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Spatio-temporal variation in wave power and implications for electricity supply

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ABSTRACT

Wave energy resources are intermittent and variable over both spatial and temporal scales. This is of concern when considering the supply of power to the electricity grid. This paper investigates whether deploying arrays of devices across multiple spatially separated sites can reduce intermittency of supply and step changes in generated power, thereby smoothing the contribution of wave energy to power supply. The primary focus is on the southwest UK; SWAN wave model hindcast data are analysed to assess the correlation of the resource across multiple sites and the variability of power levels with wave directionality. Power matrices are used to calculate step changes in the generated power with increasing numbers of sites. This is extended to national and European scales using ECMWF hindcast data to analyse the impacts of generating power at multiple sites over wider areas. Results show that at all scales the step change in generated power and the percentage of time with zero generation decreases with increasing numbers of sites before plateauing. This has positive implications for performance of electricity grids with high levels of renewable penetration.

1. Introduction

Concerns are often raised over intermittency of electricity generation from renewable sources and associated cost implications as the market share of renewable energy increases [2,13,22]. Depending on the penetration level of renewable generation, intermittency can create problems for grid management [19,35]. Traditionally, electricity demand is predicted and a matching supply is arranged in a pre-set manner. With more intermittent supplies, high levels of flexible balancing plants are required and availability of balancing plants limits the amount of intermittent power that can be integrated into the grid. For example, in Ireland it is estimated that in the period up to 2020 the balancing services will substantially contribute to limiting the proportion of electricity generated from intermittent renewables at any moment to 75% [41].

Marine energy, in the form of wave and tidal stream, is a relative newcomer to the field of renewable electricity generation. Tidal and wave resources differ significantly in their temporal variability. Tidal energy is highly predictable, with spatially phased cyclical intermittency driven by the relative motions of the Earth, Moon and Sun. Studies have investigated the potential reduced intermittency in generated power due to out of phase energy extraction sites around the Northwest European shelf [34,38]. For the first generation (high energy) tidal sites, many key locations are in phase, meaning that peaks in production are amplified and troughs remain [38]. However, as technology develops and allows exploitation of lower energy sites, phase differences between second generation lower flow sites may be more beneficial [39].

Wave energy is less predictable than tidal energy, although more predictable than wind or solar [45]. Wave energy supply is irregular and varies on timescales from individual waves through to long-term variation in storm frequency [30,32]. Resource estimations for wave energy to date have focused on the spatial variability of parameters to define sites [1,5,25,27,52] or considerations of temporal variation to refine forecasts of extractable power [43,55].

Here we consider intermittency of energy supply on timescales from hours to days. High frequency changes in power quality (e.g. Refs. [4,29]), while important, are outside the scope of this contribution. A range of resource assessments have investigated the reduction in intermittency achieved with co-located wind and

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wave farms (e.g Refs. [6,42]), but few resource assessments have focused solely on wave energy intermittency at these spatio-temporal scales. In contrast, a large body of work has investigated characteristics of wind energy intermittency when multiple sites are considered (e.g. Refs. [3,23,26,28]). These studies illustrate how combining power generation from multiple sites leads to reduced intermittency and that the reduction in intermittency depends on the correlation of the resource between sites, with combinations of less well correlated sites providing greater reductions.

An important parameter for electricity supply is the step change in generated power, i.e. the output power change over a certain time interval [28]. Time intervals considered in the literature include 10 min, half hourly, hourly and daily. Step change is also important for electricity markets; for the United Kingdom market the half hour ahead model is particularly important whereas for the North American electricity markets 5 min, half hourly and hourly markets are all used. Smaller step change (lesser variation) is preferable for energy supply since it indicates smoother supply. Uncontrolled step changes are higher for renewable sources such as wind or wave compared to conventional generation. Maximum step change over a specified time series is a useful metric which can be used to compare sites. It has been shown that the value of maximum step change in supply can be reduced based on interconnecting multiple sites for wind energy [28].

This contribution seeks to assess the premise that, as has been shown for wind, intermittency in wave energy supply may be reduced when multiple spatially separated sites are considered. Complex coastal bathymetry, tidal effects [18,24] and varying storm tracks mean that sites in the same region with similar resource levels may exhibit differences in wave energy in the time domain due to differing exposure to varying wave direction or lags between storm peaks at different locations. Therefore, spatially separated sites may aid in reducing the intermittency of wave energy output to the national grid. Robertson et al. [46] identify times where there is a 100% variation in power output from two wave farms sites in close proximity due to variation in swell exposure. From the grid integration perspective, a consideration of the wave energy at spatially separated sites can provide a better understanding of the amount of wave energy that can be connected to the grid without requirement for additional balancing options.

The work described here considers the impact of combinations of wave energy deployment sites at three spatial scales (Fig. 1): regional, national and continental. A detailed assessment is performed for the Southwest United Kingdom, using ten years of SWAN model [9] hindcast data. The spatial variability of the available resource across the region is described, followed by an investigation into the impacts of power generation at different combinations of sites. Subsequently, the consequences of combinations of site at national (Republic of Ireland and Great Britain) and European scales is presented. Hindcast data from the ECMWF ERA-interim dataset [15] are used. While wave energy contributions to renewable energy over a European scale is somewhat academic in terms of actual grid supply, it is still beneficial to consider European-scale deployment given the combined commitment to combat climate change and reduce carbon emissions.

This study is important to the development of the industry because it demonstrates that the contribution of wave energy to future electricity supply may be poorly represented if considerations of intermittency are based on knowledge of intermittency at one site. Consideration of input of renewable sources such as wave must be considered with multiple sites in the time domain on both a regional (for the distribution network) and national (for the transmission network) basis to give a true reflection of their potential future contribution to grid supply.

2. Study regions

The Northwest European shelf (Fig. 1) is the focus of this study, with four case studies: a regional scale example of the Southwest United Kingdom (SW UK); two national level cases for the Republic

