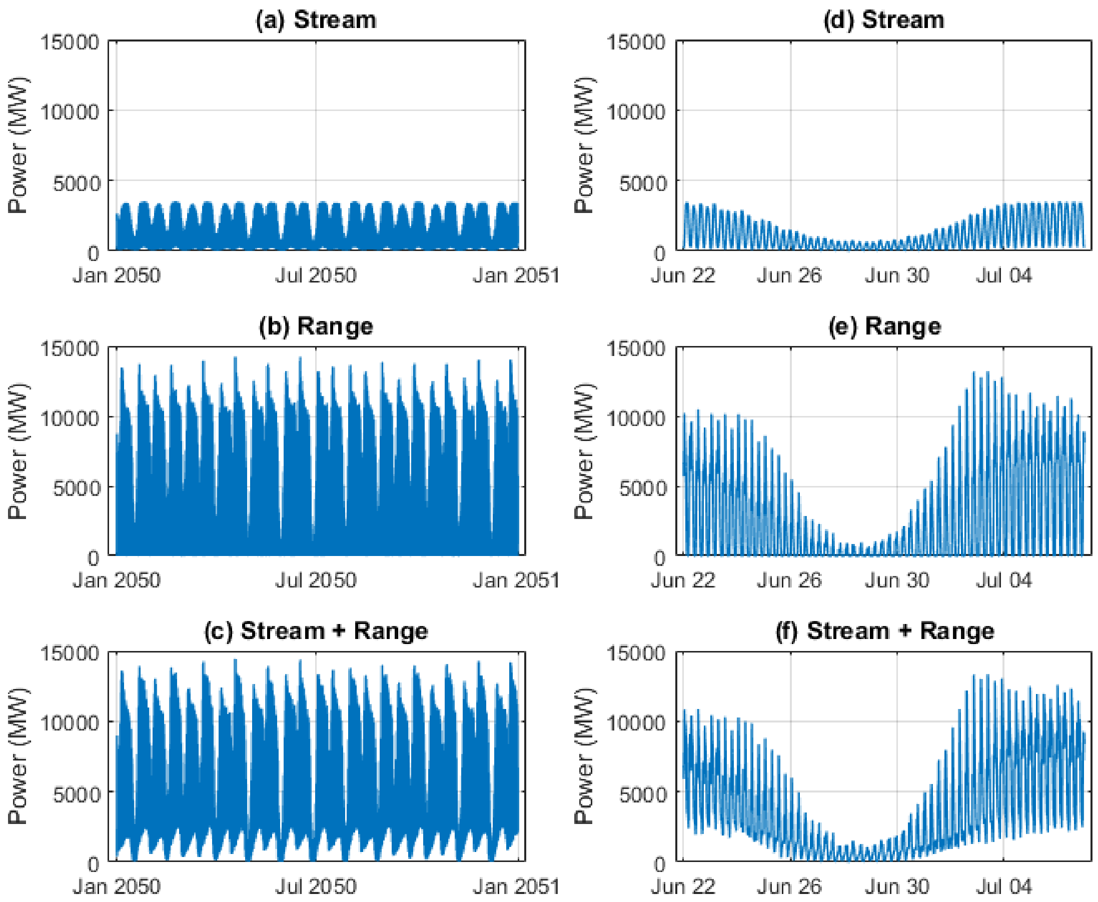


Figure 4: Max50 scenario - forecast power generation time series from tidal stream and tidal range schemes over (a-c) 2050 and (d-f) a spring neap cycle.

The maximum total instantaneous power generated by the tidal range schemes is 14.2 GW, 28% lower than the 19.83 GW total installed capacity. Compared to tidal stream, this higher level of phase difference between the tidal range schemes may be useful in minimising periods of no/low power generation. When combined, the maximum power generation from both tidal stream and tidal range projects again varies throughout the month from ~1 GW at neap tides to 14.4 GW during spring tides. Results show that by building out both tidal stream and tidal range schemes, periods with zero total generation are minimised. During spring tides the combined power is maintained above c. 2 GW at all times, because of differences in phasing of generation from tidal stream and tidal range projects. Tidal stream schemes generate in periods when flow speed exceeds c. 1 m/s, whilst tidal range generates around slack tide.

The two scenarios studied above indicated that the appropriate use of tidal schemes can reduce the 'shortfall' events highlighted in Figure 2. Additional methods to enhance integration of tidal energy into the electricity system are discussed in the next section.

3.5 Energy storage rating for baseload generation

The analysis carried out above shows that both tidal generation scenarios do not provide enough diversity to provide a constant power supply, in agreement with previous literature (17, 18). However, as described in Section 2.7, the predictability of tidal generation allows sizing energy storage to provide continuous generation year-around.

