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Wave resource variability: Impacts on wave power supply over regional to international scales

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Abstract

The intermittent, irregular and variable nature of the wave energy resource has implications for the supply of wave-generated electricity into the grid; intermittency of renewable power may lead to frequency and voltage fluctuations in the transmission and distribution networks. This study analyses the wave resource over different spatial scales to investigate the potential impacts of the resource variability on the grid supply. It is found that the deployment of multiple wave energy sites results in a reduction in step changes in power, leading to an overall smoothing of the wave-generated electrical power.

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Keywords: Wave resource; Resource variability; Intermittancy; SWAN; Grid integration

1. Introduction

The wave energy resource is intermittent, irregular and variable in nature, with implications for the supply of wave-generated electricity into the grid. Issues relating to resource intermittency and its mitigation through the

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development of spatially separated sites have been widely researched in the wind industry (e.g. [1,2]), but have received little attention to date in the less mature wave industry. As a resource, wave energy is significantly less predictable than tidal energy, although more so than wind and solar [3]. However, the temporal and spatial variability of the wave resource could prove problematic for grid integration if wave energy was to reach the point of large-scale deployment with high levels of grid penetration.

For all intermittent renewable technologies there are two grid-related areas of concern; at the transmission network level intermittency will cause frequency fluctuation, while at the distribution network level, it will cause voltage fluctuations. Supply needs to match demand in order for the system frequency to be maintained at its nominal value, for example 50.00Hz ±1% in the UK. Electricity demand is typically predicted in advance, enabling a matching supply to be arranged. The utilisation of intermittent renewable supplies means these also need to be predicted in order to effectively plan for a matching supply from fossil fuel plants. In addition to this planned matching process between demand and supply, the transmission system operator needs to control the frequency in real-time via operation of gas-fired generation units and back-up generation plants. The availability of these balancing plants is a limiting factor on the grid-integrated intermittent power. This can be seen in Ireland, where the proportion of power from intermittent renewable sources at any time is estimated to be limited to 75% up to 2020, primarily due to the available balancing services [4]. Intermittent power might also cause voltage fluctuation in the local distribution network.

A potential mitigation against these effects, demonstrated in studies for the wind industry (e.g. [1,2]), is the development of multiple, spatially separated sites in order to smooth the supply of power to the grid. From a wave resource perspective, localised geography, weather patterns and tidal conditions can lead to notable differences in levels of resource across regions exposed to a similar wave climate. Therefore, as for the wind industry there is the potential to develop appropriately sited wave farms to contribute to the smoothing, i.e. reduction in short-term variability, and grid integration of wave-generated power. A key parameter when considering electricity supply is the step change, i.e. the change in output power over a specified time period (e.g. 10mins, 30mins, 1hr, 24hr). Smaller step changes indicate a smoother power supply, and they are more beneficial for the grid integration. An example of this is presented in Fig. 1, which shows a temporal sub-section of the wave height records from two buoys separated by 150km in the Southwest UK, and demonstrates a time where an average of the two sites lessens the variability of the wave energy. The peak of the storm occurs 3.5hrs earlier at site 1 than at site 2 and wave heights are greater at site 1 prior to the peak; post-peak, wave heights are greater at site 2. For this case, were wave energy converters to be deployed at both sites then some intermittency in the contribution of wave energy to the national grid could be reduced. For example, the large variations in wave height for both sites between 00:00 and 03:00 (upward for site 1, downward for site 2) would produce large step changes in power output when considered independently. The combined record shows a slower variation because the upward and downward spikes cancel each other out and hence combined power output would show a much smaller step change over an hourly time period.

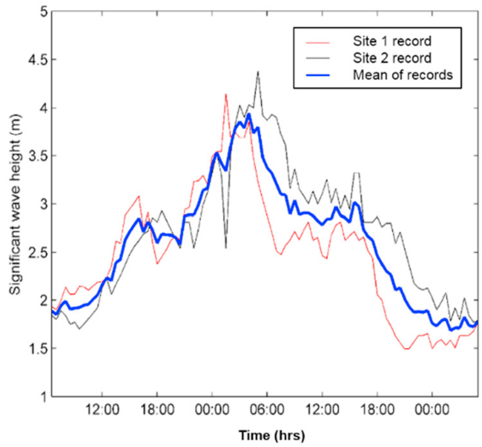

Fig. 1. Example storm event illustrating the potential smoothing achieved through generating wave power at two sites 150km apart.