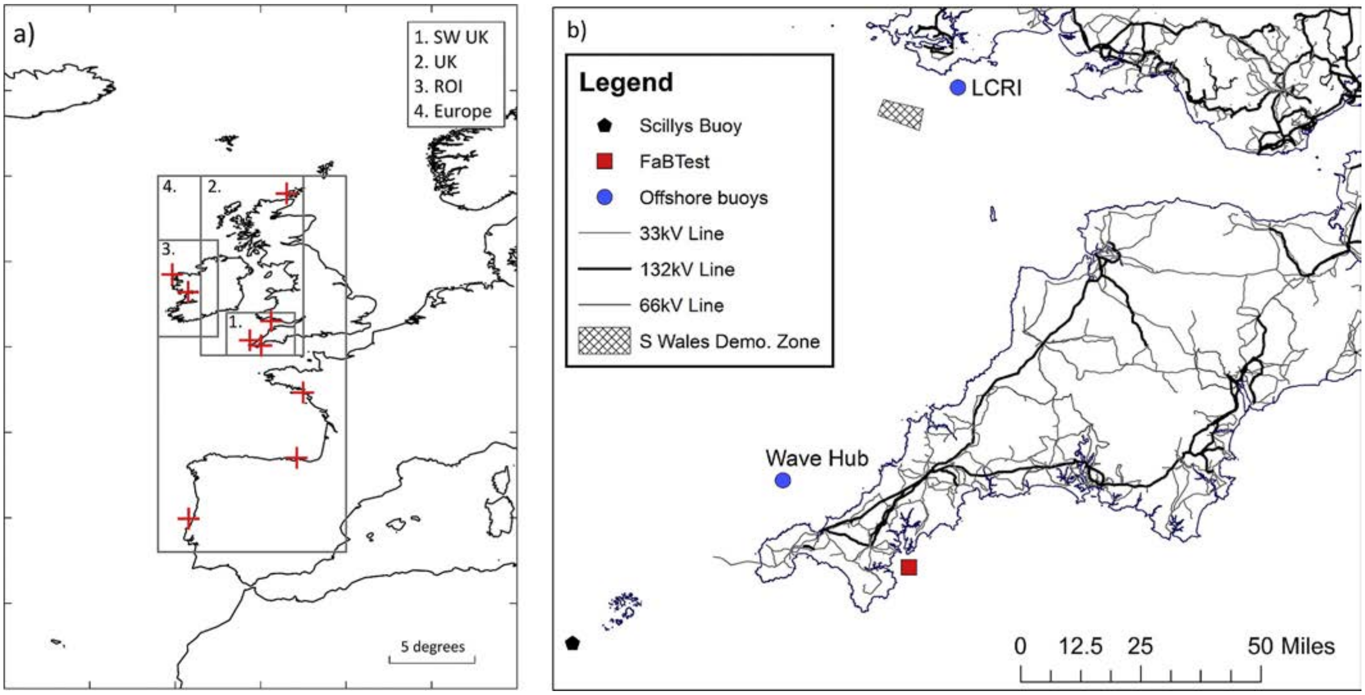

Fig. 1. Maps of a) Western Europe with the 4 study regions highlighted and existing wave energy test facilities marked as red crosses; b) the South West UK showing the location of the different wave buoys used, the South Wales demonstration zone and existing power lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of Ireland (ROI) and the Atlantic-facing UK (UK); and a multinational case of Atlantic-facing Europe (EUR). Particular reference is paid to the regional scale study of SW UK.

2.1. Southwest UK

The Southwest UK is exposed to swell seas from both the Atlantic Ocean and Bay of Biscay, as well as local wind seas. Some locations in Cornwall are also exposed to easterly sea states originating in the English Channel. There has been a strong focus on wave energy in the region for over a decade. Wave Hub is a 20 MW grid-connected test site off the north coast of Cornwall, established in 2010, with its first wave energy test device deployed in 2014. Other testing facilities are also available in the region, including the South Wales Demonstration Zone, for demonstration of pre-commercial arrays, and the Falmouth Bay nursery test site (FaBTest). Grid infrastructure is good in much of this area due to presence of other power generation sites such as the Pembroke gas power station, although it becomes increasingly constrained as it heads southwest into Cornwall. The Southwest UK is also the first region in the UK to be designated as a marine energy park; the South West Marine Energy Park (SWMEP) was established in 2012 to accelerate the growth of the industry [44].

2.2. United Kingdom

In addition to the southwest region, the wave energy resource in the UK is found primarily in Scotland; its Atlantic-facing coastlines benefit from the UK's largest sea states, with average wave power levels of 25–35 kW/m predicted off Orkney [57]. Scotland has seen significant investment in marine renewables and is home to the European Marine Energy Centre (EMEC) in Orkney, where multiple wave energy devices have been tested at both an offshore grid-connected test site and a more sheltered nursery site since 2003. A particular challenge in Scotland is the remoteness of the sites where the best wave energy resources are found; grid upgrades and new cable installation will therefore be required in order to fully exploit the available resource [49].

2.3. Republic of Ireland

A number of wave energy resource assessments have been conducted for the seas off Ireland (e.g. Refs. [10,20,21], highlighting the large available resource and the industry potential. A range of both laboratory and offshore wave energy test facilities are available, notably the Galway Bay test site and the grid-connected offshore Atlantic Marine Energy Test Site (AMETS) currently under development off the west coast [16].

2.4. Europe

Western and northern Europe has a theoretical potential wave energy resource of 2500 TWh/yr [37], although the exploitable resource will be significantly lower. In context, the total European electricity generation in 2014 was 3030 TWh [17]. This resource is primarily located off the Atlantic-facing regions of Portugal, Spain, France, Ireland and the UK. Each of these nations has seen investment over the past decade to develop wave energy test sites and support the growth of the industry. In addition to the test sites described in the previous sections, developments include Oceanplug in the Portugese Pilot Zone [40], the Biscay Marine Energy Platform, bimep, in northern Spain [8] and the SEM-REV site in western France [51]. Well-developed grid infrastructure is present in many of these areas. High voltage direct current (HVDC) interconnectors, allowing the trading of electricity between countries, are present. The UK has existing interconnectors with France (2 GW capacity), Ireland (1 GW capacity) and The Netherlands (1 GW capacity) and an additional 10 GW of interconnection is proposed by 2025 [54]. Strong electrical links exist between Spain and Portugal through the MIBEL or Iberian electricity market. A 2 GW interconnector links the Iberian market to France.

3. Data sources and methodology

3.1. Wave buoys

Data were available from three wave buoys in the SW UK domain: at the Wave Hub site [11]; southwest of the Isles of Scilly [56]; and close to the South Wales Demonstration Zone, operated by the Low Carbon Research Institute (LCRI) at Swansea University illustrated in Fig. 2. Although the buoy datasets only overlap for short periods of time, they are used in this study to validate the SWAN model (Wave Hub and LCRI buoys) and provide a reference point for directional wave data in the region (Scilly buoy, further described in Section 4.1).

3.2. SWAN model data

The spectral wave model SWAN 41.10 [9] was used to model the variability in wave conditions across Southwest UK over a 10-year period. SWAN is specifically designed for use in coastal regions and incorporates depth-limited effects including refraction and bottom friction in addition to deep water processes including whitecapping, nonlinear interactions and transfer of wind energy. The SWAN model used in this study is an extended version of the setup described in detail by Ref. [55]. The original model domain covered the area from 4 to 7° west, and from 49 to 51° north. For this study, the northern boundary was extended to 52° north to incorporate the South Wales coastline (Fig. 2). The model was run over a 1 km resolution regular domain. This was assumed to be sufficiently detailed, given that all output locations were at 50 m or deeper and therefore few depth-limited effects would be felt. Model boundary conditions were taken from the 1.5° resolution European Centre for Medium-range Weather Forecasting (ECMWF) ERA-interim WAM wave model [15], with ECMWF outputs interpolated to the boundaries of the SWAN model to provide variable inputs along all four boundaries. Wind speeds and directions from the same source [15] were applied across the domain. Currents were excluded due to the focus on deeper water sites rather than

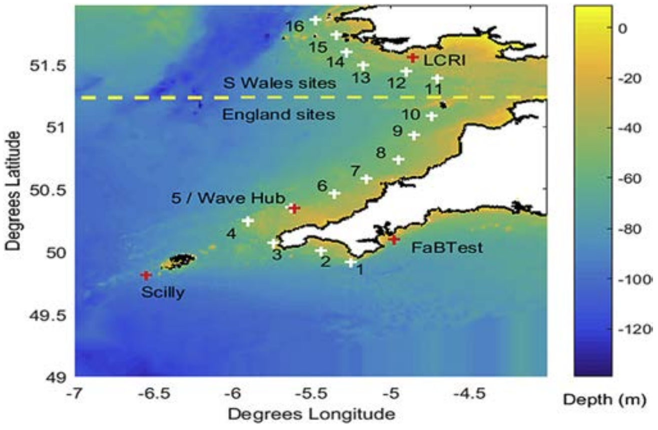

Fig. 2. SWAN model domain showing wave parameter output locations (navy crosses) and buoy locations (red crosses). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shallower water nearshore sites where the role of currents is more significant. The model was run in non-stationary mode with a 60 min timestep over the 10-year period 1998–2007. The model was extensively calibrated and validated when originally established [55]. Additional validation to account for the extended grid domain is presented in Fig. 3 using data from two wave buoys deployed at the Wave Hub and LCRI test sites. Fig. 3 shows both scatter and timeseries plots for significant wave height and peak period. For both locations, the wave height scatter shows good agreement between buoy and model data. The timeseries subset shows that the model picks up the timing and general shape of the measured data but the storm peaks are under-represented and some higher frequency variability is lost. Peak period is less well modelled, with greater variability in the scatter plot, but the timeseries shows the general magnitude is well represented. Values of relative bias and scatter index, as defined in Ref. [55]; are of similar order of magnitude to the original validation for H_S. Peak period shows a larger scatter index compared to the previously tested mean period.

