Characterising the wave power potential of the Scottish coastal environment

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Manuscript: Characterizing the wave power potential of the Scottish coastal environment

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ABSTRACT

The study focuses around the energetic waters of Scotland, that has expressed high interest in the development of wave energy farms. There are only a few long-term suitable studies characterising coastal locations. A detail coastal resource assessment is provided, focusing on wave energy and site characterisation. Mean nearshore energy content in the Western coasts is $\geq 50kW/m$, and on the East $\approx 10kW/m$. Monthly and seasonal analysis outline available resource and annual variations.

Availability of production is also examined, West coastlines present higher levels, however depending on resource and wave converters operational range significant differences are shown. Availability levels on the East coastline are low $\approx 40\%$ due to lower wave heights, while Western locations record consistently over 80% at both scenarios examined. Results discuss the potential applicability of favourable wave converters, and characteristics which achieve maximum utilisation based on the local environment.

KEYWORDS

Numerical Modelling ; Wave Power ; Resource Assessment ; Availability ; Scottish coastal environment

1. Introduction

United Kingdom (UK) and especially Scotland is exposed to some of the most energetic waters in Europe, with annual average resource exceeding 60-70 kW/m at intermediate depths (Cornett, 2008; Reguero, Menéndez, Méndez, Mínguez, & Losada, 2012). Though this is encouraging, coastal and more accessible resources are not always the same with different physical processes affecting the final content. Growing interest for the development of wave energy require, long-term and properly assessed energy estimates based on the metocean climate. Several studies have utilised long-term databases of wave climates to characterise the potential wave energy production with different converters (E. Rusu & Onea, 2016; L. Rusu & Onea, 2015).

Buoy data have been used throughout the years for monitoring of the wave climate, and lately of wave energy studies (Vögler & Venugopal, 2012) Gathering wave data is a cumbersome process that often does not allow overall site energy characterisation. Spatially sparse buoy records are particularly lacking at coastal shallow locations, and deeper buoys cannot be used to carry out coastal resource assessments. In addition, short time recordings (active deployment years), often do not allow in depth examination of the wave climate. In order to overcome the lack of data numerical wave models have been utilised, initially for the construction of studies involved in climate analysis (Agarwal, 2015; Caires & Sterl, 2005; Sterl & Caires, 2005; Swail, Ceccacci, Cox, & Cob, 2000). Long-term evaluation of wave data are the basis for analysis of energy levels, and provide robust estimations on opportunities of specific areas.

While numerical wave models offer an alternative for gathering data, their operation, construction, calibration, and validation is a lengthy and often difficult process. There is no "quick" way in the construction of a reliable model, considerations and processes tuned by the user affect results directly. Historical studies (hindcasts) by numerical models serve as a rich repository of information that can be used for site and resource characterisation of large domains. In Table. 1, a number of available studies (large scale) and their operative systems are presented. As seen for larger domains, most studies focus on the Atlantic ocean region, providing hindcasts for Climate Change and environmental studies.

Application at Atlantic European coastlines contributed significantly in the identification of climate patterns, quantification of extreme values and wave analysis. Amongst the longest studies is the work of Agarwal (2015) focused on identification of Climate Change in the offshore environment and corresponding extreme value levels. This extensive dataset of over 100 years, allowed investigation of Climate Change trends in the Atlantic and UK coasts. In the seminal work of Caires and Sterl (2005), the Atlantic extreme return wave periods were quantified, alongside a thorough discussion on the limitations of oceanic models in regards to nearshore areas. In terms of wave energy and different application for wave energy converters E. Rusu (2014) used data from an oceanic model and the provided robust energy estimation around a variety of European coastlines. Table 2, presents an overview of dedicated models for the North Atlantic and Scottish regions.

