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Citation for published version:
Pennock, S, Coles, D, Angeloudis, A, Bhattacharya, S & Jeffrey, H 2022, 'Temporal complementarity of marine renewables with wind and solar generation: implications for GB system benefits', *Applied Energy*, vol. 319, 119276. https://doi.org/10.1016/j.apenergy.2022.119276

Digital Object Identifier (DOI):
10.1016/j.apenergy.2022.119276

Published In:
Applied Energy

Applied Energy 319 (2022) 119276

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Temporal complementarity of marine renewables with wind and solar generation: Implications for GB system benefits

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HIGHLIGHTS

- Temporal characterisation of wave and tidal resource availability for Great Britain.
- Ten metrics used to explore temporal characterisation and supply-demand matching.
- Generation profiles with marine energy consistently outperform those without.
- Correlation with load is not a suitable metric to establish supply-demand alignment.
- Detailed discussion of potential GB power system benefits from marine energy.

ARTICLE INFO

Keywords:
Marine energy
Temporal characterisation
System integration
Wave energy
Tidal stream energy

ABSTRACT

Wave and tidal energy have the potential to provide benefits to power systems with high proportions of stochastic renewable generation. This is particularly applicable in combination with wind and solar photovoltaics, as the offsetting of these renewable resources results in more reliable renewable generation. This study utilises ten metrics to quantify the temporal complementarity and supply-demand balancing requirements of the energy mix in Great Britain, to investigate the potential magnitude of these system benefits. Wave and tidal generation profiles are created using historical resource data and hydrodynamic models. The results show that the inclusion of wave and tidal generation creates a renewable energy mix which is more available under multiple conditions: throughout a year of operation; at times of peak demand; for multiple consecutive hourly time periods; and at times when wind and solar generation are not available. Three regional case studies also show that the inclusion of marine energy allows for improved regional supply-demand matching, reducing instances of energy shortage and excess and potentially relieving transmission congestion at particularly constrained locations within GB. Finally, the implications of these findings are discussed in terms of GB wholesale market operation, system balancing and system security.

1. Introduction

The International Energy Agency have identified that 75% of the CO_2 emissions reduction required in the transition to long term decarbonisation will have to come from technologies which are not yet commercially deployed [1]. Marine energy technologies, which generate renewable electricity from waves and tides, have a large global resource and thus the potential to form part of the long-term energy mix. This potential is recognised by the European Commission, which has set European deployment targets for marine energy of 1GW by 2030 and 40GW by 2050.

The UK is currently a world-leader in marine energy technology development, research and deployment. There are two operational tidal stream arrays, with 6 MW installed capacity at SIMEC Atlantis' MeyGen site [2], and 0.5 MW at Nova Innovation's Bluemull Sound site [3]. Orbital Marine Power's 2 MW floating tidal stream device has also been deployed in the UK, at the Fall of Warness site [4]. The world-leading Wave Energy Scotland programme, funded by the Scottish

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https://doi.org/10.1016/j.apenergy.2022.119276
Received 29 November 2021; Received in revised form 1 March 2022; Accepted 10 May 2022
Available online 19 May 2022

Government, utilises a focused pre-commercial procurement programme to develop innovative solutions to the technical challenges facing the wave energy sector [5]. The UK is also home to the European Marine Energy Centre, which has hosted the highest numbers of marine energy converters around the world, with 13 grid connected test berths across 5 sites [6].

Currently, forecasts for future net-zero energy mixes in the UK rely heavily on established renewable technologies such as wind and solar, supported by large deployment of storage such as batteries and green hydrogen to ensure that demand can be met at times of low wind and solar resource [7,8]. However, it is postulated here that ocean energy technologies, which have been shown to have resource that is temporally offset with wind and solar [9,10], could potentially assist with demand–supply matching without incurring the electrical losses associated with energy storage.

Introducing a new power generation technology on to the grid can have impacts over a range of electricity and ancillary services markets, as well as on the operation of the electricity network. Such impacts include [11]:

- Wholesale electricity market operation, ensuring consistent availability of low cost, low carbon electricity generation.
- System balancing mechanisms and markets, ensuring accurate forecasts of generation output.
- Capacity markets, particularly ensuring system security through reliable electricity production during periods of high demand.
- Electricity network constraints, ensuring new forms of generation can be connected near demand centres, or in locations/instances where the network is not impacted by operational constraints such as thermal, voltage and inertial requirements.

Introducing ocean energy technologies to energy mixes could positively impact power systems and markets in a number of ways. Wave and tidal resource generation is often temporally offset from established renewable resources such as wind and solar, with combined wave and wind deployments as a particular focus for resource offsetting studies [9]. Wave and wind resource are known to have a low correlation for the western offshore areas in Europe, with combined generation profiles which include ocean energy resulting in a lower variation of power output and instances of zero power output [10]. Combined deployments between ocean energy and established renewables could also improve the cost-effectiveness of offshore renewable deployments, sharing infrastructure such as anchors, moorings and power cables.

Furthermore, ocean energy generation profiles are shown to be more available and persistent for four sites spanning the USA and Scotland [12]. Balancing costs and requirements are projected to reduce by the inclusion of ocean energy in renewable energy mixes as per a number of studies [12–14]. While several studies discuss the potential for positive system impacts related to deploying ocean energy, none were found which focus on the combined contributions from wave and tidal energy sources within the electricity system of Great Britain (GB), a prime example of nation that stands to benefit from wave and tidal energy. In addition to this, many examples in the literature are limited to correlation coefficients (within generation and load profiles) as a means to explore temporal and spatial resource offsetting and capacity factors as a route to assess availability of generation profiles [15–18]. This study addresses this gap in the literature, extending the methodological approach to ten different metrics designed to quantify the complementarity of wave and tidal generation profiles with established renewables and load for the GB system.

The key objectives of this study are to:

- Create hourly power generation time series for GB which are representative of current wave and tidal generation technologies, including the simulation of tidal streams at sub-km resolution.
- Analyse the contribution of wave and tidal generation within the electricity system of GB using a novel assessment method. Accordingly, ten temporal characterisation metrics are utilised, interrogating the availability, persistence and versatility of individual and combined generation profiles, alongside modelling of net load and import/export requirements of specific regions within GB.
- Compare temporal characterisation analyses with electricity system modelling, to investigate the additional insights gained from using a larger suite of metrics, compared with the historical reliance on correlation coefficients and capacity factors.
- Compare whole system analysis with regional case studies for GB, highlighting the value of using higher resolution modelling for spatially sensitive renewable resources.

2. Methods

This study generates and analyses time series data representing stochastic renewable generation (onshore and offshore wind, solar, wave, tidal stream, and tidal range) and load for the GB power system. A full year of stochastic renewable resource, generation and load data is used, consistently for the year 2019. 2019 is selected as a reasonably representative year, following analysis of generation capacity factors between 2015 and 2020. The study uses four temporal characterisation metrics (correlation coefficients, resource availability, resource persistence, resource versatility) and six power generation performance metrics (annual energy yield, capacity factor, effective load carrying capacity, percentage renewable energy consumption, energy shortfall and energy excess) to quantify the power system impacts of including marine energy with electricity generation profiles. The following subsections outline the scenarios considered, the data inputs and sources, and the metrics used in this analysis.

2.1. Scenarios

2.1.1. GB System case study

There is currently 24GW of wind [19] and 13GW of solar PV generation [20] installed in the GB system. Taking this proportional breakdown, combined technology mix time series have been created to represent this current renewable capacity in GB, and the potential renewable capacity including up to 10GW of wave, tidal stream and/or tidal range in the GB energy mix. Table 1 shows the proportional installed capacities used for the five technology mixes investigated in the GB system case study analysis.

2.1.2. Regional case studies

Three regional case studies have been selected, as zones within the GB power system which experience transmission constraints [21], and have a significant marine energy resource. These regions will be referred to as Orkney & North, Argyll, and South-West England. Table 2 indicates

Table 1
Generation mix scenarios analysed for GB system case study.

Technology mix	Installed capacity (GW and % of renewables mix)				
	Wind	Solar	Wave	Tidal stream	Tidal range
Wind & Solar	24 GW (65%)	13 GW (35%)	–	–	–
Wind & Solar & Wave	24 GW (51%)	13 GW (28%)	10 GW (21%)	–	–
Wind & Solar & Tidal stream	24 GW (51%)	13 GW (28%)	–	10 GW (21%)	–
Wind & Solar & Tidal range	24 GW (51%)	13 GW (28%)	–	–	10 GW (21%)
Wind & Solar & Wave & Tidal stream & Tidal range	24 GW (51%)	13 GW (28%)	3.3 GW (7%)	3.3 GW (7%)	3.3 GW (7%)

Table 2
Generation mix scenarios analysed for regional case studies.

Region	Technology mix	Installed capacity (MW)					
		Onshore wind	Solar PV	Offshore wind	Wave	Tidal stream	Tidal range
Orkney & North	Onshore wind & Wave	1876.3	–	–	1030	–	–
	Onshore wind & Tidal stream	1876.3	–	–	–	1030	–
	Onshore wind & Wave & Tidal stream	1876.3	–	–	515	515	–
	Onshore wind & Offshore wind	1876.3	–	1030	–	–	–
Argyll	Onshore wind & Wave	341	–	–	142	–	–
	Onshore wind & Tidal stream	341	–	–	–	142	–
	Onshore wind & Wave & Tidal stream	341	–	–	71	71	–
	Onshore wind & Offshore wind	341	–	142	–	–	–
South-West England	Solar PV & Onshore wind	333.1	3233	–	–	–	–
	Solar PV & Onshore wind & Wave	333.1	3233	–	300	–	–
	Solar PV & Onshore wind & Tidal stream	333.1	3233	–	–	300	–
	Solar PV & Onshore wind & Tidal range	333.1	3233	–	–	–	2500
	Solar PV & Onshore wind & Wave & Tidal stream & Tidal range	333.1	3233	–	150	150	2500
	Solar PV & Onshore wind & Offshore wind	333.1	3233	300	–	–	–

the current installed capacity of onshore wind and solar PV within these regions, and the assumptions for potential future installed capacities of marine energy. Current installed capacities of wind and solar are taken from the UK Government Renewable Energy Planning Database [22], which lists operational sites by region. Potential future installed capacities of offshore wind, wave and tidal stream or range allocated to each region are based on the estimated capacities of the tidal energy sites within that region, as the resource with potentially the highest constraints. Tidal range is included only for the South-West England region, with an installed capacity of 2.5GW assumed for a tidal range development in the South-West region, within the Bristol Channel.

2.2. Data inputs

The following sections detail the sources used for generation and load time series data. Historical load data and historical wind and solar generation is available at GB scale. For regional analyses, hypothetical time series had to be created to represent regional wind, solar PV, wave and tidal generation. 2019 has been chosen to represent a typical example year. A time series here is defined as $X = \{x(1), x(2), \ldots, x(t), \ldots, x(T)\}$, where the time window ranges from $t = 1$ h to $t = T = 8760$ h for an hourly time series representing one full year of data. Fig. 1 shows the variation in hourly capacity factor of different renewable power generation technologies over a year, based on the 2019 resources in the South West of England. The wind and wave resource is greatest during the winter months, whilst the solar PV resource is greatest during summer months in the northern hemisphere. The tidal stream and tidal range resource is cyclic, with the magnitude of the resource remaining consistent on a monthly basis.