This study utilises wave buoy data, supported by numerical modelling, to analyse the wave resource over different spatial scales to investigate the potential impacts of the temporal and spatial resource variability on the grid supply. The primary focus is the Southwest UK (SW UK), home to multiple existing and proposed wave energy test sites and with coastlines exposed to all potential wave directions. One of the key areas of consideration is an assessment of the variation in available power at sites across the region for different directional sea states, which could then be exploited when considering the selection of sites for future development to benefit grid integration. However, this is not just a regional consideration. The issue will become increasingly relevant at wider geographical scales with the development of European high voltage direct current (HVDC) interconnectors in Atlantic-facing Europe. The UK currently shares interconnectors with France, Ireland and the Netherlands, with the potential for a further 10GW of connection by 2025 with countries including Belgium, Norway, Denmark and Iceland [5]. In mainland Europe, electrical connections exist between Portugal and Spain, and Spain and France. Thus, a balancing of wave-generated electricity on international scales will be a potential future option.

The SW UK study methodology is outlined in Section 2 and results presented in Section 3. The study is also extended to consider how results extend to national- and international-scale developments, referencing results published by the authors in [6]. The results are discussed in the context of the development of the wave energy industry in Section 4.

2. Methodology

2.1. Southwest UK wave buoy data

Concurrent buoy data were acquired for a 9 month period (Jun ‘15 – Feb ‘16) for six sites in SW UK, four offshore (40-90m depth) and two nearshore (~15m depth) (Fig. 2). Three of the offshore buoys are located at or close to the region’s wave energy test sites: Wave Hub, off the exposed north coast of Cornwall, FaBTest, off the more sheltered south coast, and the Low Carbon Research Institute (LCRI) buoy located close to the South Wales Demonstration Zone. The fourth, the Scilly buoy, is exposed to wave conditions from all directions and is therefore used as a reference point for this study. The two nearshore buoy locations, Perranporth, off the North Cornwall coast, and Porthleven, off the south, are representative of sites where nearshore wave energy conversion (WEC) devices may be deployed. The characteristics of each site are presented in Table 1. With the exception of FaBTest, the offshore buoys experience similar mean wave conditions with directions from the W-SW. However, FaBTest, sheltered from the predominant westerly conditions, experiences significant wave heights (H_s) of approximately a third of the other sites, with directions from the S-SE. The two nearshore buoys experience similar sea states, with heights lower than the offshore sites. The mean directions at these sites are approximately normal to the alignment of the shoreline due to the refraction of the waves entering the nearshore area.

The buoy records were analysed to assess the variability of wave heights around the region relative to sea state direction. This is important in the context of this study, because if different sites experience the largest wave heights in different directional sea states, then there is more scope for both power smoothing and reducing the times of zero wave energy generation. Additionally, relative wave heights were calculated between the pair of offshore buoys experiencing similar conditions (Wave Hub and LCRI) and the pair of nearshore buoys (Perranporth and Porthleven). The percentage relative wave height is calculated as the ratio between the site with the lower mean wave height and the site with the larger mean wave height for both pairs of sites. For the offshore this is then the LCRI H_s divided by the Wave Hub H_s and for the nearshore is the Porthleven H_s divided by the Perranporth H_s.

Table 1. Site characteristics for the six buoy locations.

Buoy site	Lat.	Lon.	Water depth	Tidal range	Mean H_s	Mean T_p	Mean dir.	Deployment date	Data provider
Wave Hub	50.35	-5.61	50m CD	6.1m	2.3	10.2	258	22/05/2015	CCO [7]
FABTest	50.05	-5.04	40m CD	6.0m	0.8	6.1	167	18/03/2012	University of Exeter
LCRI	51.56	-4.86	40m CD	6.3m	2.1	9.5	239	23/09/2014	Swansea University
Scilly	49.82	-6.55	90m CD	6.1m	2.9	10.8	255	11/10/2014	Cefas Wavenet [8]
Perranporth	50.35	-5.17	14m CD	6.1m	1.8	10.6	284	18/12/2006	CCO
Porthleven	50.06	-5.31	15m CD	4.7m	1.5	10.1	232	16/10/2011	CCO