Output wave parameters (H_s, T_e, T_p and mean direction) were produced at 16 evenly spaced locations around West and North Cornwall, North Devon and South Wales (Fig. 2). All output locations sit on the 50 m depth contour to reflect suitable positioning for offshore wave device deployment. Additional outputs were also requested at the WaveHub, LCRI buoy and FabTest sites. FabTest is included due to its exposure to waves incident from the east.

3.3. ECMWF ERA-interim data

Hindcast model data from the ECMWF ERA-interim dataset [15]

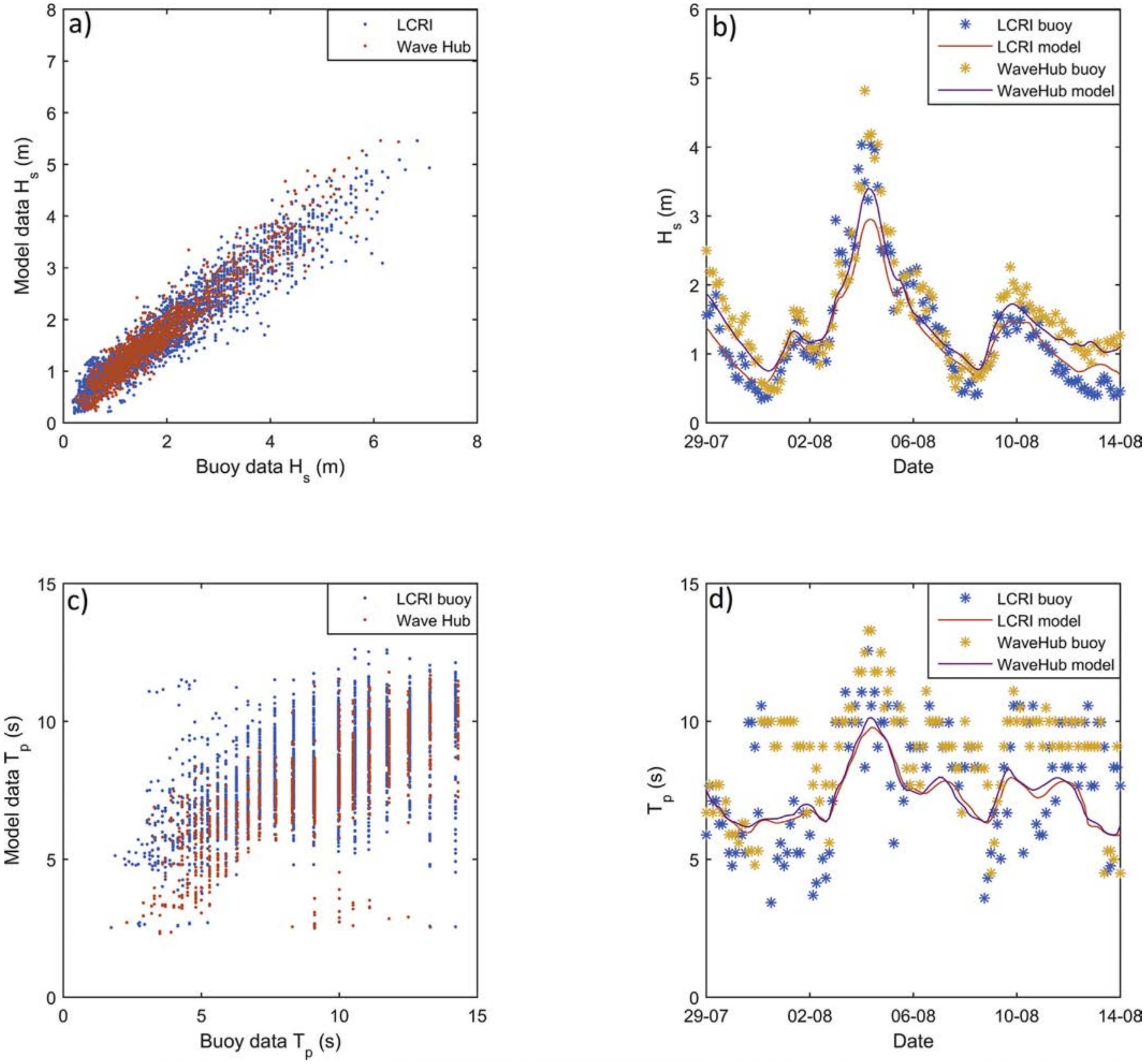

Fig. 3. A comparison between modelled and measured data. a) a scatter plot of modelled against measured Hs; b) a short subset of the Hs time series; c) a scatter plot of modelled against measured Tp; and d) a short subset of the Tp time series.

is used to extend this analysis to a national and European level, utilising a decade of wave data from January 2006–January 2016. Temporal resolution is 6 h and extracted spatial resolution is 0.125 deg.

Potential areas were defined based on a device specific depth constraint of 40–100 m and a capacity factor greater than 25% calculated via a power matrix (see section 3.4). From this area, 9 sites were selected for ROI, 15 for UK and 29 for Europe (Fig. 4). These sites were arbitrarily selected while ensuring geographical spread and that sites did not occupy the same model grid cell (duplicating the power time series). The number of sites was limited by the model resolution.

3.4. Calculation of power

To examine the spatial variability in available wave power around the SW UK region, mean power over the 10-year dataset was calculated based on the deep water power equation,

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

where P is the wave power in W/m, H_s is the significant wave height, T_e is the energy period and ρ is the water density. All the output locations are at approximately 50 m depth, therefore although there will be some seabed interaction with lower frequency wave components, the use of the deep water calculation will not introduce significant errors. Comparison between the deep water power calculation and spectral power calculation for 2015 showed that the deep water calculation produced power values on average 1.5 kW/m (~7%) lower than the spectral calculation. However, since this study is concerned with the spatial variability of the resource rather than the absolute available resource this is not considered to be significant.

Different wave energy converters will extract different proportions of the available power because devices are designed to operate within a range of wave heights and periods and to maximise power extraction at a specific frequency band. Thus, it is necessary to consider generated power by use of device specific power matrices. Power matrices are commercially sensitive and while some early device power matrices, such as the Pelamis P1, are in the public domain, more recent matrices are unavailable. Instead, a theoretical matrix calculated by Ref. [7] is used to determine extracted power. The small bottom referenced heaving buoy (Bref-HB) is used which is similar in design to the Seabased WEC from Sweden [12, 31, 50]. Characteristics of the hypothetical WEC are listed in Table 1 and the power matrix displayed in Fig. 5. Power is obtained from the wave parameter time-series using the matrix as a look-up table. For H_s-T_p pairs outside of the power matrix parameter space, for example under extreme storm waves, the generated power is set to zero.