For Scottish waters one of the most commonly used assessments is the first dedicated wave power map by ABP-MER (2014), prepared in 2007 for the UK government. At point of its publication in 2007 the map offered valuable information, concerning areas with high concentration of wave power. Although, considerations must be taken by limitations of the second generation model and coarse resolution as discussed in Neill and Hashemi (2013). Another limitation is the temporal hindcast duration of just 7 years, which restrict it applicability for wave energy assessment (Ingram, Smith, Bittencourt-Ferreira, & Smith, 2011).

Since then several studies have contributed in the characterisation of North Atlantic coastlines. The studies can be classified in three ways, first as UK based, medium, and limited area studies (covering a small coastline). Transitions from deep water to nearshore location, also prompts the use of different numerical models appropriate to resolve nearshore mechanics Ingram et al. (2011); Venugopal et al. (2011).

A study by Gallagher, Tiron, and Dias (2013) produced wave power resource for the areas of the North Atlantic and Ireland using an oceanic model. Gleizon (2014); Gleizon, Campuzano, García, Gomez, and Martinez (2015) focused on limited areas of the Scottish and North Sea with a nearshore model, and assessed wave energy though for a limited duration.

Neill and Hashemi (2013) used a nested mesh approach for the Mid-Atlantic and then several smaller domains including North Atlantic location for wave energy assessment. Lavidas (2015); Lavidas, Venugopal, and Friedrich (2017a) utilised a high resolution spatial mesh to examine the wave climate, wave resource, quantify wave energy converters (WECs) performance and extreme conditions around multiple locations of the Scottish and North Sea coasts. As seen, majority of the models are appropriate to resolve coastal conditions and provide high level information. Although, one of the limiting parameters to consider is their small time duration. The EQUIMAR protocols (Ingram et al., 2011) suggest a minimum duration of 10 years for the proper quantification of wave and energy conditions in a region.

1.1. *Gap of information*

Studies presented previously, underline the growing efforts to accurately describe the wave environment. As seen in Tables 1-2, several limitations can be identified. Majority of models utilised in both the Atlantic and UK region are oceanic. Such models can deliver highly skilled assessments for deep water environments. Their limitations is their reduced capabilities to account for nearshore physics such as diffraction, refraction, triads etc.. Recently in their modelling approach they do incorporate some level of such solutions (Tolman & development Group, 2014), but they are still not suitable for detail coastal analysis. Literature has identified their limitations and outreach at nearshore locations (Caires & Sterl, 2005; Cañellas, Orfila, Méndez, Menéndez, & Tintoré, 2007; Mackay, Bahaj, & Challenor, 2010; Neill & Hashemi, 2013; Venugopal et al., 2010).

Oceanic models are more efficient in large areas utilising coarse resolutions and multi-nesting schemes (Agarwal, 2015). Such low resolution domains are not appropriate for coastal characterisation, as they do not account for the complexities of the shorelines and reduce the physical interaction of non-linear terms in neashore waters (Neill & Hashemi, 2013). To conduct assessment of nearshore regions appropriate wave numerical models, with enhanced non-linear solutions, high-resolution bathymetries and computational efficiency are suggested. Caires and Gent (2008) indicated that running oceanic models at shallower regions is not suitable, as they fail to fully described the non-linear effects encountered. Similarly Gautier and Caires (2015); Neill and Hashemi (2013) discuss the need for higher resolution with appropriate nearshore physical configurations for coastal evaluations.

Asides, the selection and resolution of the model another factor has to be taken into account the temporal duration. Due to variability and nature of the wave resource, studies should accommodate significant temporal periods of investigation. It is proposed that for a resource assessment hindcast at least 10 years are required, in order to capture the intra-annual, seasonal and monthly variations of the wave environment Ingram et al. (2011); Smith (2014).

Table 2 presents the majority of studies (of at least 1 year duration). Most appropriate nearshore models (SWAN, MIKE21) focused in the UK and Scotland do not satisfy the required 10 year mark. Oceanic models for the UK and North Atlantic while they do satisfy the time duration, they do not possess adequate high resolution. This creates a gap in the examination of nearshore areas, that require a long periods of investigation, higher spatial resolutions and appropriate physical considerations.