2.2.1. Tidal resource and generation

To characterise the tidal stream and tidal range resource, regional coastal ocean flow models were configured in the *Thetis* coastal ocean model [23] to simulate the variability in the tidal stream resource at sites of interest. The domains of the four regional models are shown in Fig. 2. *Thetis* solves the non-conservative form of the non-linear shallow-water equations and has been employed in several studies [24–26] contemplating the impact assessment and optimisation of tidal stream and tidal range energy schemes. Model validation has been conducted previously in the main regions of tidal stream/range resource such as the Pentland Firth and Orkney isles [27], Irish Sea and Bristol Channel and the English Channel [28]. The spatial resolution of the models has been refined in areas of interest for tidal stream/range energy extraction. The coordinates representing each individual areas is based on a study commissioned by The Carbon Trust [29], the location of which are also shown in Fig. 2, and listed in Table 3.

At the tidal stream sites, velocity magnitude predictions were exported at a 100 s intervals over a simulation period of 3 months. The

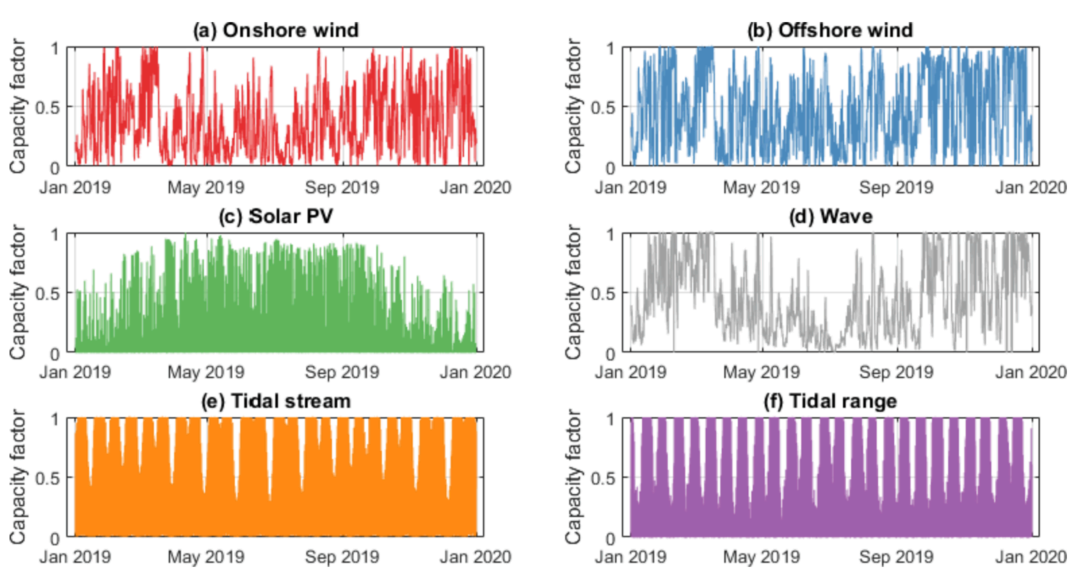

Fig. 1. Hourly variation in the 2019 capacity factor of (a) onshore wind, (b) offshore wind, (c) solar PV, (d) wave, (e) tidal stream, and (f) tidal range, for the South West England region.

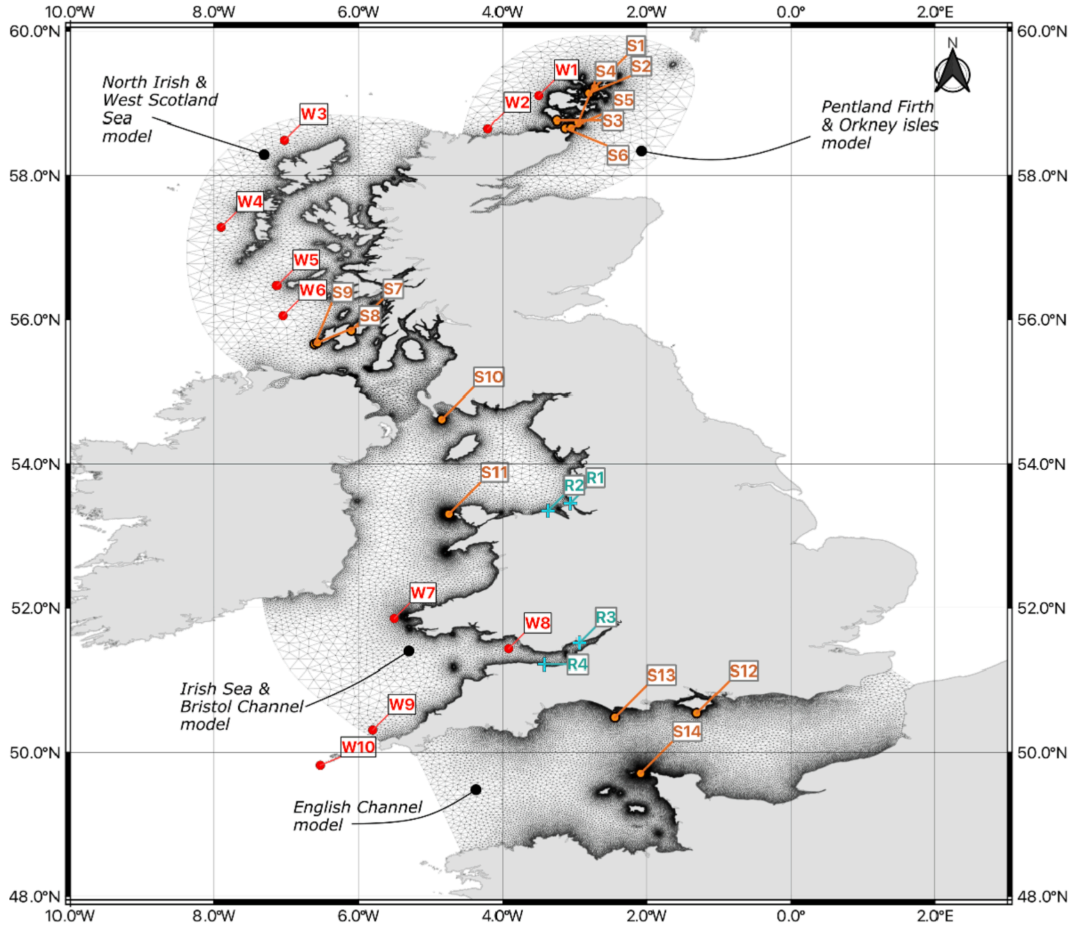

Fig. 2. Tidal models configured to characterise the tidal energy resource at prospective tidal stream (S) and range sites (R). Locations for wave data (W) are also included.

Table 3
Tidal stream & range site locations used for GB and regional case studies.

ID	Region	Site	Data Source	Coordinates (Lat, Lon)
S1	Orkney & North	Westray South	Thetis	59.13, −2.80
S2	Orkney & North	Lashy Sound	Thetis	59.21, −2.72
S3	Orkney & North	MeyGen	Thetis	58.66, −3.13
S4	Orkney & North	Brough Ness	Thetis	58.72, −2.95
S5	Orkney & North	Ness of Duncansby	Thetis	58.66, −3.05
S6	Orkney & North	Brims	Thetis	58.76, −3.25
S7	Argyll	Sound of Islay	Thetis	55.84, −6.10
S8	Argyll	West Islay	Thetis	55.66, −6.61
S9	Argyll	Islay demo	Thetis	55.67, −6.57
S10	Other GB	Mull of Galloway	Thetis	54.62, −4.84
S11	Other GB	Morlais	Thetis	53.30, −4.74
S12	Other GB	Isle of Wight	Thetis	50.54, −1.30
S13	South West	Portland Bill	Thetis	50.49, −2.44
S14	Other GB	Alderney Race	Thetis	49.71, −2.08
R1	Other GB	Liverpool	Thetis	53.41, −3.02
R2	Other GB	Llandudno	Thetis	53.33, −3.83
R3	Other GB	Newport	Thetis	51.55, −2.98
R4	South West	Watchet	Thetis	51.22, −3.42

data was extrapolated using harmonic analysis [30] to obtain the 2019 annual data set for each site. The installed capacity at each site was informed by The Carbon Trust report [29]. It is assumed that each tidal stream power plant achieves a capacity factor of 0.4, based on the performance of the operational MeyGen array [31]. With knowledge of the installed capacity, and the capacity factor, the total swept area of the arrays was established to derive each sites power timeseries. This method neglects the impacts the added drag of the turbines has on the flow, and power generation, which will be the subject of further research.

For speculative tidal range sites, elevation vs time series was similarly extracted and harmonically reconstructed to be used as an input for a zero-dimensional (0-D) operation model that simulates the functions of tidal range power plants based on a two-way generation scenario. The design of the scheme considered follows the methodology described in Neill et al. [32], and applied in Todeschini et al. [33]. As with the tidal stream analysis herein, it must be remarked that the 0-D method ignores impacts [34] from the presence of tidal range structures that typically affect energy outputs in a detrimental way, but equally neglects operation optimisation opportunities to maximise energy that can compensate for these shortfalls [35].

2.2.2. *Wave resource and generation*

Wave resource characterisation was conducted using E.U. Copernicus Marine Service Information, with hourly wave resource data (significant wave height and energy period) for 2019 extracted from the European North West Shelf – Ocean Wave Analysis [36] for six locations. This data product utilises the WAVEWATCH III wave model coupled with a 1.5 km grid resolution ocean model of the European North West shelf. In addition to this, measured wave resource data using directional Waverider buoys was available for four locations, sourced from the Centre for Environment, Fisheries and Aquaculture Science (Cefas) WaveNet database [37]. The region, site, data source and coordinates of each of these ten locations are shown in Table 4.

Hourly significant wave height and energy period data were converted to hourly wave generation availability profiles utilising a power matrix from CorPower Ocean, a leading wave energy developer [38]. The power matrix is commercially sensitive and not publically available. This power matrix provides data for the generation output of the CorPower Ocean WEC over a range of sea states, and the output generation for each hourly sea state is divided by the device rated power to calculate the hourly availability for each site. The GB wave resource availability profile is then the average of these ten sites for each hour of the year.

2.2.3. GB demand, wind and solar generation

GB historic demand data for 2019 has been extracted from the data portal managed by the GB electricity system operator, National Grid ESO [39]. Half-hourly transmission system demand data were averaged to produce demand for each hourly timestep. Embedded wind and solar PV generation and installed capacities from the demand data file are also used to produce GB-wide wind and solar availability profiles.