4. Results

4.1. Description of resource for the Southwest United Kingdom

Fig. 6 shows wave roses for four spatially distributed output points around the SW UK domain (Fig. 2). Point 1 in South Cornwall and the point at the LCRI site have the majority of waves approaching form the south west while the point at Wave Hub and output location 9 have waves most commonly incident from the west, reflecting their locations and local geography. However, the more exposed Wave Hub and South Cornwall (point 1) sites see the greatest variability in wave direction.

Of particular interest was comparison of conditions at the Wave Hub and LCRI sites to assess regional scale complementarity. Fig. 7

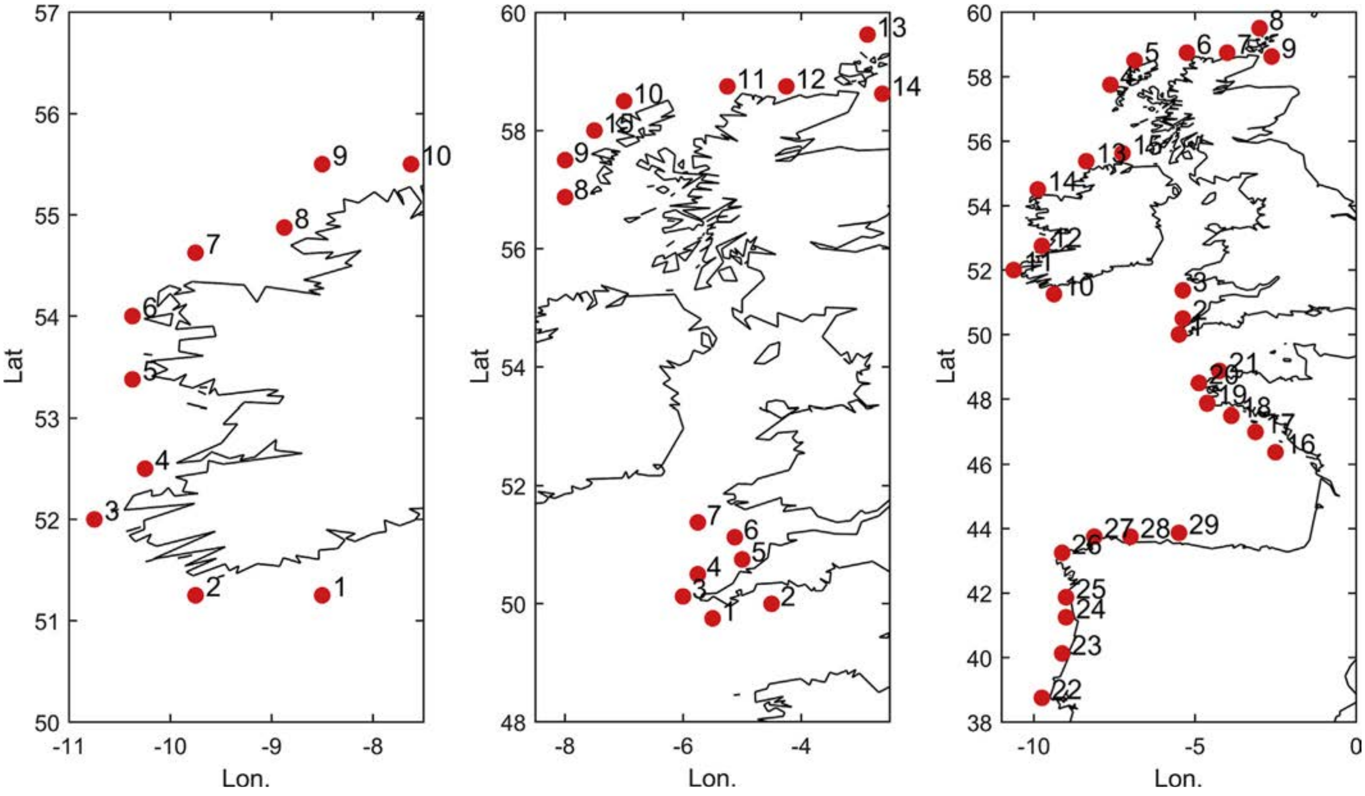

Fig. 4. Sites selected for the three cases a) ROI, b) UK and c) Europe.

Table 1
Properties of the BrefHB matrix used in this study (from Ref. [7]).

Maximum power	15.5 kW	
Water depth	40–100 m	
PTO model	Linear	
Draft	0.63 m	
Displacement	2.83 m^3	
Characteristic Mass	31 Mg	
Buoy/flap mass	1000 kg	
Char. Surface area	42 m^2	
Buoy specific parameters	Diameter	3 m
	Stroke length	1.8 m

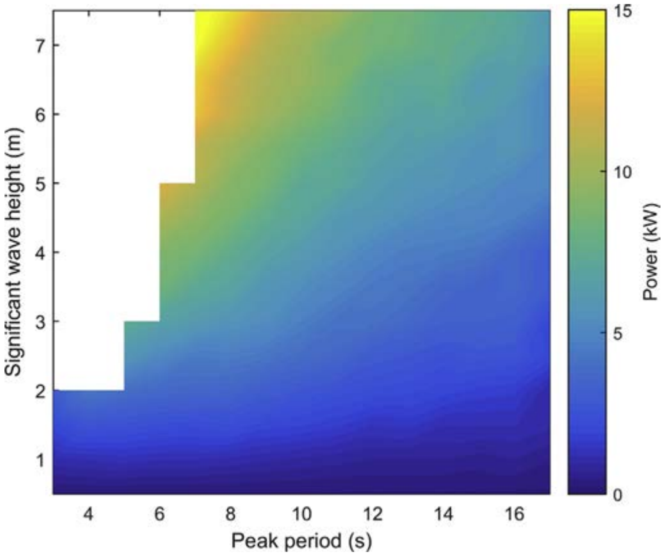

Fig. 5. A visual representation of the Bref-HB power matrix (from Ref. [7]).

shows H_s-H_s scatter plots for both buoy and model data. It can be seen that there is a good correlation between wave heights at the locations despite differing wave exposure: the r^2 value between the two sites is 0.84 for the buoy measured data and 0.96 for the model data.

Average power for the 16 output locations, plus the FaBTest site, are shown in Fig. 8. Results are in line with what would intuitively be expected. FaBTest, sheltered from westerly seas, experiences the lowest level of power. The site with the highest power levels is the exposed location 4, with power reducing as one moves east along the north coast of Cornwall to location 10. Locations 11–16 lie off the south coast of Wales, with power increasing again as one progresses west to the exposed locations 13 and 14 before reducing again in the slightly more sheltered locations 15 and 16.

One of the aims of this study is to investigate how power levels vary with differing wave direction around the coastline. Therefore, the wave directions at the Scilly buoy were used as the reference offshore direction and average power then calculated at each location for waves from the four directional segments:

- East (wave directions 45°–135°) – 6% of sea states
- South (wave directions 135°–225°) – 9.8% of sea states
- West (wave directions 225°–315°) – 77.2% of sea states
- North (wave directions 315°–45°) – 7% of sea states

The results are presented in Fig. 9. The spatial variation in wave power around the coastline is clearly dependant on offshore wave direction. For example, the locations off the south coast of Cornwall experience greater power from southerly sea states and a significant contribution from easterlies. Along the north coast of Cornwall, power is greatest from westerlies, with both northerly waves, due to the available fetch, and southerlies due to refraction contributing significantly. The contribution to power levels from the northerly waves decreases moving eastward along the north coast of Cornwall and into the South Wales locations due to the decreased fetch, whereas southerly sea states show increasing levels of power at the Welsh locations. However, the low proportion of easterly, southerly and northerly sea states should be noted, since these provide only 23% of the total sea states.