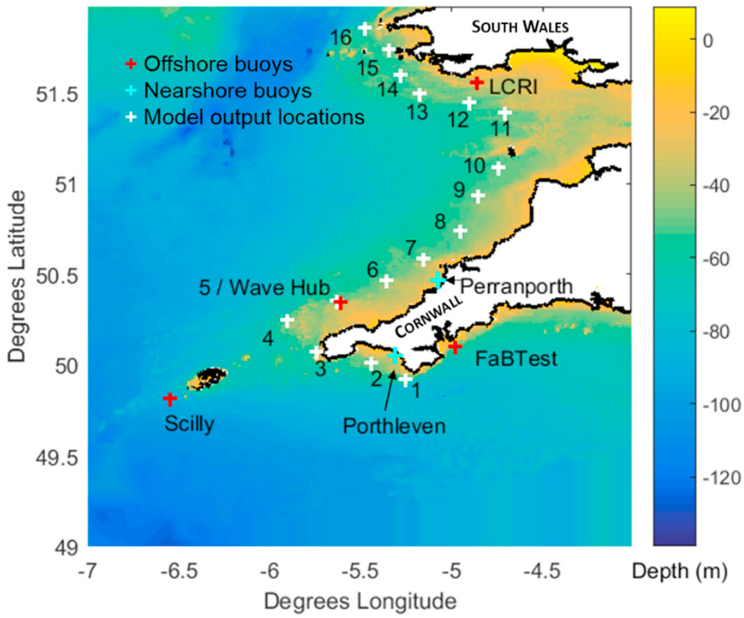

Fig. 2. Offshore buoy, nearshore buoy and model output locations used for data analysis in SW UK.

2.2. Southwest UK wave model data

Additional data points and a longer dataset were provided by a regional wave model simulation. The spectral model SWAN (version 41.10) [9], developed for use in nearshore regions and accounting for both depth-limited and deep water wave propagation processes and energy losses (including whitecapping, bottom friction and depth-induced breaking), was applied across the geographical domain shown in Fig. 2. The model used was an extension of the validated set-up described by Van Nieuwkoop et al. in their 2012 study [10], with the northern grid boundary extended to 52°N. Additional validation studies using data from the Wave Hub and LCRI buoys indicated comparative levels of performance with the original model. The model was run at 1km resolution with wave parameter boundary inputs acquired from the ECMWF ERA-Interim dataset [11]. Output wave parameters were produced at hourly intervals at the six wave buoy locations and an additional 16 approximately evenly spaced sites on the 50m depth contour around the SW UK coastline (Fig. 3), and the available wave power, P (kW/m), calculated using the deep water power equation:

$$P = \frac{\rho g^2 H_s^2 T_e}{64\pi} \quad (1)$$

where ρ is the density of sea water (taken as 1025 kg/m^3), H_s is the significant wave height and T_e is the energy period. Since the output locations were predominantly at 50m depth or deeper, this was assumed to provide sufficiently accurate results.

Output data were processed to analyse the variability of mean available power per directional sector of the sea state (north (315°-45°), east (45°-135°), south (135°-225°) and west (225°-315°)), using the output at the Scilly buoy to provide the reference direction. This allows the varying wave heights and directionality around the region's coastlines to be assessed more fully and over a more representative time scale.

2.3. Power calculations

Time series of potential power generation at each location in Fig. 2 were calculated using power matrices from two hypothetical wave energy converter (WEC) devices: a small bottom-referenced offshore heaving buoy (for model output locations and offshore buoy sites) and a bottom-fixed oscillating flap (for the nearshore buoy locations) (Fig. 3). These are taken from theoretical calculations presented by Babarit et al. [12]. The maximum step change in power, defined as the change in output power over a specified period, was calculated over 1hr and 24hr periods for the two pairs of buoy locations (offshore and nearshore), using measured and modelled data, and the 16 additional wave model output locations as a percentage of installed capacity, assuming the same installed capacity at every offshore or nearshore site.

For the buoy locations, the maximum step change in power was considered first for the individual locations and then for the combined offshore or nearshore sites. The analysis was then extended to the 16 model output locations. The maximum step change was calculated for all combinations of 1-8 sites out of the total 16, and the minimum value out of all combinations for each number of sites was identified.