2.2.4. Regional demand, wind and solar generation

Regional demand hourly profiles have been scaled based on the GB historical demand data and the Department for Business, Energy and Industrial Strategy subnational energy statistics [40]. The scaling factors used are 0.61%, 0.19% and 4.76% for Orkney & North, Argyll and the South West, respectively. The GB and regional demand profiles are shown in Fig. 3, illustrating higher levels of demand during winter months, and the relatively low demand of the Orkney & North, and Argyll regions.

Regional wind and solar generation time series have been created for a number of sites, detailed in Table 5. The open source Renewables Ninja tool [41] is used to create hourly power output time series for each of these locations, utilising the global MERRA-2 reanalysis model [42], a Global Solar Energy Estimator model [43] and a Virtual Wind Farm model [44]. The sites with largest deployed capacity in each region from the REPD are used to represent the overall generation profile, and the wind turbine power curve used to represent each site is summarised in Table 5. For solar PV, the default solar panel (no tracking, 35degree tilt, 180degree azimuth) is used to represent a typical solar panel in the South West region.

2.3. Metrics

This section outlines the formulations for each of the chosen metrics. Correlation coefficients are common in several previous resource analyses [15–18]. Resource availability, persistence and versatility have been developed especially for this work, and are originally documented in Bhattacharya et al [12]. Balancing metrics relating to the power and energy shortfalls/surplus takes a similar approach to the one adopted in Coles et al [45].

Table 4
Wave site locations used for GB and regional case studies.

ID	Region	Site	Data source	Coordinates (Lat, Lon)
W1	Orkney & North	Billia Croo	Copernicus	59.10, −3.50
W2	Orkney & North	Farr Point	Copernicus	58.65, −4.20
W3	Other GB	West of Lewis	Copernicus	58.49, −7.03
W4	Other GB	West of Hebrides	Cefas	57.28, −7.90
W5	Other GB	Tiree	Copernicus	56.47, −7.13
W6	Argyll	Blackstones	Cefas	56.05, −7.05
W7	Other GB	Pembrokeshire	Copernicus	51.85, −5.50
W8	Other GB	Scarweather	Cefas	51.43, −3.92
W9	South West	Penzance	Copernicus	50.31, −5.80
W10	South West	St Marys Point	Cefas	49.82, −6.53

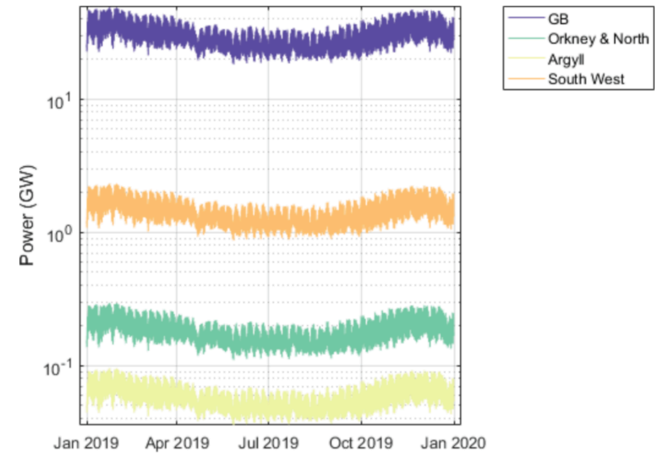

Fig. 3. Comparison of the GB and regional demand profiles.

Table 5
Wind and solar PV sites, locations and power curve model used for regional case studies.

Region	Technology	Site	Turbine power curve	Coordinates (Lat, Lon)
Orkney & North	Onshore wind	Camster Strathy North Baille	Vestas V80 2000 Senvion MM82/2050 Nordex N90/2500	58.41, −3.27 58.52, −4.04 58.57, −3.68
Orkney & North	Offshore wind	Scotwind N1 Scotwind NE2	Vestas V164 9500 Vestas V164 9500	58.92, −3.99 58.86, −2.42
Argyll	Onshore wind	A'Chruach An Suidhe Carraig Gheal	Senvion MM92/2000 Enercon E44/900 Siemens 2.3 MW	56.15, −5.31 56.22, −5.22 56.34, −5.29
Argyll	Offshore wind	Scotwind W1	Vestas V164 9500	55.95, −6.62
South West	Solar PV	Cornwall Wiltshire Dorset	N/A N/A N/A	50.51, −4.59 51.08, −2.42 50.74, −2.38
South West	Onshore wind	Fullabrook Down Delabole	Vestas V90 3000 Enercon E-70 2.3 MW	51.16, −4.10 50.64, −4.71
South West	Offshore wind	CE Round 3 – Isle of Wight	Vestas V164 9500	50.52, −1.84

2.3.1. Correlation coefficient

The correlation coefficient metric provides a quantitative measure of the relative profile shape of two power time series. It is used in this study to quantify how well hourly generation time series profiles (X) correspond to demand time series profiles (Y). Accordingly, correlation coefficient is calculated as:

$$CC(X,Y) = \frac{\sum_{t=1}^{T}\left((x(t)-\bar{x})(y(t)-\bar{y})\right)}{\sqrt{\sum_{t=1}^{T}\left((x(t)-\bar{x})^2(y(t)-\bar{y})^2\right)}} \tag{1}$$

where $x(t)$ and $y(t)$ are the hourly generation and demand data points over the total time window, i.e. [1, T], and $\bar{x}$ and $\bar{y}$ are the sample means of time series X and Y, respectively.

2.3.2. Resource availability

The resource availability $(RA(\breve{x})$ metric provides a quantitative measure of how often a generation resource is generating energy above a specified lower threshold. Define a lower threshold $\breve{x}$ such that if at any instant$t$, if$x(t)\rangle\breve{x}$, the instantaneous availability of resource (denoted as $ra(t)$) is instantiated as 1, otherwise 0. For the total time window, the (time-averaged) RA index can be calculated as:

$$RA = \frac{1}{T}\sum\nolimits_{t=1}^{T} ra(t) \tag{2}$$

For an electrical generator feeding a power grid, the lower threshold $\breve{x}$ is typically a finite value (often computed as a percentage of the rated output of the generator) to cover for different types of no-load machine losses. For this study, a threshold of$\breve{x} = 20\%$ has been chosen, corresponding to the current equivalent firm capacity of wind energy in the GB power system [46]. The resource availability results reported in this study therefore show the proportion of the time series which exceeds this threshold.

2.3.3. Resource persistence

The resource persistence (RP $(\breve{x}, \tau)$) metric provides a quantitative measure of continuous availability of the resource over a sub-window of the overall time window under consideration. We define a sub-window of length τ such that $\tau < T$(this sub-window is smaller than the length of the overall time window under consideration). For all sub-windows $j = 1, 2, ..., T - \tau + 1$, compute the instantaneous persistence $rp(j)$ as follows:

$$rp(j) = \begin{cases} 1, if ra(k) = 1, \forall k \in \{j, j+\tau-1\} \\ 0, otherwise \end{cases} \tag{3}$$

Now, for the overall duration [0, T], RP can be found as:

$$RP = \frac{1}{T-\tau+1}\sum\nolimits_{t=1}^{T-\tau+1} rp(t) \tag{4}$$

For the purpose of this study, $\tau = 3$ consecutive hours at the availability threshold of$\breve{x} = 20\%$ were chosen to calculate resource persistence.

2.3.4. Resource versatility

The resource versatility ($RV(\breve{x})$) metric provides a quantitative measure of availability of Resource A (in comparison to other resources, say B and C) in a time instant when B and C are not. This measure of instantaneous versatility can be averaged across the full-time window $[0, T]$ under consideration to obtain the resource versatility metric for the resource A. Mathematically, the instantaneous versatility of resource A, relative to B and C can be denoted as:

$$rv_A^{B,C}(t) = \begin{cases} 1, if ra_A(t) = 1 and ra_B(t) = ra_C(t) = 0 \\ 0, otherwise \end{cases} \tag{5}$$

The time averaged versatility (RV) can be found as:

$$RV = \frac{1}{T}\sum_t rv_A^{B,C}(t) \tag{6}$$

2.3.5. Effective load carrying capacity

The Effective Load Carrying Capacity (ELCC) metric calculates the impact of introducing a new generator to the power system on the ability of generation to consistently meet peak demand. It describes the additional load able to be met by a new generator, whilst maintaining a consistent power system reliability. ELCC requires detailed power system reliability modelling to compute, and so the simplified capacity factor method [47,48] has been used to generate a proxy for ELCC in this analysis. In this method, the average capacity factor of added renewable generation for the top n% of demand hours is used to approximate ELCC.

2.3.6. Power shortfall and excess

In each regional case study, annual energy demand and annual renewable energy production is quantified, enabling the annual shortfall/excess renewable energy production to be calculated. The occurrence of instantaneous power shortfall/surplus is also quantified. The difference between the power demand and the renewable power generation is calculated at each timestep throughout the year. This power shortfall/surplus data was then binned to display the magnitude of power shortages/surpluses throughout the year, and their occurrence. A similar approach was implemented to quantify the occurrence of energy shortages/surpluses. For each period with a continuous shortage/surplus in renewable power, the energy shortage/surplus is quantified, and then plotted to display the magnitude in energy shortfalls/surpluses, and their occurrence over a year.

3. Results

3.1. GB System case study

The resultant capacity factors, resource availability and resource persistence for the GB system scale technologies and technology mixes outlined in Table 1 are shown in Table 6. It can be seen that wave and tidal stream generation produce the highest capacity factors, noting that the GB scale 'wind' technology category encompasses both onshore and offshore wind.

In terms of resource availability, the results in Table 6 show that the wind and wave generation profiles perform well against this metric as single technologies, both achieving hourly capacity factors over 20% for more than 70% of the year. The combined generation profile including wind, solar and tidal stream performs best against the resource availability metric, at 0.77, even though this profile does not have the highest capacity factor. This suggests that the offsetting between these forms of renewable generation results in a combined generation profile which is significantly more available when compared with the current renewable energy mix.

In terms of resource persistence, Table 6 shows wave energy performing best against this metric as a singular technology. The combined generation profile including wind, solar and wave performs best against the resource persistence metric, at 0.68. All of the technology mixes which include wave energy meet the 20% availability threshold for at least three consecutive hours for more than 65% of the year. It is particularly important to have persistent sources of renewable generation to meet demand for efficient low-carbon power system operation. Less persistent generation profiles, with higher volatility, can lead to increased requirements for power system balancing [49].

Table 6
Renewable energy technology mixes investigated for GB system case study and resultant capacity factors, resource availability (RA) and resource persistence (RP).