4.2. Combinations of multiple sites

Multiple sites were analysed using the time series of generated power for all spatial scale scenarios. For the SW UK scenario, this was further split into the entire SW region (18 sites), sites closest to the English coast (10 sites) and sites closest to the Welsh coast (8 sites). Various parameters related to power output were assessed for increasing numbers of sites. These parameters were: maximum step changes in power over 1 h and 24 h; time spent idle; and power levels exceeded for 25%, 50% and 75% of the time. In all cases it is assumed that equal numbers of the bottom referenced heaving buoy (offshore device) would be installed at each site. This means that increasing the number of sites means increasing total capacity and therefore power parameters are presented as percentages of installed capacity. Parameters were calculated for all combinations of $\binom{n}{k}$ or 'n choose k' sites, where n is the total number of sites for each of the three cases and k is between 1 and 8. The extreme value (minimum or maximum) of each parameter for combinations of k sites was determined and plotted against k. Therefore, the discussion of Figs. 11–13 below shows the results of choosing the best sites in combination.

It has been shown in wind energy research that greater benefits occur when less well correlated sites are combined [28], hence Fig. 10 graphically displays correlation coefficients for generated power between the various sites for all four spatial scales. For the SW UK, correlations between power generation time series were high and statistically significant in all cases. It is interesting to note that the sites in South Cornwall (sites 1–2) are better correlated with sites in South Wales (sites 11–14) than the west and north Cornwall sites, despite these sites being closer. This demonstrates the importance of directional exposure in the region. While correlation coefficients are not always large for the other tested scales, in all cases correlation was significant at the 95% level. Correlation coefficients range from 0.25 to 0.82 for the ROI, from 0.11 to 0.86 for GB and from 0.06 to 0.87 for Europe. In general, correlations between sites are lower for the case considering all of Europe which is unsurprising given the greater geographical spread. For the GB case the sites in the south are well-correlated and the sites in the north well-correlated but there is less correlation between south and north. The ROI case shows generally greater correlations due to both the geographical proximity and the similarity in wave exposure.

4.2.1. Percentage of time idle

Deployment of WECs at multiple sites cannot prevent there being times at which there is no contribution from wave energy to the grid. However, multiple sites reduce the amount of time of zero power output. This is the case over all tested spatial scales and is shown in Fig. 11. The rate of reduction slows with an increasing number of sites and for all cases, minimal additional benefit is gained by increasing the number of sites above 4 (SWAN data) or 5 (ECMWF data). The level at which the minimum percentage plateaus decreases as the geographical scale and number of available

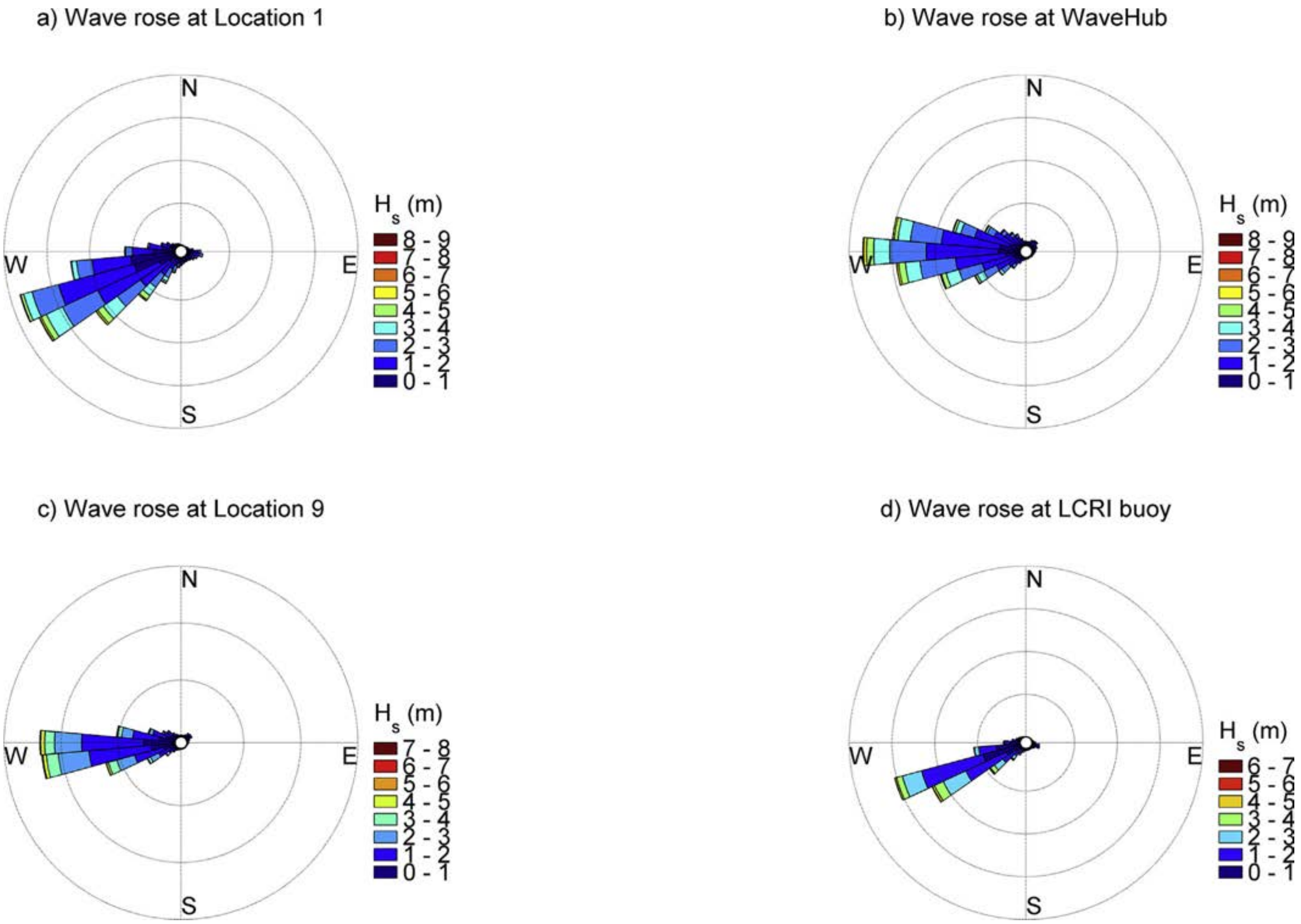

Fig. 6. Wave roses for four points around the SW UK (locations in Fig. 2).

sites increases (correlation decreases). For the Welsh case this level is 12%, for England, the SW UK and ROI between 6 and 7%, for UK around 3% and for Europe it drops to ~0.5%.