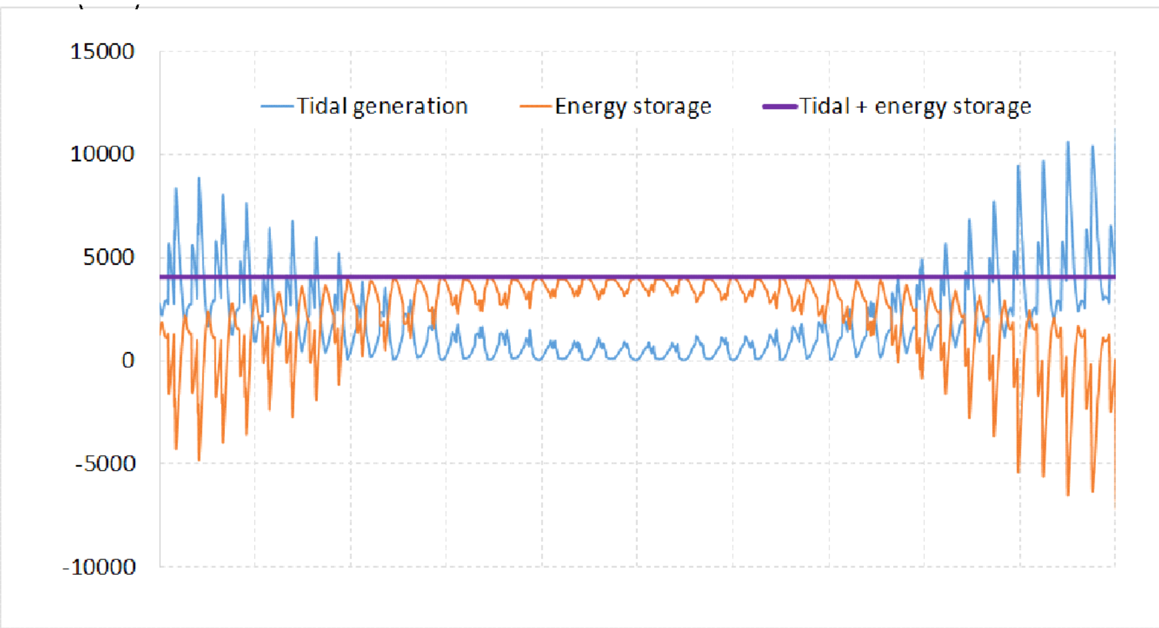


Figure 5: Power generation profile for the case when tidal generation (Max50) is combined with energy storage to achieve constant generation.

The approach adopted is exemplified in Figure 5 for the Max50 scenario, where three power curves are indicated: tidal generation, energy storage exchange, and the combination of the two. 'Tidal generation' includes both tidal stream and tidal range. 'Energy storage' shows the power flow in and out of the battery: positive power corresponds to battery discharging (i.e. acting as power supply), negative power to battery charging. The curve 'tidal energy + energy storage' corresponds to an average and constant generation obtained by combining tidal generation and energy storage charge and discharge. For the case of Max50 scenario, it is approximately 4.53 GW, for the case FES50, it is approximately 2.3 GW.

To put this number in context, in 2019, the installed nuclear capacity in the UK was 9.25 GW, while projected values for 2050 vary between 5.45 and 15.92 GW (5). Therefore, the average tidal generation obtained from the proposed scenarios could be a significant proportion of nuclear capacity.

In terms of energy storage requirements to achieve constant output generation, the following ratings are required, based on the assumptions described in Section 2.7: 360 GWh/4 GW for FES50 and 757 GWh/10 GW for Max50. These ratings are driven by two main factors:

- Reduced generation on neap tides for a few consecutive days (as shown in Figure 3.f and Figure 4.f) drives the need for large energy ratings (GWh). Allowing a reduced power output for the combined tidal power and energy storage curve (purple trace) during neap tides would lead to a significant reduction in energy storage requirements.
- The power rating of the energy storage units (GW) is mostly determined by the 'fixed control' assumed for the tidal plants (Section 2.6) that results in synchronised generation and fast power variations in the tidal generation profile. The power rating of the energy storage unit would be reduced by adjusting the water holding pattern of the tidal range sites, although this modification may impact overall generation output (37).

The Authors recognise that the cost and environmental impact of large energy storage units may be excessive. However, in the future energy systems, various solutions to achieve a constant generation may be available instead of considering dedicated energy storage. Taking into account that up to 200 GWh energy storage (pumped hydro, battery, compressed air and liquid air), up to 14 TWh hydrogen, and up to 96 TWh for interconnectors are forecast to be in service by 2050 (26), the grid may be able to accommodate tidal variability and dedicated large energy storage units may not be required. Simultaneously, by developing tidal energy power-plants, large longer-term energy storage units could be reduced – potentially making a more resilient and economically efficient national electricity grid.

4. Conclusions

This paper focused on the impact of medium-term variability of tidal energy in the future UK power grid. Wind and solar variability has been evaluated based on historical data, while tidal energy variability has been calculated based on forecast tidal power generation for two scenarios.

The results show that the short-term power variability of tidal energy is low, as tidal elevations and flow speeds do not fluctuate on sub-minute time scales. Medium-term variability is less than other renewable sources as tides repeat approximately every 12 hours. Therefore, the gap in generation lulls is reduced compared to those observed from historical data of wind and solar resources.

The aggregation of UK tidal energy projects shows that generation from various sites is broadly in phase, and therefore medium-term variability can still be observed. Nevertheless, tidal energy can bring positive contributions to the medium-term variability of the future energy mix, because it is cyclic, persistent and can be predicted in advance. Through the spring tide part of each month, continuous (although variable) and predictable generation is achieved, thus further helping with planning and reducing times when standby generation is used.

The paper showed that it is possible to size energy storage to result in a constant tidal power output. Due to neap tides, the amount of storage that is required to achieve this result is significant. However, the size of energy storage units may be reduced by relaxing some of the conservative assumptions made in this work. Additionally, it may not be necessary to install dedicated energy storage for the tidal resource, as it is expected that the future energy system will already include substantial flexibility.

As a result of this work, we conclude that tidal energy is a valuable energy source for the UK and can complement other technologies such as wind and solar.

Future work in this area will investigate approaches to smooth the tidal generation profiles and identify methods to adjust local demand profiles to follow more closely the tidal generation. We also look to collaborate with other researchers who may have an interest on weather-dependent energy resources and development of a system-level model with detailed generation forecast.

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