Technology mix	Capacity factor	RA (0.2)	RP (0.2,3)
Wind	0.34	0.74	0.71
Solar PV	0.10	0.22	0.16
Wave	0.42	0.77	0.76
Tidal Stream	0.40	0.66	0.36
Tidal Range	0.21	0.41	0.09
Wind & Solar	0.26	0.63	0.59
Wind & Solar & Wave	0.30	0.71	0.68
Wind & Solar & Tidal stream	0.30	0.77	0.62
Wind & Solar & Tidal Range	0.24	0.62	0.51
Wind & Solar & Wave & Tidal Stream & Tidal Range	0.28	0.73	0.66

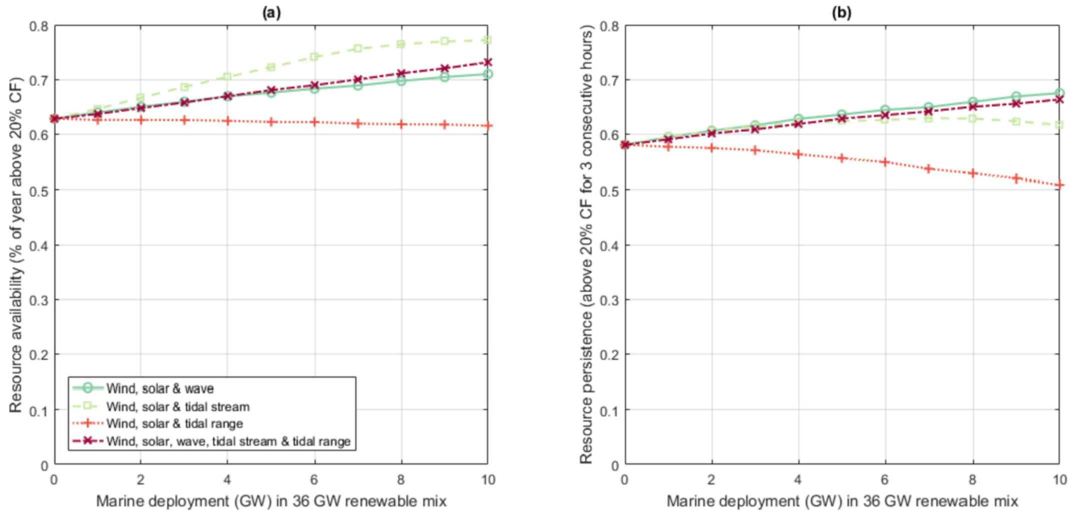

Fig. 4. Resource availability (a) and persistence (b) with varying marine energy deployment in the GB renewable energy mix.

Fig. 4a shows the resource availability results for the technology mixes which include marine energy, in which the marine energy deployment is increased from 0 GW (representing only wind and solar in the renewables mix) to 10 GW, in 1 GW increments. It can be seen that including wave and tidal stream within these generation mixes consistently improves the availability of the generation profile compared with the 0 GW case. The combined profile of wind, solar and tidal stream performs best, where the inclusion of 10 GW of tidal stream increases resource availability by 22%. 10 GW is close to the 11.5 GW practical tidal stream resource estimate recently reviewed in [50]. Fig. 4b shows the corresponding resource persistence results. The combined profile of wind, solar and wave performs best against this metric, with the inclusion of 10 GW of wave deployment increasing resource persistence by 15% relative to the case with no marine renewables.

Resource versatility results find that wave generation is available above the 20% RV(0.2) criteria for 6% of the year at times when wind and solar are not, with tidal stream RV(0.2) at 11% of the year and tidal range RV(0.2) at 3% of the year.

Table 7 shows the correlation of each of these signals with load, at four temporal resolutions: hourly, daily, weekly and monthly. It can be seen that there are no strong correlations (i.e. approaching a value of 1) between load and any generation profile at an hourly or daily timescale. However, wave and wind generation profiles are increasingly correlated with load over weekly and monthly timescales. In terms of the combined technology mixes, it can be seen that including wave energy consistently improves correlation with load over all four temporal resolutions.

Correlation coefficients between generation and load have been explored over four temporal resolutions, as the comparative results over each of these resolutions can infer system benefits in relation to a number of electricity and ancillary services markets. Hourly profiles can be used to represent hour-to-hour balancing of generation output and can reflect intra-day balancing and reserves requirements. Daily and weekly profiles can reflect mid-long term system requirements, such as scheduling thermal generation and longer-term reserves. Weekly to monthly profiles can reflect long term seasonal storage requirements. These results show a particular improvement in correlation at longer timescales when wave energy is included within the generation profile, suggesting that including wave energy within the GB technology mix could reduce requirements for scheduling thermal (nuclear and fossil fuel) generation and long-term energy storage.

Fig. 5 shows the approximated ELCC over the top 1–10% of demand hours for each type of renewable generation. It can be seen that wave and tidal stream perform better against this metric than all other forms of generation, and that tidal range performs better than solar PV. This suggests that an energy mix including these forms of marine energy would have more generation available at times of peak demand, improving system security and potentially reducing the need for burning fossil fuels in peaking plants.

Table 7
Correlation coefficients with load, for each GB renewable energy technology mix and four temporal resolutions.

Technology mix	Correlation coefficient with load profile			
	Hourly	Daily	Weekly	Monthly
Wind	0.201	0.298	0.584	0.750
Solar	−0.029	−0.678	−0.853	−0.916
Wave	0.291	0.450	0.691	0.820
Tidal Stream	−0.006	−0.009	−0.011	−0.160
Tidal Range	0.021	0.034	0.048	−0.113
Wind & Solar	0.177	0.171	0.452	0.628
Wind & Solar & Wave	0.239	0.306	0.579	0.737
Wind & Solar & Tidal stream	0.127	0.148	0.403	0.617
Wind & Solar & Tidal range	0.169	0.166	0.443	0.618
Wind & Solar & Wave & Tidal stream & Tidal range	0.204	0.236	0.517	0.682

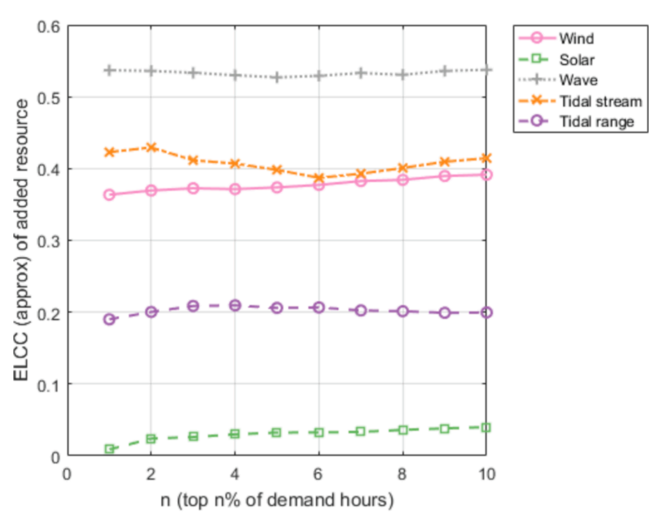

Fig. 5. Approximated effective load carrying capacity over top n% of demand hours for each type of renewable generation.

3.2. Regional case studies

3.2.1. Orkney and North Scotland

Table 8 shows the temporal characterisation results for the Orkney & North Scotland region. It can be seen that offshore wind has a particularly high capacity factor, corresponding to a hypothetical offshore wind farm at the ScotWind N1 site. This capacity factor of 53% is not too dissimilar to sites nearby which have achieved annual capacity factors of 46.3% (Beatrice) and 57.1% (Kincardine) [51]. Wave generation has the highest correlation with load, which is interesting as this region has the lowest wave energy capacity factor of the three considered. However, none of the generation profiles have a particularly meaningful correlation with load within the hourly data presented in Table 8. In terms of resource availability and persistence, wind performs well against these metrics for this region. The combined technology mixes including tidal stream perform best against the resource availability metric and the combined technology mixes including wave energy perform best against the resource persistence metric. The combined technology mix of onshore wind, wave and tidal stream perform best overall for both resource availability and resource persistence, though any combined technology mix including offshore renewables performs better against these metrics compared with the existing onshore wind alone.

Fig. 6a shows the relationship between increasing deployments of offshore renewables for the Orkney & North Scotland region and the resultant resource availability. The combined generation profile of onshore wind and tidal stream consistently performs best against this metric, closely followed with the combined generation profile of onshore wind, wave and tidal stream. Fig. 6b shows the corresponding resource persistence results. The combined generation profile of onshore wind and wave generation performs best against this metric. The combined generation profile of onshore wind and tidal stream performs less well after 600 MW installed capacity, seeming to reach an inflexion point, after which additional tidal stream generation reduces the resource persistence results due to its cyclical nature. Including additional offshore wind within the generation mix does not make a noticeable improvement to resource availability or persistence, likely due to the correlation between onshore and offshore wind in this region. There is a 10% improvement in resource availability and 6.5% improvement in resource persistence when an additional 1 GW of wave and tidal stream is included in the generation mix, compared with an additional 1 GW of offshore wind.

The resource versatility results find that wave generation is available for 14% of the year at times when onshore wind is not for the Orkney and North region. The resource versatility RV(0.2) of tidal stream and offshore wind is 17% and 7% of the year respectively.

Table 9 summarises the performance of the energy systems in Orkney and North Scotland. The regions annual energy demand is 1,620 GWh/year, which is far exceeded by renewable energy production in all cases, making the region a net exporter of energy. The wind only scenario achieves an annual energy production that is approximately 10% greater than the scenarios that include tidal stream and/or wave power, as a result of a higher capacity factor. Regardless of this, the level of renewable energy delivered to the regional demand is approximately the same in all cases, at 1,600 GWh.

Periods of power shortfall/surplus are shown in Fig. 7. The tidal stream and/or wave power scenarios have a relatively low annual energy shortfall, of less than 20 GWh, whilst the wind only scenario has an annual shortfall of over 50 GWh. This is partly a reflection of tidal and wave's greater correlation coefficient and resource availability. Given the low levels of annual energy shortfalls relative to demand, this is not seen as a major benefit. However, demand is expected to approximately double in the future [52], which could change this perspective.

Whilst wave has the highest correlation with load, this does not translate through when it comes to the annual excess/shortfall of energy. For example, the cases that use onshore wind and either tidal stream or wave, perform very similarly, even though wave and tidal stream have a correlation with load of 0.27 and –0.01 respectively. This raises the question of whether correlation with load is a suitable metric to establish alignment between supply and demand.

Annual excess energy is approximately 10% greater in the wind only case than the cases that include tidal stream and/or wave energy. This is beneficial if the necessary infrastructure to either export excess power to high demand centres or store it locally, is in place, or is economically feasible to develop in the future. Fig. 8a shows the occurrence of power shortages/surplus. Results clearly indicate that using wave and/or tidal stream reduces the occurrence of high excess power instances, relative to the wind only case. For example, in the wind only case, excess power exceeds 2.4 GW over 9% of the year. This reduces to 1%, 5% and 1% of the year when tidal stream, wave, and both tidal stream and wave are used respectively.

Fig. 8b shows the occurrence of energy shortage/surplus. Given that the region is a net exporter, all systems give a greater range of energy surplus periods, up to 700 MWh. In general, the inclusion of tidal stream and/or wave reduces the occurrence of high energy surplus periods. For example, in the wind only case, periods with an energy surplus greater than 100 MWh occurs 18% of the time. This reduces to 10% once tidal stream and wave power capacity replaces some of the wind capacity.