4.2.2. *Generation exceedance curves*

While the percentage of time for which no power is generated reduces with increasing number of sites, so too does the power level exceeded for various percentages of time. It is desirable to have larger values of power level exceeded for a given duration and hence these results illustrate a negative aspect of combinations of sites when all sites are assumed to have equal capacity. With only one site, the site with greatest power generation is picked, and the power levels exceeded for a given proportion of the time are greatest. As less optimal sites are included, the power levels reduce. This is shown in Fig. 12 which shows the percentage of installed capacity that generation exceeds for 25%, 50% and 75% of the time. For the SW UK, shown in Fig. 12a, there is very little difference in the level of power exceeded 25% of the time for any of the three cases or any number of sites. At the 50% and 75% level, a lower power is exceeded for the Welsh sites. This varies between 5 and 10% of the installed capacity. Increasing number of sites reduces the power level exceeded for 50% and 75% of the time. The rate of this reduction is linear and is similar for all six combinations. Similar patterns are observed over the larger geographical scales (Fig. 12b), the exception is the initial sharp drop at the 75% level for both ROI and Europe between one and two sites.

4.2.3. *Step changes in power supply*

Analysis of step changes over one hour is presented in Fig. 13. It is desirable to minimise the maximum step change for a given generation scenario. Therefore, for every combination of k sites, the combined power time series was calculated and the maximum value of step change for each time series found. From these sets of maximum step change values, the minimum value was determined and plotted against k. This represents the optimal combination of k sites to minimise step change. Increasing from one to two sites reduces the minimum value of the maximum step change substantially. Step change is considered both on an hourly and 24 hourly basis for the SW UK where SWAN model data could be used, whereas only 24 h step changes were considered using the ECMWF data due to the temporal resolution of the data. For the hourly step change, all three cases show similar patterns: an increasing number of sites reduces the maximum step change for up to four sites, whereupon the reduction plateaus. This is an important result as it clearly demonstrates that multiple spatially separated sites could be beneficial to the integration of wave energy in to electrical grid. Less impact is noticeable for the 24 h step change. This is particularly the case when considering only the Welsh sites. The GB and Europe cases show similar patterns where the minimum value of maximum daily step change becomes smaller with an increasing number of sites. The rate of this reduction drops off after 5 sites. For the ROI case, an increasing number of sites has less impact on maximum step change. Additionally, beyond 4 sites the maximum

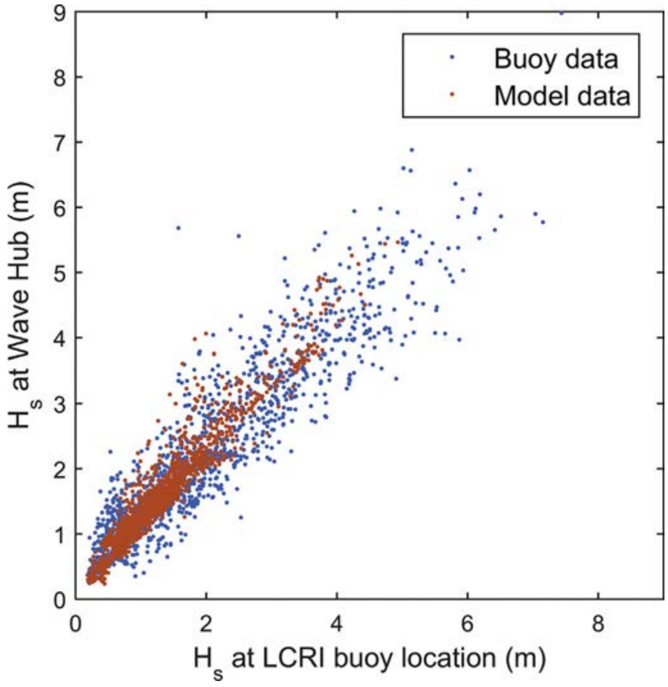

Fig. 7. Scatter plots of Hs at the WaveHub site against Hs at the LCRI site for both model and buoy data.

step change starts to increase again. It is believed that this lesser reduction is due to the greater correlation between sites and the increase over 4 sites is due to the lesser number of sites (9) meaning that the problem becomes over constrained.

5. Discussion

The results clearly demonstrate that considering multiple wave energy deployment sites leads to a reduction in step changes in power, a reduction in time of zero generation and a reduction in power level exceeded for a given time percentage. These results hold true over all spatial scales considered from a regional to international level. These results are positive from a grid integration perspective. However after a certain number of sites, the benefits of increasing site number reduces.

Differences in wave directional exposure is a significant factor in our results, which is influenced by bathymetry and storm tracks. These storm tracks are influenced by the jet stream whose behaviour varies both seasonally and under the influences of longer term atmospheric oscillations. Thus maximising the range of directional exposure of sites maximises generation opportunities.

At a regional scale, the similarity between wave resources at the Wave Hub site and at the LCRI buoy close to the proposed array demonstration zone is positive for developers. It means there is a clear pathway from device demonstration at Wave Hub to precommercial arrays in the demonstration zone under similar environmental conditions. One aspect that has not been considered in

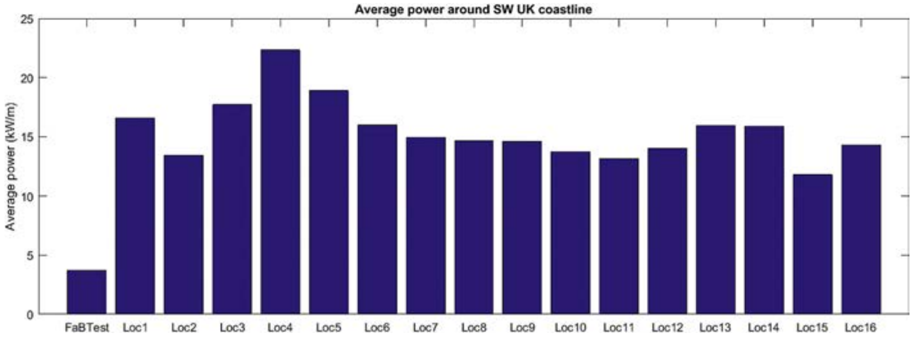

Fig. 8. Average wave power over 10-year hindcast duration at the model output locations shown in Fig. 2.

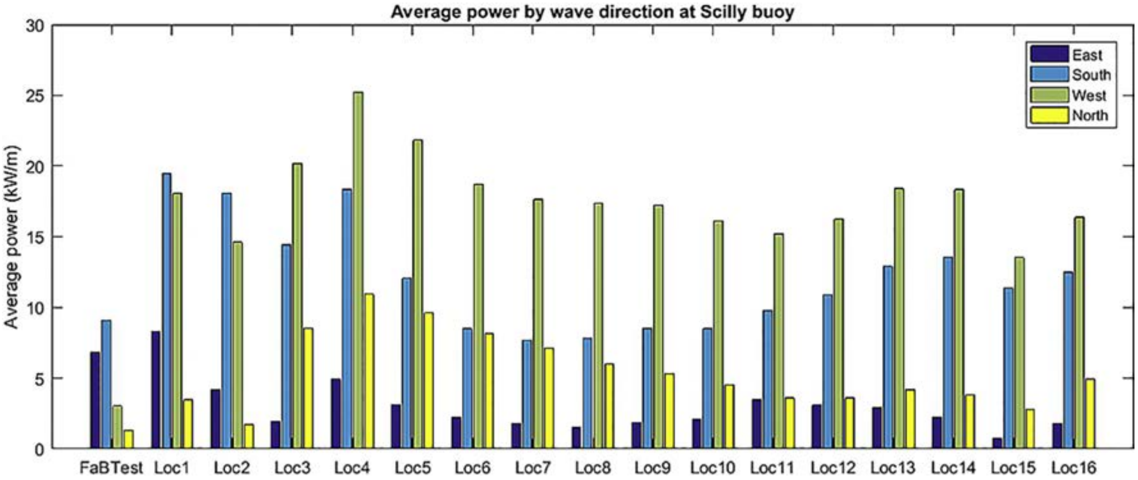

Fig. 9. Average wave power at each hindcast model output location binned by wave direction at the Scilly buoy location. The locations are marked in Fig. 2.