2.4. Extension to national and international scales

The study was extended to national (UK, Rep. of Ireland) and international (Atlantic-facing Europe) scales using ECMWF ERA-Interim model data [11] (Fig. 4). Six-hourly data from a 10-year period (Jan 2006 – Jan 2016) were extracted at 0.125° resolution at depths between 40 and 100m. Sites were selected for analysis, shown as red dots in Fig. 4, based on geographical spread and ensuring that no more than one site occupies each model grid cell. The same process to calculate the minimum value of the maximum step change for each combination of sites was performed.

3. Results

3.1. Wave buoy data analysis

Directional analysis of the sea states experienced at each buoy location are presented in Fig. 5b, with Fig. 5a showing the spread of directions and significant wave heights over the 9-month period from the reference Scilly wave buoy. The plot shows mean heights for different directional sectors where wave direction for each data point in the time series was determined from the Scilly buoy. Clear differences in wave exposure are shown. For the offshore buoys, the LCRI buoy has larger mean wave heights for waves incident between the SE and WSW while wave heights are larger at the Wave Hub from other directions. Similarly the nearshore buoy at Porthleven (south coast) has larger mean wave heights for directions between 100-260° (ESE – WSW) while wave heights are larger at Perranporth for other directions. The site at FaBTest has smaller mean wave heights than the other buoys for all directional sectors apart from the east. These conditions are commonly associated with wind-sea generated by easterly strong winds in the English Channel; at such times swell incident from the Atlantic is often low energy.

(a)

Significant wave height (m)	4	5	6	7	8	9	10	11	12	13	14	15	16
7				15	12.9	10.9	10	8.8	8.6	8.2	7.6	7.3	6.8
				13.5	11.6	10.4	9.8	9	7.6	7.3	7.5	6.2	6.4
6				13.1	11.3	10.1	9.1	8.3	7.5	6.7	6.9	6.4	5.8
				11.1	10.1	8.9	8.1	7.5	6.8	6.4	6.1	5.5	5.8
5			12.2	10.8	9.2	8.6	7.3	7.2	6.3	5.9	5.7	5.4	5.0
			10.6	9.5	8.7	7.6	7.0	6.1	5.9	5.4	5.1	5.0	4.7
4			8.9	8.6	7.6	6.8	6.2	5.6	5.0	4.6	4.5	4.3	3.6
			8.4	7.3	6.9	5.8	5.4	4.9	4.4	4.2	3.7	3.4	3.6
3		7.4	6.7	6.2	5.7	5.4	4.7	4.1	4.1	3.7	3.3	3.3	3.2
		6.0	5.2	4.5	4.6	4.3	3.9	3.6	3.0	2.8	2.5	2.7	2.6
2	4.4	4.0	3.7	3.6	3.5	3.1	2.8	2.5	2.3	2.2	2.0	1.8	1.7
	2.6	2.5	2.3	2.2	2.3	2.0	1.9	1.7	1.4	1.5	1.2	1.2	1.2
1	1.2	1.3	1.2	1.2	1.1	1.0	0.9	0.8	0.7	0.7	0.7	0.6	0.7

Peak period (s)

(b)

Significant wave height (m)	4	5	6	7	8	9	10	11	12	13	14	15	16
7				2871	3119	3131	3127	3176	3332	2877	2925	2676	2658
				2778	3044	3001	2989	3211	2986	2896	2716	2455	2309
6				2406	2713	2776	2344	2705	2451	2396	2182	2414	2133
				1979	2339	2308	2115	2389	2120	2012	1940	1518	1587
5			1247	1670	1965	1962	2097	2002	1833	1798	1814	1459	1442
			1219	1408	1644	1677	1807	1641	1662	1562	1404	1370	1191
4			843	1093	1352	1427	1430	1390	1158	1224	1139	1138	863
			655	934	1032	1085	1241	1075	973	925	862	747	688
3		368	503	693	799	824	876	792	759	704	546	579	554
		254	378	467	568	623	616	601	519	523	481	390	428
2	75	160	233	301	380	408	383	399	329	365	319	265	259
	63	92	126	168	201	213	201	239	207	198	183	150	154
1	27	39	57	76	87	104	109	100	101	98	94	94	87

Peak period (s)

Fig. 3. Power matrices showing absorbed power in kW per sea state bin for hypothetical WEC devices: (a) an offshore bottom-referenced heaving buoy, (b) a nearshore bottom-fixed oscillating flap (from [12]).