North Scotland currently has an electrical grid boundary capacity limit, which is a measure of the electrical power that can be transmitted to other regions, of 1 GW at the B0 boundary, North of Inverness [21]. The significant reduction in high excess power and energy occurrence that is achieved through the use of tidal stream and wave energy may provide system benefits, such as a reduction in the additional transmission capacity required to export excess power, for example.

Table 8
Renewable energy technology mixes investigated for the Orkney & North case study and resultant capacity factors, correlation with load, resource availability and resource persistence.

Technology mix	Capacity factor	Correlation with load	RA (0.2)	RP (0.2,3)
Onshore wind	0.45	0.06	0.74	0.71
Offshore wind	0.53	0.05	0.80	0.77
Wave	0.42	0.27	0.69	0.67
Tidal stream	0.41	−0.01	0.63	0.31
Onshore wind & Wave	0.44	0.15	0.80	0.78
Onshore wind & Tidal stream	0.44	0.05	0.84	0.73
Onshore wind & Wave & Tidal stream	0.44	0.11	0.84	0.77
Onshore wind & Offshore wind	0.48	0.05	0.76	0.73

3.2.2. Argyll

Table 10 shows the temporal characterisation results for the Argyll region. It can be seen again that offshore wind has a particularly high capacity factor, corresponding to a hypothetical offshore wind farm at the ScotWind W1 site. Wave generation again has the highest hourly correlation with load. In terms of resource availability and persistence, wind performs well against these metrics for this region, and offshore wind in particular this time. As in the Orkney & North Scotland region, the combined technology mixes including tidal stream perform best against the resource availability metric and the combined technology mixes including wave energy perform best against the resource persistence metric. The combined technology mix of onshore wind, wave and tidal stream perform best overall for both resource availability and resource persistence, though any combined technology mix including offshore renewables performs better against these metrics compared with onshore wind alone.

Fig. 9a shows the relationship between increasing deployments of offshore renewables for the Argyll region and the resultant resource availability. As with the Orkney and North Scotland region results, the combined generation profile of onshore wind and tidal stream

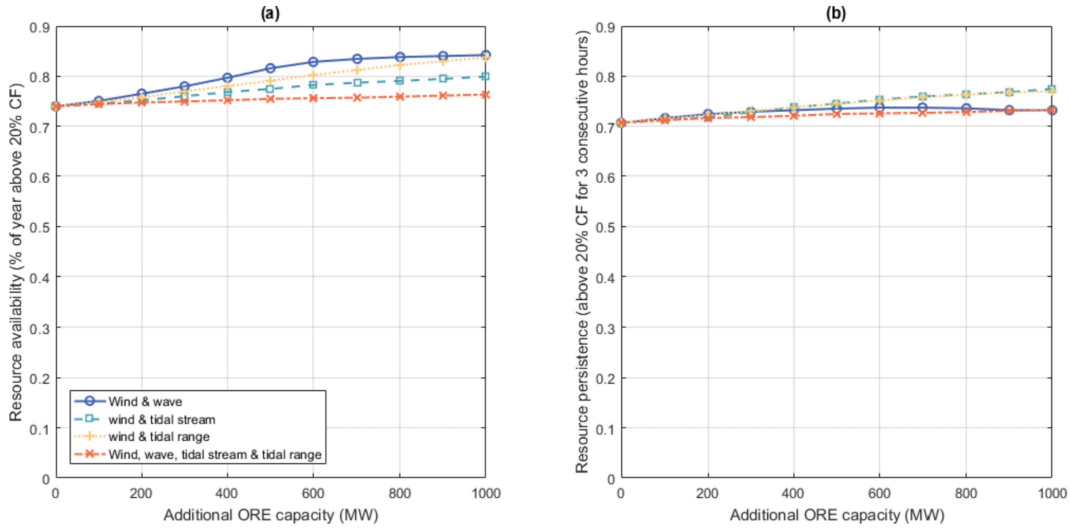

Fig. 6. Resource availability (a) and persistence (b) with varying marine energy deployment in the Orkney & North regional energy mix.

Table 9
Performance of the Orkney and North Scotland energy system scenarios, based on current demand.

Technology mix	Total installed capacity	Annual energy yield	Capacity factor	Regional renewable energy consumption (% of energy yield)	Annual energy shortfall	Annual excess energy
Onshore wind & Tidal stream	2.9 GW	11,073 GWh	0.43	1,604 GWh (15%)	16.1 GWh	9,468 GWh
Onshore wind & wave	2.9 GW	11,171 GWh	0.44	1,605 GWh (14%)	15.5 GWh	9,566 GWh
Onshore wind & Tidal stream & wave	2.9 GW	11,122 GWh	0.44	1615 GWh (15%)	5.3 GWh	9,506 GWh
Onshore wind & Offshore wind	2.9 GW	12,198 GWh	0.48	1569 GWh (13%)	51.2 GWh	10,629 GWh

consistently performs best against this metric, closely followed with the combined generation profile of onshore wind, wave and tidal stream. Fig. 9b shows the corresponding resource persistence results. For the Argyll region, the combined generation profile of onshore wind, wave and tidal stream consistently performs best against this metric, with the combined generation profile of onshore wind and tidal stream reaching an inflexion point after 50 MW installed capacity. Interestingly, offshore wind performs similarly to wave energy within for both resource availability and persistence for the Argyll region, where previously in the Orkney and North Scotland region additional offshore wind generation had very little impact on these metrics. There is a 5% improvement in resource availability and 11% improvement in resource persistence when an additional 140 MW of wave and tidal stream is included in the generation mix, compared with an additional 140 MW of offshore wind.

Resource versatility results find that wave generation is available for 14% of the year at times when onshore wind is not for the Argyll region, with tidal stream RV(0.2) at 19% of the year and offshore wind RV(0.2) at 13% of the year.

Table 11 summarises the performance of the energy systems considered in Argyll. Argyll's annual electrical energy demand is 522 GWh. In all cases the annual energy yield of the renewable plant far exceeds this, by over 300%, demonstrating the regions role as a net exporter of renewable power.

In all cases the annual shortfall in renewable energy is lower than 2% of annual energy yield, since the installed renewable power capacity is significantly higher than the maximum power demand. This means that even in low resource periods, demand can often be met. When onshore wind is combined with either/both tidal stream and wave, renewable power can meet approximately 10% more of the demand than the wind only case, even though annual energy yield is lower. As was the case in the North Scotland case study, this is surprising, given that tidal stream has a relatively low correlation coefficient with load. This again indicates that correlation with load is not a suitable metric to establish alignment between supply and demand.

Fig. 10 shows the instantaneous power shortages and surplus over 2019. Surplus power events are clearly more common than power shortages, as a result of high renewable power capacity relative to power demand. Power shortages are most common during the summer months, when the wind and wave resource is lowest. The monthly consistency of tidal stream power means that its inclusion in the energy mix helps reduce power shortages during the summer months.

In the wind only case, the combination of high annual energy yield, and a relatively high shortfall in annual energy, results in a high annual surplus in renewable energy, of 1329 GWh/year. Results presented in Fig. 11a show that the maximum level of power surplus reached is 450 MW, in the cases that uses wind only, and wave power. Currently, Argyll's grid boundary capacity is 430 MW at boundary B3b [21]. This difference of 20 MW indicates that far less grid infrastructure upgrades would be needed in order to export all excess power, compared to the Orkney & North case study, based on the installed capacities and demand profiles considered here. The wind only scenario has the greatest occurrence of high power shortages. Combining wind with tidal stream and/or wave reduces the occurrence of high power shortages, as was the case in Orkney & North.

Fig. 11b shows the annual occurrence of energy shortage/surplus for each of the four cases. Results show that in all four cases, periods of sustained power shortage are associated with an energy that does not exceed 25 MWh. Using tidal stream significantly reduces the occurrence of periods with high energy surplus.

3.2.3. South-West England

Table 12 shows the temporal characterisation results for the South-

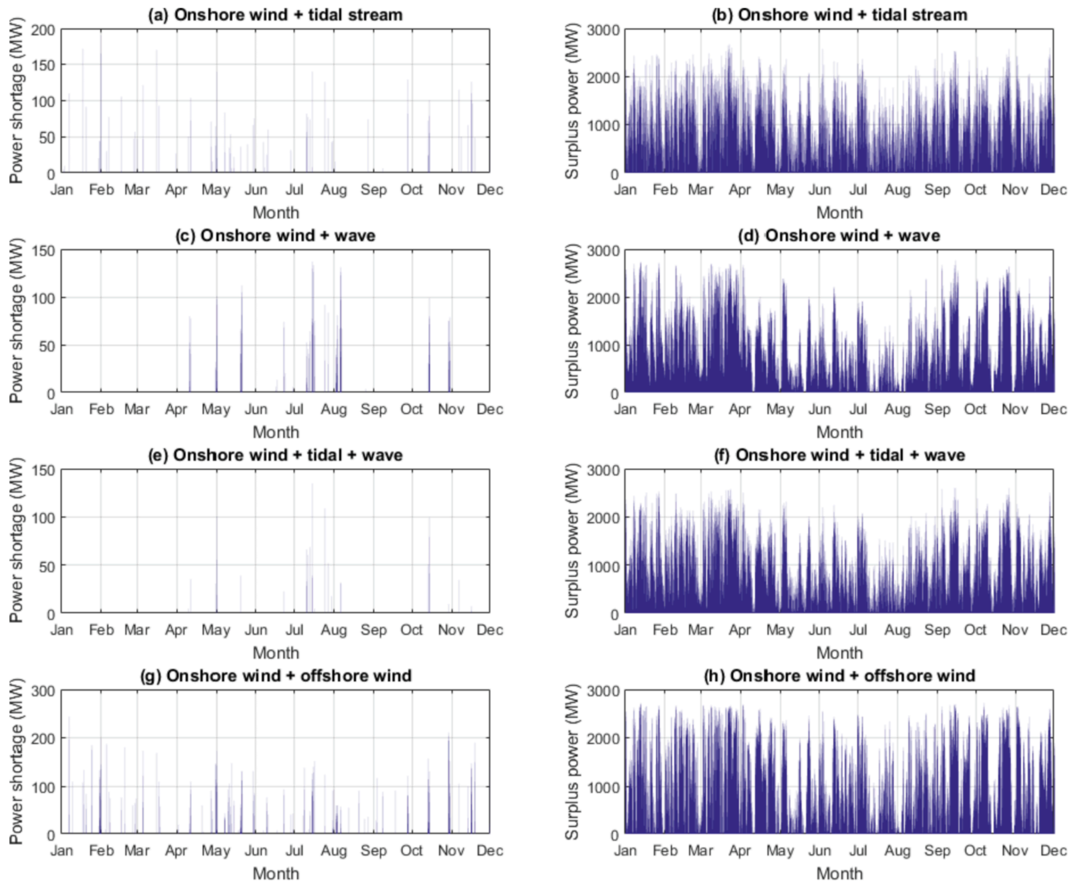

Fig. 7. Timeseries of Orkney and North Scotland's instantaneous power shortage (a, c, e, g) and power surplus (b, d, f, h).