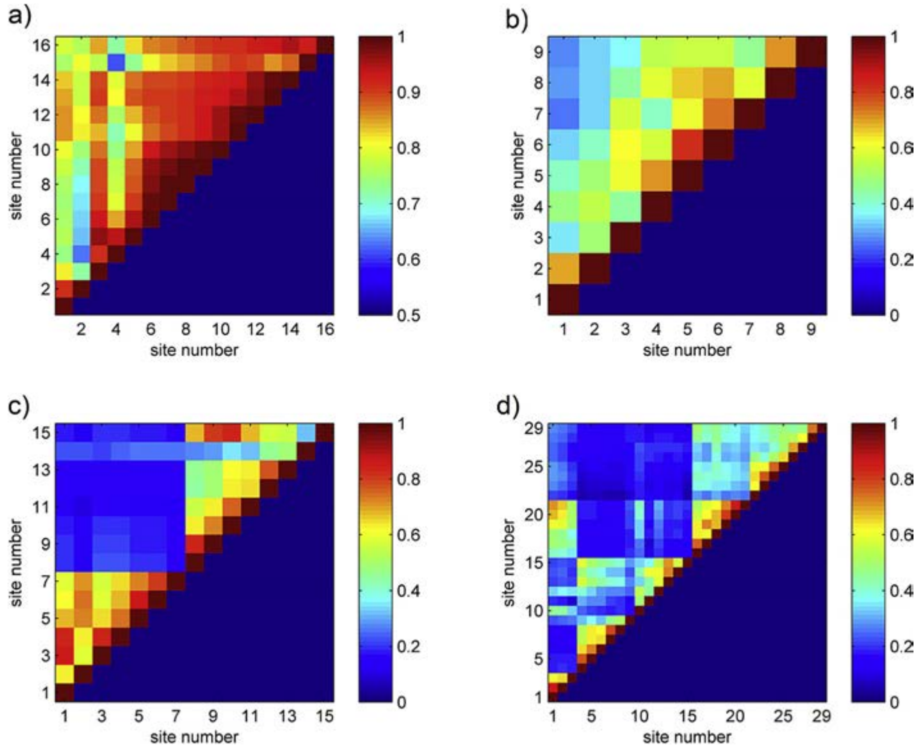

Fig. 10. Correlation coefficients (colour shading) between sites for the four cases: a) SW UK, b) ROI, c) UK and d) Europe. The site numbers are included on Fig. 2 and 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

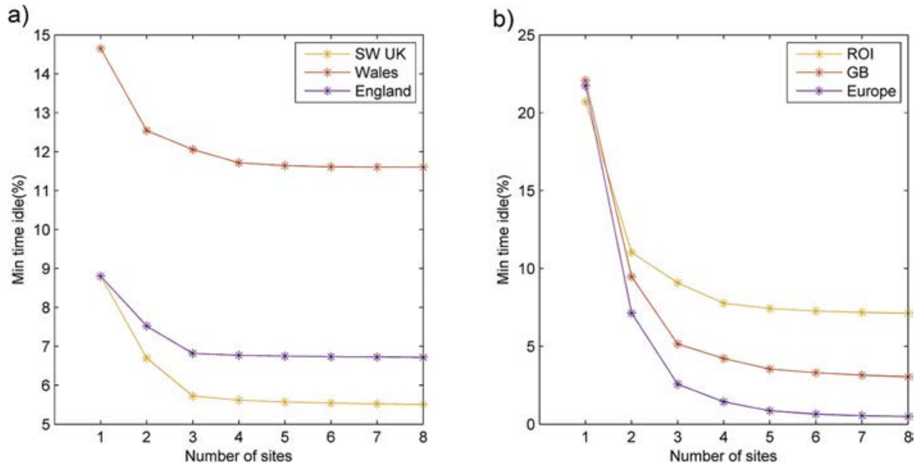

Fig. 11. Minimum time with zero power generation for the optimal combination of a given number of sites: a) for the SW UK using Swan data and b) for the national and European scenarios using ECMWF data.

this contribution and which may be relevant to regional scale resource variability is the influence of tidal effects on wave climate [24,33]. Tidal modulation of wave height is particularly prevalent in the South Wales region [18] and has also been described for the Cornish coastline [14]. Modulation is dependent on tidal phase which varies around the region and hence tidal effects are likely to enhance spatio-temporal variations in resource and increase the magnitude of the results presented here.

From a grid integration perspective, analysis of the wave power at spatially separated sites demonstrates that the effect of intermittency on frequency variation can be reduced, allowing a better judgement to be made on the amount of wave power that can be integrated into the grid compared to a decision based solely on scaling up the effect of intermittency at one particular site. However, at the distribution network level the effect of intermittency on the voltage fluctuation will depend on the distribution network structure, points of connections and the geographical locations. The results presented here show that the maximum step change in power is significantly reduced by considering multiple local sites compared to only one site in the Southwest UK. Therefore, there is good potential that the effect on voltage fluctuation can be reduced, but further studies that consider the structure of the distribution network are required to confirm the premise.

There are consistencies between the work presented here and the literature on wind energy. Katzenstein et al. [28] consider step changes in supply from wind energy and while the geographic