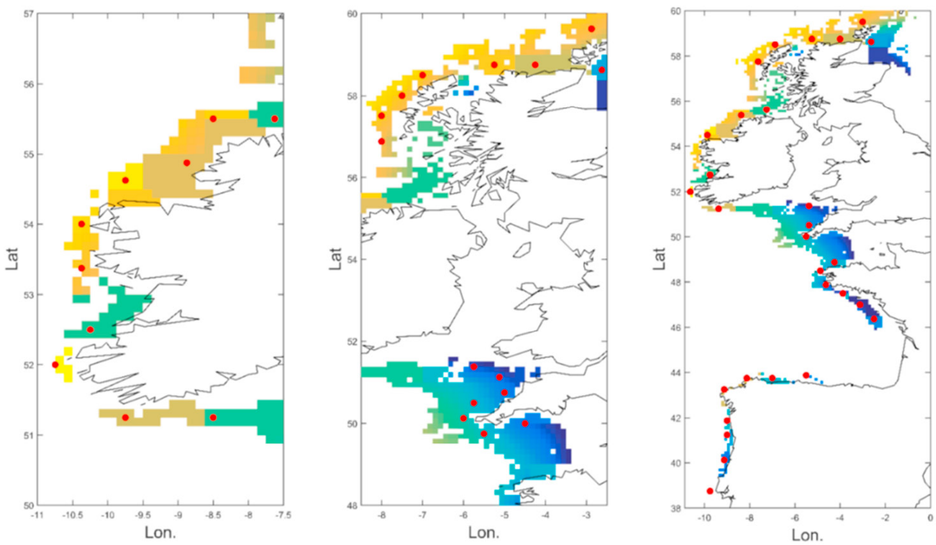

Fig. 4. ECMWF ERA-Interim data points for national- and international-scale study.

Results analysing the comparative relative wave heights between the pair of offshore buoys and pair of nearshore buoys are presented in Fig. 6. Each point on the scatter plot is one data point from the 9 month time series of buoy data and indicates at each time-step which buoy of the two pairs experiences the larger significant wave heights. The relative wave height is given as a percentage, where values less than 100% indicate Wave Hub wave heights greater than LCRI and Perranporth wave heights greater than Porthleven. For 59% of the time, relative wave heights are higher at both Wave Hub and Perranporth, and for 76% of the time the two more southerly exposed buoys are either both greater than or both lesser than the more northerly exposed buoys which demonstrates the amount of time that directional dependence influences wave height on a regional scale. The lesser time with waves being greater at the LCRI buoy and at Porthleven reflects the fact that waves from the northwest are more common than waves from the southwest during the period of buoy measured data, as shown in Fig. 5a. Since both sets of buoys experience the waves generated by the same low pressure systems, the times at which the sites with greater exposure to waves from the south have larger waves is similar for both nearshore and offshore sites.

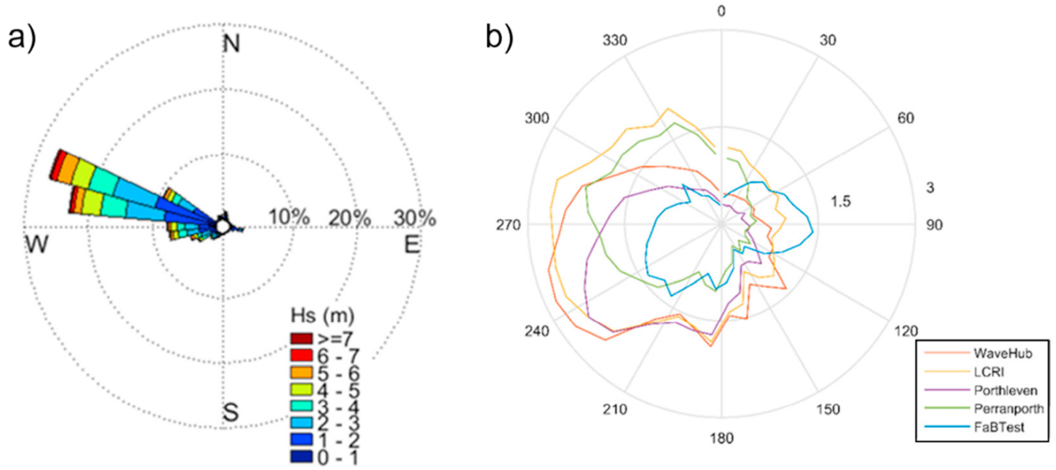

Fig. 5. (a) Wave rose illustrating distribution of significant wave heights and directions at the reference Scilly wave buoy; (b) Mean significant wave height per 10° directional sector for the wave buoys (excluding Scilly).