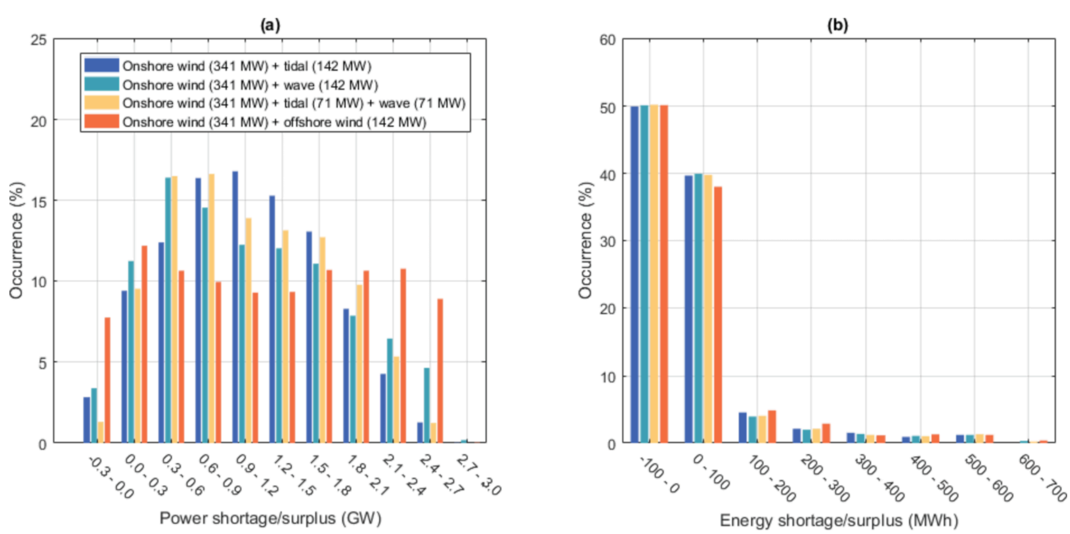

Fig. 8. Annual occurrence of (a) power shortage/excess, and (b) energy shortage/excess.

West England region. Wave generation has a particularly high capacity factor in this region and yet again has the highest hourly correlation with load. Tidal range has also been included in this region, with a potential 2.5GW installed capacity at the South-West Lagoon site. In terms of resource availability and persistence, offshore wind and wave perform well against these metrics for this region. There is a high installed capacity of solar PV generation in this region, which performs poorly against the resource availability and persistence metrics even when combined with other forms of generation. The separate technologies of offshore wind, onshore wind and wave perform best overall for both resource availability and resource persistence, though any combined technology mix including offshore renewables performs better against these metrics compared with solar PV alone. Interestingly, although tidal range does not perform well in terms of capacity factor or correlation with load, the combined generation profiles including tidal range perform best of all the combined generation profiles against the resource availability metric. This indicates that the offsetting between tidal range and the existing solar and wind generation profiles results in

Table 10
Renewable energy technology mixes investigated for the Argyll case study and resultant capacity factors, correlation with load, resource availability and resource persistence.

Technology mix	Capacity factor	Correlation with load	RA (0.2)	RP (0.2,3)
Onshore wind	0.39	0.04	0.69	0.65
Offshore wind	0.53	0.06	0.81	0.78
Wave	0.44	0.22	0.64	0.60
Tidal stream	0.40	−0.01	0.60	0.30
Onshore wind & Wave	0.40	0.12	0.75	0.71
Onshore wind & Tidal stream	0.39	0.03	0.79	0.68
Onshore wind & Wave & Tidal stream	0.40	0.09	0.79	0.72
Onshore wind & Offshore wind	0.43	0.05	0.75	0.72

a combined generation profile which is significantly more available than the current generation mix alone.

Fig. 12a shows the relationship between increasing deployments of offshore renewables for the South-West England region and the resultant resource availability, and Fig. 12b shows the corresponding resource persistence results. Tidal range is not included in the Fig. 12 plots as it is not appropriate to include lower installed capacities of this large-scale technology. All combined generation mixes including offshore renewables perform well against the resource availability and persistence metrics for this region, compared with the existing installed capacity of solar PV and onshore wind. Interestingly, unlike the other regional results, the combined generation profiles including additional wave and offshore wind capacity perform best against the resource availability and persistence metrics for the South-West England region, with the higher installed solar PV in the region having very little correlation with these technologies. The combined generation profiles including tidal stream also perform fairly well against the resource availability and persistence metrics. The resource persistence results for the profile including tidal stream do not show an inflection point for installed capacities up to 300 MW. There is a 7% improvement in resource availability and 10% improvement in resource persistence when an additional 300 MW of wave or offshore wind is included in the generation mix, compared with the current existing generation mix of onshore wind and solar PV.

Resource versatility results find that wave generation is available for 12% of the year at times when onshore wind and solar are not for the Argyll region, with tidal stream RV(0.2) at 14% of the year, tidal range RV(0.2) at 7% of the year and offshore wind RV(0.2) at 10% of the year.

A summary of the South West's systems annual performance is provided in Table 13. The region has an annual demand of 12.1 TWh. Based on the renewable power scenarios considered, annual energy production is around 6 TWh/year when tidal range is excluded, of which around 5 TWh/year is used in the region, making it a net importer of energy. The energy systems (excluding tidal range) all import around 7.6 TWh/year. Excess renewable energy production, is 0.9 TWh/year in all cases. The inclusion of 2.5 GW of tidal range capacity reduces the annual energy shortfall by approximately 2 TWh, to 5.5 TWh, and increases excess annual energy by 2 GWh, to 2.9 GWh.

Fig. 13 shows the instantaneous power shortages and exceedance over 2019. Power shortage is highest during the winter months, as a result of the low solar resource and high solar PV installed capacity. The

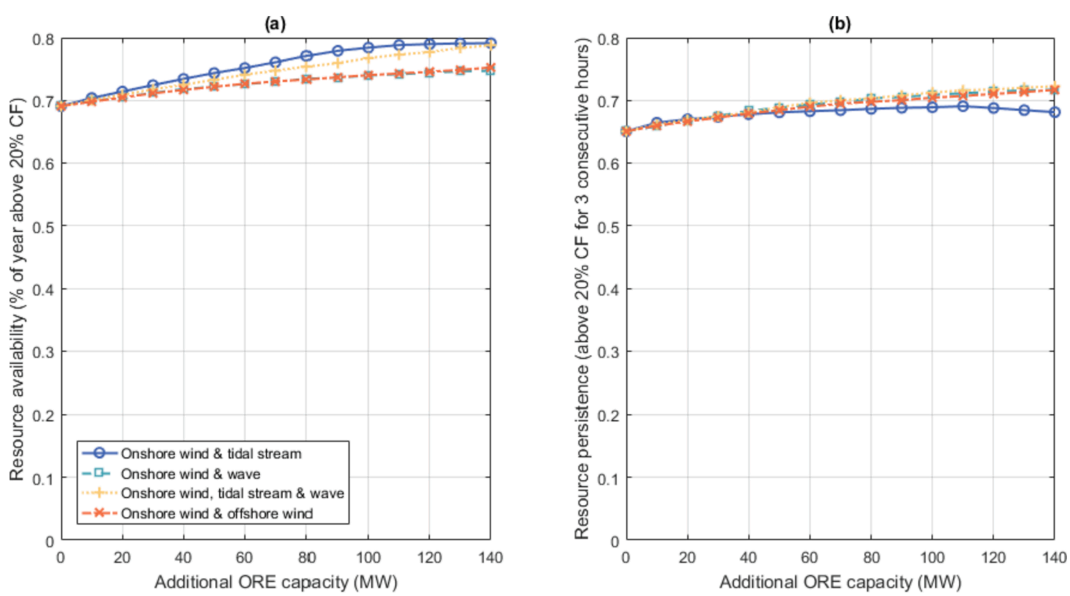

Fig. 9. Resource availability (a) and persistence (b) with varying marine energy deployment in the Argyll regional energy mix.

Table 11
Performance of the Argyll energy system scenarios, based on current demand.

Technology mix	Total installed capacity	Annual energy yield	Capacity factor	Regional renewable energy consumption (% of energy yield)	Annual energy shortfall	Annual excess energy
Onshore wind & Tidal stream	0.5 GW	1642 GWh	0.39	503 GWh (31%)	19 GWh	1139 GWh
Onshore wind & wave	0.5 GW	1698 GWh	0.40	500 GWh (29%)	22 GWh	1198 GWh
Onshore wind & Tidal stream & wave	0.5 GW	1670 GWh	0.39	510 GWh (31%)	13 GWh	1160 GWh
Onshore wind & Offshore wind	0.5 GW	1816 GWh	0.43	486 GWh (27%)	36 GWh	1329 GWh

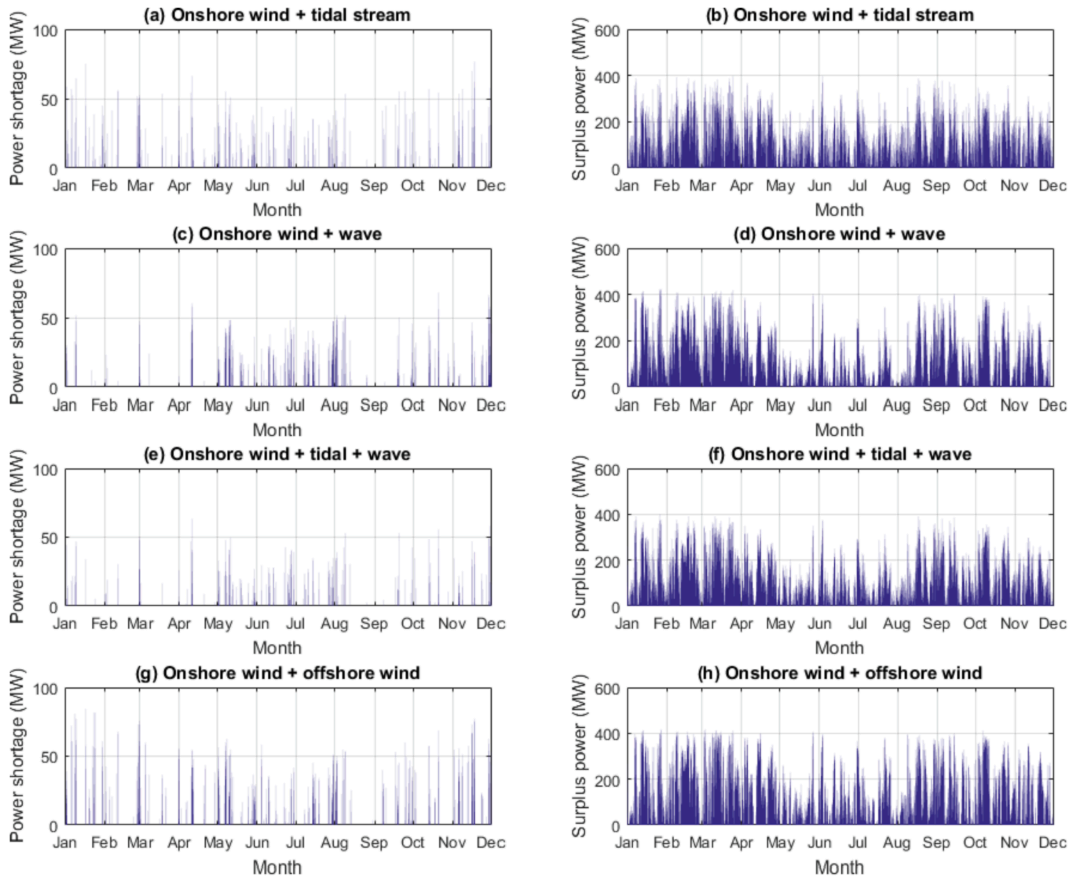

Fig. 10. Timeseries of Argyll's instantaneous power shortage (a, c, e, g) and power surplus (b, d, f, h).