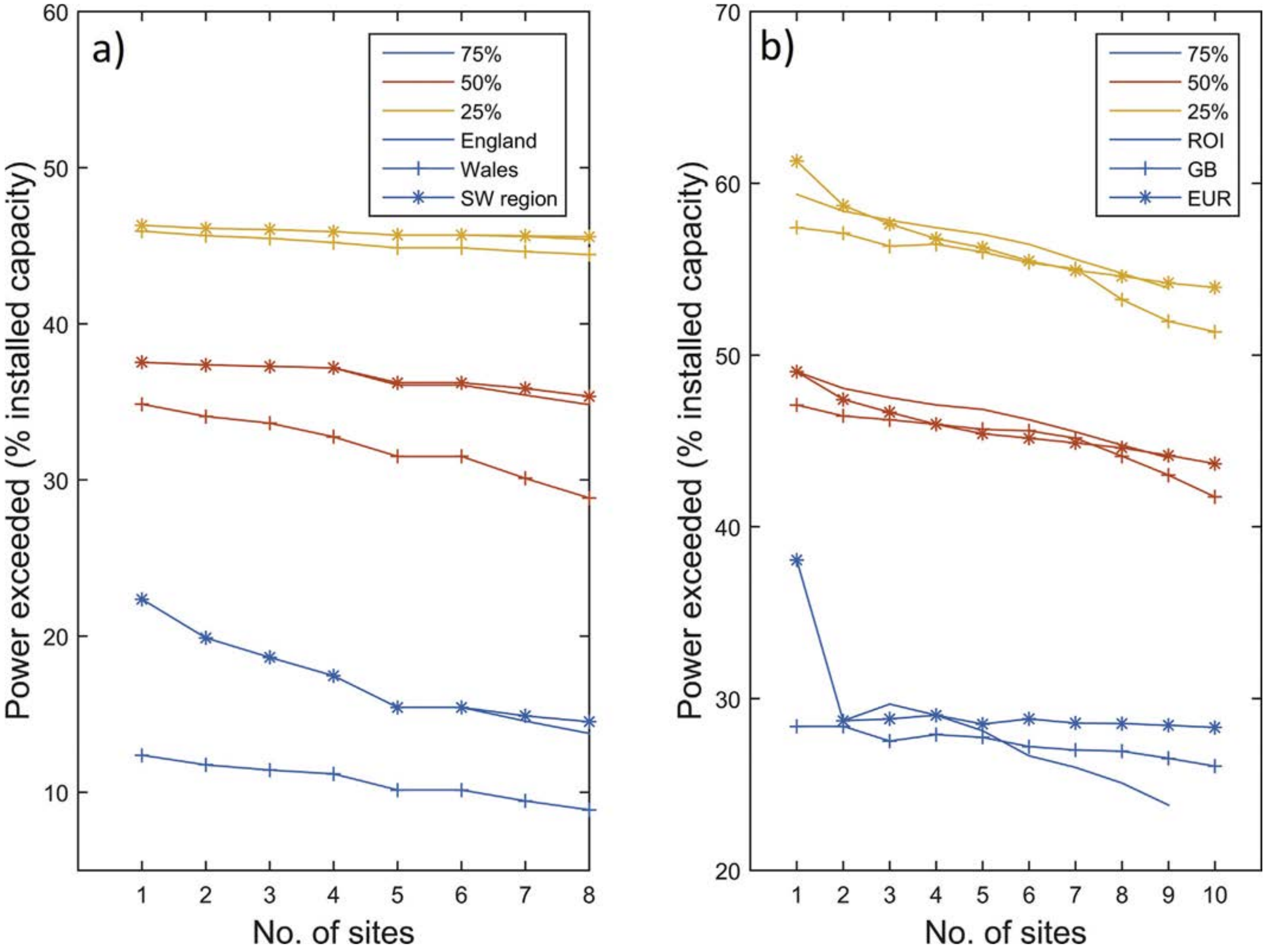

Fig. 12. The power level as a percentage of installed capacity that is exceeded for over 25, 50, 75% of the time for increasing number of sites in combination. a) shows the SW UK analysis and b) shows the national and European scale analysis.

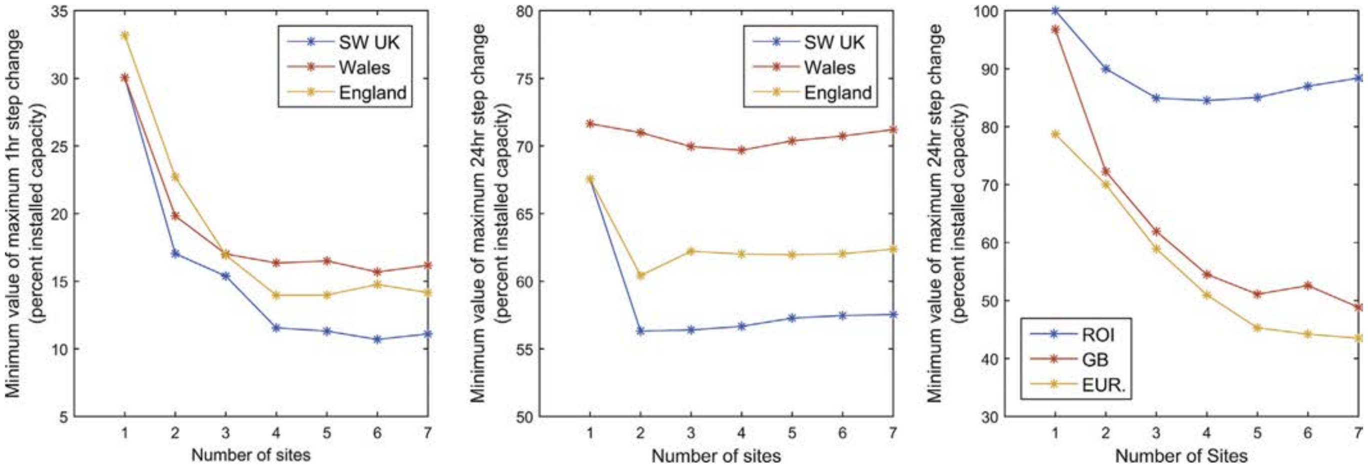

Fig. 13. The minimum value of maximum step change for each set of combinations of k sites for the SW UK case with a) a one hour time interval, b) a 24 h time interval and c) for the national and European scales with a 24 h time interval.

location, scale and number of sites is quite different to the presented study, there are some similarities in the results: the benefit is greatest for the first few sites and plateaus as more sites are added and greater benefit is seen for the short time period compared to the 24 h case. Gunteroo and Schlosser [23] conclude that benefits of aggregation increase with decreasing correlation between sites, something that is also indicated by the results presented here. They consider cases of different independent system operators in the United States and determine that benefits of aggregation saturate beyond 10 sites. This is a larger number of sites than found here for the regional and national analysis but similar for to the step change analysis at a European level.

The methodology used here considered installing equal capacity at each site. This means that total installed capacity increases with increasing number of sites. Therefore, while the step change measured as percentage of installed capacity goes down, the actual step change may remain similar or increase. An alternative approach, and one worthy of future research, would be to set a total level of installed capacity and then to consider the benefits to power smoothing and grid integration of splitting that capacity between varying number of sites. If amount of installed capacity was not held constant between sites this might result in a complex optimisation problem, however benefits would likely be maximised.

An area for consideration on the basis of these results is whether there should be a role for governments or national bodies, such as the Crown Estate in the UK, to pre-select development sites to allow for benefits to the grid, rather than developers selecting sites on the basis of the available resource and operational logistics. This is not without precedent; in 2010 the Crown Estate announced agreements for leases for eleven wave and tidal stream projects in the waters of the Pentland Firth and Orkney Islands in northern Scotland. The agreements gave the developers rights over the seabed for site investigation and project development for the duration of the agreement, although the projects would still be subject to the statutory consenting process. Although grid integration was not a significant factor in the selection of these sites, a future approach where spatio-temporal variations in the resource are prioritised on a UK-wide basis, for example, could lead to a solution beneficial to grid performance.

Future analysis might consider the synergy of all renewable sources in a region and their total contribution to electricity supply. If, for example, wind and wave climates were poorly correlated, the combination of wind and wave might further reduce intermittency.

6. Conclusions

Data from a validated numerical model show that the wave direction for the largest wave heights and power levels vary around the southwest of the UK, contributing to a spatio-temporal variability in the resource. On a regional basis, and extended up to a European level, this means that combinations of multiple sites for wave energy generation can be beneficial to the grid integration of wave energy, with both the duration of time for which zero power is produced and the value of maximum step change reduced. However, this is at the expense of bulk power output with the percentages of installed capacity generation that was exceeded for given proportions of time reducing.

At a regional level the benefits of combining sites level off beyond four sites, whereas at a national scale benefits do not level off until 5–6 sites are considered in combination. For the European scale, this varies between 6 and 9 sites depending on the parameter assessed. In general, increasing geographic spread, which equates to lower correlations, means the benefits of considering combinations of sites are enhanced.

This research shows that considering wave energy sites in combination is important to understand the role that wave energy can play in future energy generation scenarios. Linearly scaling the intermittency shown by one site to a number of sites will underestimate the potential of wave energy. This is an important and positive result for the wave energy industry and for energy policy makers.

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