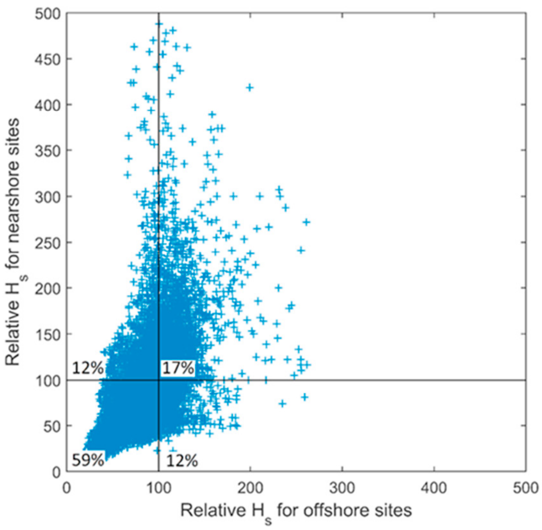

Fig. 6. Scatter plot of relative wave heights from the offshore and nearshore buoys showing percentages of points in each quadrant.

3.2. Model data analysis

Output from the SWAN wave model simulation allows the buoy analysis presented in the previous section to be extended across the region. Fig. 7 presents the average wave power at each model output location plus the FaBTest site, binned per directional sector based on modelled wave direction at the exposed Scilly buoy location. Clear trends in the data around the coastline can be seen. The most powerful waves, for all sites except FaBTest and locations 1 and 2 off the south coast of Cornwall, occur from westerly directions. These peak at the exposed location 4 (25kW/m) before reducing along the north coast of Cornwall and then increasing slightly moving west in South Wales.

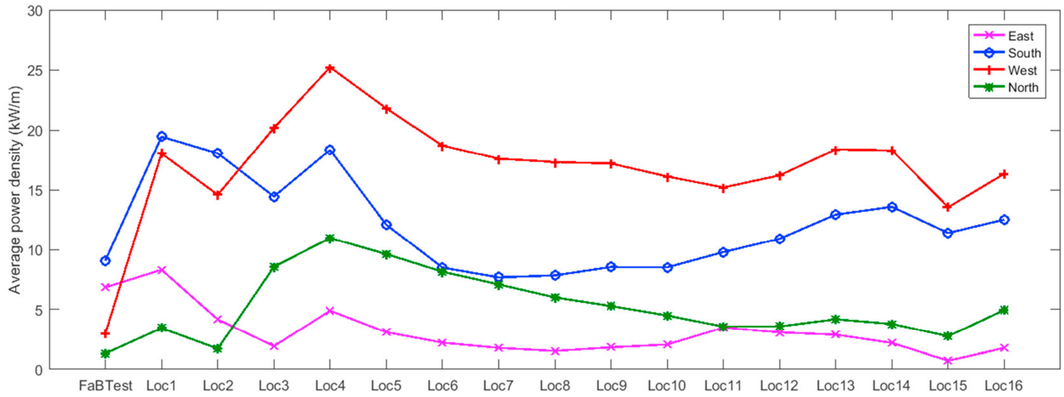

Fig. 7. Average wave power at each hindcast model output location (see Fig. 2) binned by reference wave direction at the Scilly buoy.

Northerly and southerly waves affect the coastlines differently as would be expected, given their orientations. Northerly waves have a shorter fetch and are most powerful along the north coast of Cornwall (locations 3-8), whereas southerly waves are most powerful off the south-facing coastlines, with a significant drop-off in power in North Cornwall. Easterly waves provide the lowest power levels, below 5kW/m, at all sites except FaBTest and location 1 which are exposed to the English Channel.

3.3. Power calculations – SW UK

Maximum step changes in power were calculated over 1 hr and 24 hr periods for the offshore and nearshore buoys, individually and in combination, as a percentage of installed capacity. The results are presented in Table 2. In all cases, combining the power generation from two sites leads to a significant reduction (around one-third) in the step change. Overall, the offshore locations experience lower step changes than the nearshore sites, and when calculations are made using the buoy data, there is little difference between the 1 hr and 24 hr step changes. However, calculations made using the longer-term model data (given in brackets in Table 2) indicate larger step changes over the 24 hr period and a lesser reduction when considering the combined power generation.