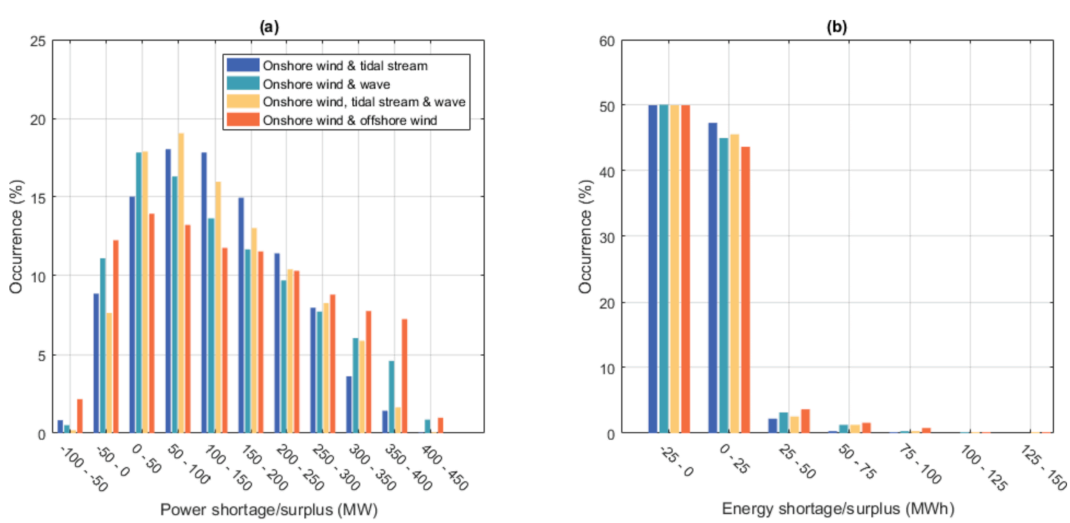

Fig. 11. Annual occurrence of (a) power, and (b) energy shortage/surplus.

inclusion of tidal range power capacity reduces power shortage, and increases excess power, homogenously over the year, as it achieves a flat capacity factor over each month.

Fig. 14a shows the annual occurrence of power shortage/surplus for each of the four cases that does not include tidal range. Unlike the other cases considered, in the South West, solar PV and onshore wind contribute the majority of the renewable energy production. This means that the systems perform similarly, because the penetration of tidal stream and wave power is not high enough for their benefits to have a significant impact on the overall system. Fig. 14b shows the annual occurrence of energy shortage/surplus for each of the four cases. The same finding is true here also. The energy shortage periods contain energy up to 50 GWh. The majority of the excess power periods also contain around 50 GWh, but do extend to 300 GWh.

The inclusion of the 2.5 GW tidal range does not reduce the maximum power shortage level, of around 2.5 GW. Power generation by tidal range exhibits four cycles per day, with zero power between cycles. This means it is not possible for power generation to coincide with all peak demand periods. The inclusion of tidal range increases the maximum excess power, from around 2 GW, to 3.6 GW.

Table 12
Renewable energy technology mixes investigated for the South-West England case study and resultant capacity factors, correlation with load, resource availability and resource persistence.

Technology mix	Capacity factor	Correlation with load	RA (0.2)	RP (0.2,3)
Solar PV	0.14	−0.01	0.26	0.19
Onshore wind	0.37	0.06	0.66	0.62
Offshore wind	0.46	0.05	0.74	0.70
Wave	0.46	0.25	0.73	0.70
Tidal stream	0.41	−0.01	0.60	0.28
Tidal range	0.21	0.02	0.32	0.06
Solar PV & Onshore wind	0.17	0.00	0.29	0.21
Solar PV & Onshore wind & Wave	0.19	0.03	0.31	0.23
Solar PV & Onshore wind & Tidal stream	0.19	0.00	0.30	0.23
Solar PV & Onshore wind & Tidal range	0.19	0.01	0.39	0.19
Solar PV & Onshore wind & Wave & Tidal stream & Tidal range	0.20	0.02	0.40	0.21
Solar PV & Onshore wind & Offshore wind	0.19	0.00	0.31	0.23

4. Discussion

4.1. Comparison of country-scale and regional results

The temporal characterisation analysis has been performed at two spatial resolutions, producing results at both a GB scale and at a regional scale. It is interesting to note that some key findings vary depending on the scale of analysis. Capacity factors, for example, are particularly high for wind at a regional level, particularly in the two Scottish regions, with wave and tidal reducing the capacity factor of the generation mixes in sections 3.2.1 and 3.2.2. However, when compared with the country-scale renewable mix of wind and solar in section 3.1, adding in wave and tidal increases the overall capacity factor of the renewable mix considerably.

With regards to the other temporal characterisation metrics, resource availability showed a larger impact for the GB scale analysis, with up to a 22% improvement for tidal stream and 16% for wave. The regional scale results showed up to a 10% improvement for tidal stream in Orkney, and up to 7% improvement for wave in south-west. Resource persistence showed a larger impact for wave in the GB scale results, with a 20% improvement, and tidal stream in regional results, with a 5% improvement in the south-west. Resource versatility produced the highest figures (greater than10%) at a regional level, and specifically for the Scottish regions. This demonstrates a higher offsetting between wind and marine renewables in the Scottish regions, which implies a higher system benefit.

Correlation coefficients are the only temporal characterisation metric that perform similarly at GB and regional scales. It has been found that including wave in both country-scale or regional energy mixes significantly improves the correlation with demand for hourly time series.

In general, over all of the analysis undertaken, tidal stream and tidal range perform particularly well against the RA metric, and wave

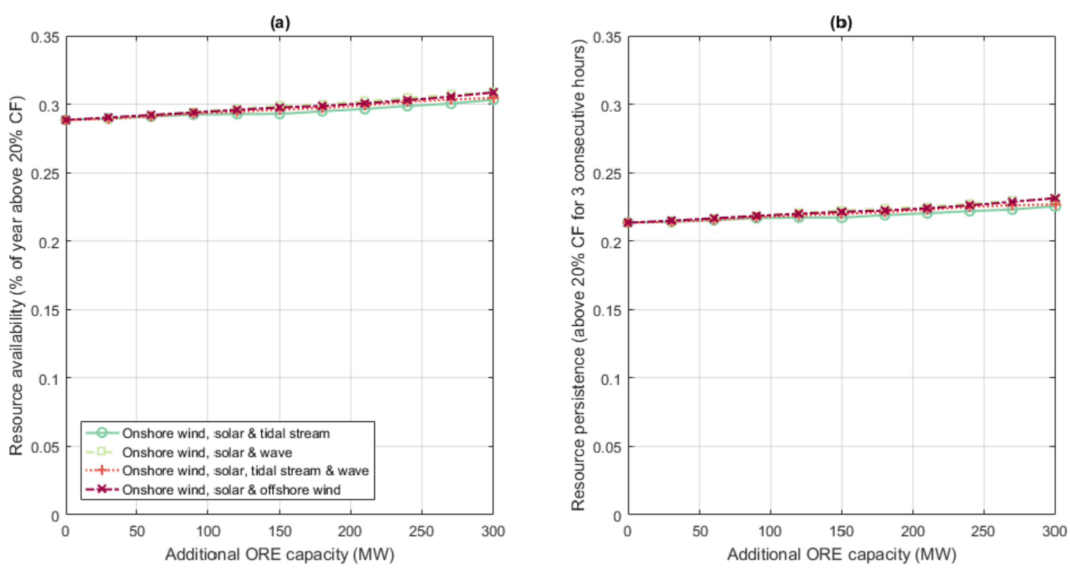

Fig. 12. Resource availability (a) and persistence (b) with varying offshore renewable energy deployment in the South-West England regional energy mix.

Table 13
Performance of the South-West energy system scenarios, based on current demand.

Technology mix	Total installed capacity	Annual energy yield	Capacity factor	Regional renewable energy consumption (% of energy yield)	Annual energy shortfall	Annual excess energy
Solar PV & Onshore wind & Tidal stream	3.8 GW	6.0 TWh	0.18	5.1 TWh (40%)	7.7 TWh	0.9 TWh
Solar PV & Onshore wind & wave	3.9 GW	6.1 TWh	0.18	5.2 TWh (41%)	7.5 TWh	0.9 TWh
Solar PV & Onshore wind & Tidal stream & wave	3.9 GW	6.0 TWh	0.18	5.2 TWh (41%)	7.6 TWh	0.9 TWh
Solar PV & Onshore wind & Offshore wind	3.9 GW	6.1 TWh	0.18	5.2 TWh (41%)	7.5 TWh	0.9 TWh
Solar PV & Onshore wind & Wave & Tidal stream & Tidal range	6.6 GW	10.1 TWh	0.18	7.2 TWh (60%)	5.5 TWh	2.9 TWh

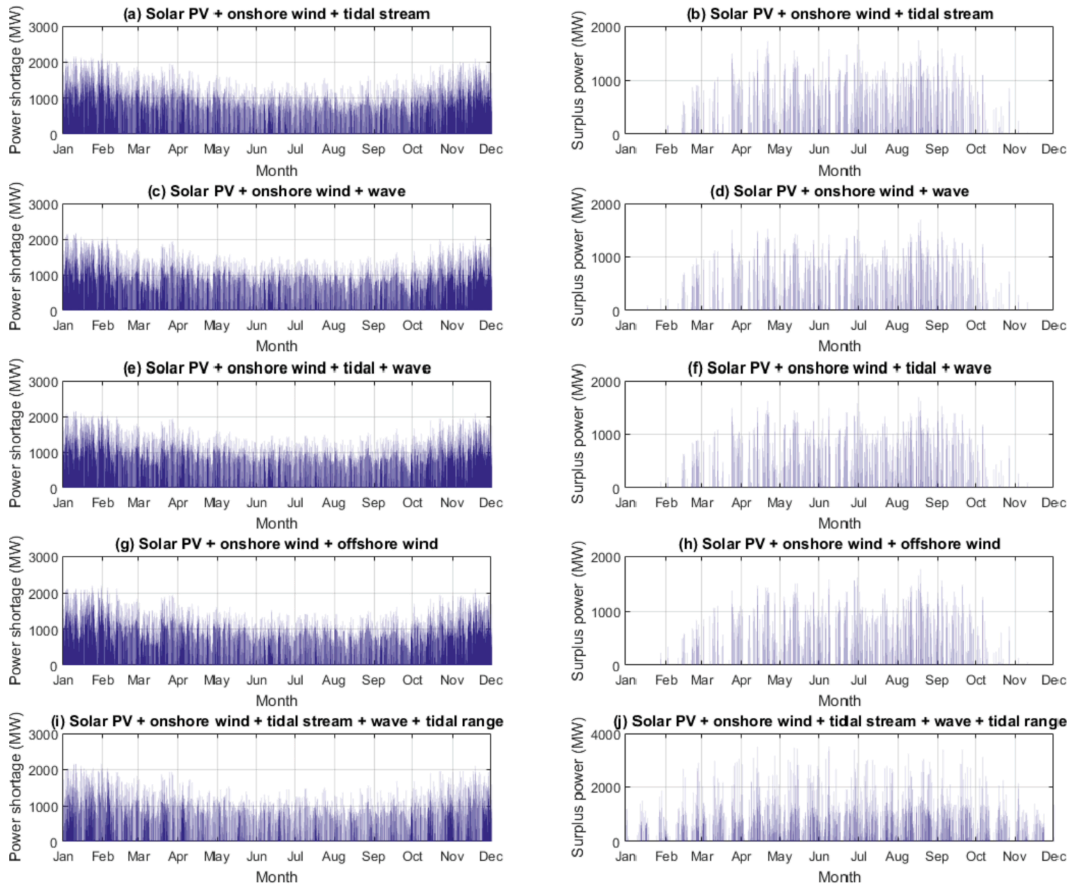

Fig. 13. Timeseries of South-West England's instantaneous power shortage (a, c, e, g) and power surplus (b, d, f, h).

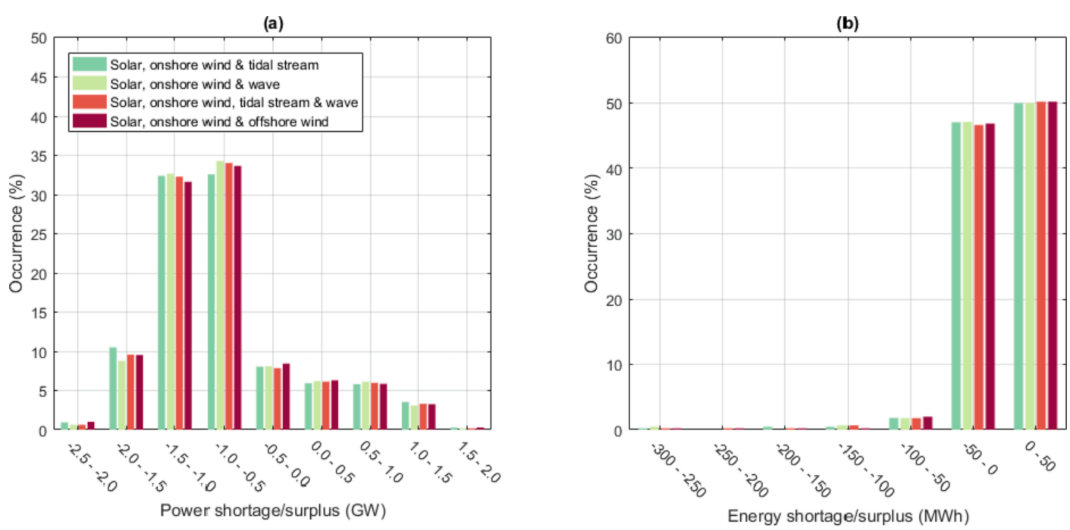

Fig. 14. Annual occurrence of (a) power, and (b) energy shortage/surplus.

particularly well against RP metric. These results ultimately show that a range of metrics can be used to quantify the temporal complementarity of generation profiles, and the more commonly used metrics of capacity factor and correlation coefficients do not capture all of the potential benefits of more diversified energy mixes.

4.2. Comparison between regional case studies

It is also of interest to compare the variation in results within the three regional case studies, chosen as regions with both marine energy resource and significant transmission constraints. For the Scottish regions, it has been found that energy mixes incorporating offshore wind with the existing installed onshore wind results in the highest energy production and capacity factors, resulting in higher levels of excess renewable energy.

However, energy mixes which instead incorporate wave and/or tidal stream were found to meet a slightly higher proportion of the regional demand, with lower annual energy shortfalls and surpluses. An energy mix including both wave and tidal stream performs best against energy shortfall, and an energy mix including tidal stream performs best in terms of minimising excess energy. This highlights that technologies with higher capacity factors and correlation with load don't necessarily perform best when modelling power balance. In fact, this quantification of system benefits is in better agreement with the resource availability metric results, in which energy mixes including tidal stream also scored highest for these regions.

Regions with high renewable energy resources such as Scotland are and will be net exporters of power. UK Government has identified the grid integration of variable generation as a key challenge for the industry as renewable power penetration increases [53]. Results presented here demonstrate that the inclusion of tidal stream and wave power capacity reduces the occurrence of high power shortages/surpluses. This has the potential to minimise additional grid infrastructure requirements, and therefore system costs. The potential cost savings of tidal stream and wave power cannot be identified only using the correlation coefficient, RA, RP and RV metrics, highlighting the need for a more holistic analysis of the future energy systems.

The south-west England region showed more significant proportional improvements in RA and RP, compared with the Scottish regions, as the current mix in the south-west is mostly solar, whereas the other regions have higher proportions of wind installed. However, the south-west region has a smaller potential capacity for offshore renewables, meaning that the power balance results were very similar for all energy mixes. Profiles including wave or offshore wind perform slightly better for this region in terms of minimising energy shortfall, which is also a consistent result with the RA and RP analysis. The region has a large tidal range resource, which if exploited, can reduce the regions annual energy shortfall, and increase its annual energy surplus.

4.3. Comparison with literature

A number of studies have been undertaken which compute correlation coefficients between renewable energy profiles and load. Correlation between wind generation and demand for the UK has been found at 0.18 using 5-minutely data [17] and 0.12 using half-hourly data [16], which are consistent with the value of 0.2 found in this study. Correlation between solar generation and load has been found to be particularly sensitive to location, with Buttler et al. producing results between −0.16 (Sweden) and 0.41 (Italy) for European regions [17]. The correlation coefficient of −0.03 found between solar PV generation and demand in this study falls within the range produced Buttler et al. Finally, this work showed the correlation between tidal stream generation and demand to be −0.01, which is consistent with the findings of Coker et al [16].

Resource availability and persistence have previously been computed by the authors for marine resources and established renewables for sites in the USA and Scotland in Bhattacharya et al. [12]. It was found that the RA(0.05) of wave was 0.94–0.99 and of tidal stream was 0.68–0.72, whereas wind and solar at corresponding sites were significantly lower. RP(0.05,3) of wave was 0.93–0.99 and of tidal was 0.40, also outperforming wind (for USA regions) and solar (for USA regions and Scotland). These results are fairly consistent with the analysis presented here, as although wave and tidal do not outperform wind in all of the GB case studies, technology mixes including wave and tidal do outperform the current renewable technology mix in all cases.

The benefits tidal stream power can provide with respect to supply–demand matching has been investigated in several studies [45,54–56]. In general, findings show that the cyclic nature of tidal stream power generation enables a greater amount of the demand to be met directly, reducing the annual shortfall in renewable power needed to meet demand. Similar studies have investigated the potential benefits of including wave power in hybrid systems that also contain wind power. In this study it has also been found that the lag between wind and wave power can help smooth the overall renewable power supply, thereby reducing reliance on imported power.

4.4. Implications for system benefits

The results presented in this paper imply a number of potential system benefits resulting from the inclusion of marine energy within the GB electricity mix. It has been shown that marine energy increases the availability and persistence of renewable generation profiles, due to offsetting with wind and solar generation. A more consistent availability of low carbon, low marginal cost, electricity generation could result in more efficient wholesale electricity market operation, lowering instances of price spikes and lowering requirements for fossil fuel peaking generators. The Scottish regional case studies showed that energy mixes with marine renewables were able to meet regional demand more consistently than energy mixes with wind alone. This could result in lower system balancing requirements and transmission network congestion for these regions. GB system balancing costs were £1.2bn in 2019 [57], and the mitigation of balancing costs is particularly important as the proportion of stochastic renewables increases. Finally, the ELCC analysis showed that energy mixes including wave and tidal stream generation were able to meet a higher proportion of peak demand compared to those without, implying a positive impact on system security.

There will be increasing importance placed on the system impacts associated with stochastic renewables as their installed capacity increases, with the UK offshore wind sector deal targeting 40GW of offshore wind by 2030 [53]. It is estimated that the equivalent cost of offshore wind energy by 2035 will be 50–100% greater than at present, as a direct result of these wider system impacts [11]. While it has been shown that marine energy could mitigate some of these impacts, it should be noted that significant cost reductions are still required for wave and tidal stream technologies as they move towards commercialisation.

5. Conclusions

This study has undertaken detailed analysis of marine energy and established renewable generation profiles for Great Britain, utilising ten metrics to quantify the temporal complementarity and power system balancing requirements at both country and regional scales. The analysis has shown that temporal characterisation metrics quantifying the availability and persistence of renewable resources correspond better to supply–demand matching metrics than more commonly used metrics, such as capacity factors and correlation with load. This provides a better understanding of how generation timeseries data can be analysed when complex electricity system models are not available.

The results indicate that the offsetting between marine generation and wind and solar generation could result in a number of benefits to the GB power system. This is particularly relevant for future, greener, energy systems as the proportion of stochastic renewable energy increases, and as sections of the heat and transport sectors are electrified to aid decarbonisation. It will be particularly important to have persistent sources of renewable generation in the future to meet demand for efficient low-carbon power system operation.

Future work will utilise the marine energy generation profiles in energy system models to further quantify the potential benefits of marine energy to both country-scale and microgrid systems, in terms of system costs and carbon emissions.

It should be noted that the additional system benefits from marine energy technologies will only be achievable if sufficient financial support is provided to these developing technologies to allow them to reach commercialisation.

Funding

S.P. and H.J. acknowledge support under the framework of the OCEANERA-NET COFUND project, which has received funding from the European Union under the Horizon 2020 Programme (European

Commission Grant Agreement No. 731200), with funding provided by the following national/ regional funding organisations: Scottish Enterprise. D.C. acknowledges the support of the Tidal Stream Industry Energiser project (TIGER), co-financed by the European Regional Development Fund through the INTERREG France (Channel) England Programme. A.A. acknowledges the support of NERC through the Industrial Innovation fellowship grant NE/R013209/2.

CRediT authorship contribution statement

Shona Pennock: Methodology, Data curation, Formal analysis, Writing – original draft. **Daniel Coles:** Methodology, Data curation, Formal analysis, Writing – original draft. **Athanasios Angeloudis:** Data curation, Writing – original draft. **Saptarshi Bhattacharya:** Methodology, Writing – original draft. **Henry Jeffrey:** Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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