Table 2. Maximum step changes in power for individual and combinations of two offshore and nearshore sites from buoy and model data as a percentage of installed capacity (model data values in brackets).

Max offshore step change (%)			Max nearshore step change (%)		
	1 hr	**24 hr**		**1 hr**	**24 hr**
LCRI	53 (47)	55 (70)	**Perranporth**	94 (70)	83 (81)
Wave Hub	56 (33)	62 (75)	**Porthleven**	90 (72)	90 (90)
Combined offshore	34 (23)	40 (67)	**Combined nearshore**	61 (36)	59 (76)

3.4. Power calculations – National and international scales

The analysis of step changes was extended from combinations of two sites up to a maximum of ten sites over 24 hr periods at a range of spatial scales:

- Cornwall sites (from SWAN model output)
- South Wales sites (SWAN model output)
- SW UK (SWAN model output)
- Atlantic-facing UK (ECMWF data)
- Republic of Ireland (ECMWF data)
- Atlantic-facing Europe (ECMWF data).

The results are illustrated in Fig. 8.

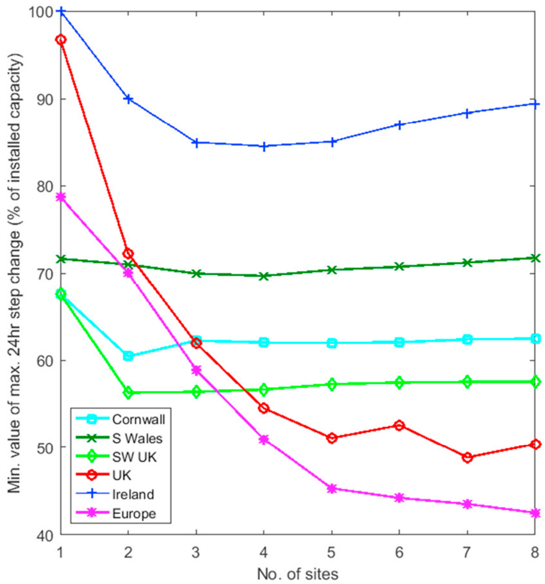

Fig. 8. Minimum values of maximum 24 hr step change for combinations of 1 to 8 sites across a range of spatial scales.

It can be seen that smaller variations in step change with increasing numbers of sites occur in regions where sites are primarily exposed to the same sea states. This is particularly evident in South Wales, however, this is also seen in Cornwall and SW UK (after an initial drop when increasing from one to two sites) and in the Republic of Ireland (after a drop from one to three sites). A far more significant drop is seen over the wider spatial scales of Atlantic-facing UK and Europe. This is due to the lower sea state correlation across sites in these areas, with their spatial extent sufficient that different parts of the region will often experience sea states from different weather systems, in addition to having very different geographical features affecting sea states locally. However, in all cases the step change plateaus once a maximum number of sites is considered, beyond which there is minimal additional benefit to considering more sites. A more detailed analysis of these results can be found in [6].

4. Discussion and conclusions

The Southwest UK provides an interesting case study for this type of assessment due its energetic wave conditions and varying coastline orientation. Analysis of offshore and nearshore buoy data illustrates the variability in wave height and power levels with wave direction at different locations around the region including the existing wave energy test and demonstration sites. When this analysis is extended to numerical modeling output with greater spatial coverage, these power level trends become clearer. Different sites will therefore produce the highest levels of power in different sea states and weather conditions. This is reflected in the significant reduction in both hourly and

24-hrly step change in power in the region when considering output from two sites in combination rather than individual sites. However, no further step change reduction is seen when considering more than two sites. It is surmised that this is due to the relatively limited spatial extent of the region and the fact that the majority of sea states, although affected by local geography, originate from the same weather systems, leading to relatively high levels of correlation across the region.

The importance of maximising the range of directional exposure of sites in order to increase the power smoothing and reduce grid-integration constraints is demonstrated by the step change results for the wider national- and international-scale study; developing multiple sites to provide exposure to the widest range of weather systems is likely to have the largest impact on reducing intermittency. There are therefore questions relating to the selection of sites for commercial-scale development, and the potential role of government or regulatory bodies in designating these, that the industry should consider. By considering potential sites on a regional and national basis, accounting for the resource variability, large-scale deployment solutions that might benefit grid integration could be identified.

Acknowledgements

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