This study presents a detail long–term high–resolution wave power assessment for the Scottish and North Sea regions. Satisfying the temporal criteria and suitability of the model for coastal estimations (Ingram et al., 2011; Venugopal et al., 2011). The model was operated from 2004 to 2014. Power levels are assessed annually, monthly, mapping the spatial distribution of the resource and providing valuable information for "hot-spot" identification. Asides wave energy content, the region is subjected to availability analysis results of which are suitable for the selection of wave energy converters (WECs) at different regions.

Finally, shallow locations extracted by the model complement the site characterisation attempt. Information are given on resource levels, availability and dominant metocean characteristics, local sea states are classified according to their joint distributions and probability of wave energy. The results allow robust presentation and discussion on the range of favourable operational conditions for WECs per region.

2. Preparing the Wave Model

The spectral model chosen is Simulating WAves Nearshore (SWAN) (Delft, 2013) 40.91ABC, the reason for this choice is the advanced coastal water mechanics solutions. Implementation of SWAN consists of various physical tuning and inputs. Data by Amante and Eakins (2014) provided the bathymetric information and a high resolution mesh with 0.025^o was constructed. Wind forcing was selected based after calibration presented in Lavidas, Venugopal, and Friedrich (2017b), a 6-hour wind product by

(Dee et al., 2011) with spatial resolution 0.125^o was used.

The area experiences large swells originating predominately from the West Atlantic, which have to be included in the model. The North Sea area has swell components from North and less from the South and East Side. To increase the computational accuracy, outputs from the oceanic (WAM) spectral wave model by ECMWF are extracted to construct boundary conditions for SWAN. Boundary conditions include spectral information along the four sea boundaries and cover the hindcast duration (see Fig. 1). Table 3 presents the extracted locations with their corresponding depths, the prefix B means that the locations co-incide with a buoy location, while prefix P suggests user selection.

Spectral conditions require designation of minima and maxima, a minimum period considered was 2 sec and maximum 24 sec, with a logarithmic increment of 1.1. The frequency domain is separated in 25 bins and the directions in 24 bins. It has to be noted that while higher spectral resolutions are feasible, they do not always offer a better hindcast (Piche, Cornett, Baker, & Nistor, 2015). In addition, when hindcasting over a large period of time for such a fine mesh and large domain, considerations on computational resource, time and storage are vital. Bottom friction uses the revised proposed approximation of van Vledder, Zijlema, and Holthuijsen (2010), triads, refraction, diffraction are also activated. The quadruplet interactions are resolved with a fully explicit solution per sweep of the source terms within the mesh (van Vledder, Herbers, Jensen, Resio, & Tracy, 2000).

The information of wind and boundary are given to the model and are computed across the given mesh shown in Fig.1, the mesh size is 10^o longitude and 6^o latitude, which constitute nearly 100,000 points for which the action balance is resolved at every timestep and for multiple iterations. Overall computational requirements took over 30 days, thus use of the high performance computing facility of the Edinburgh University was necessary (EDDIE-ECDF) to facilitate the run.

Validation of the dataset is made with buoys available by CEFAS, Center for Environment (2014), with additional multiple coastal nearshore locations of wave energy interest. The point outputs are recorded every 30 minutes, while the overall mesh information was recorded every 3 hours due to storage considerations and restrictions. Previous detailed calibrations of this model concerning wind parametrisation, quadruplet tuning, turning rates, and domain size were discussed in previous studies by the authors (Lavidas, 2016; Lavidas & Venugopal, 2015; Lavidas et al., 2017b).

3. Validation

The model run for 11 years, with a "hot" start configuration to alleviate ramp up (warm-up) periods and obtain better results from the first recording at the High Performance Computing (HPC) Edinburgh facilities. Due to the amount of hindcast data, validation information are presented in tabular form with various indices (see Eqs. 1–5) taken into account.

$$bias = \sum_{i=1}^{N} \frac{1}{N}(X_i - Y_i) \tag{1}$$

$$rms = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - Y_i)^2} \tag{2}$$

$$R = \frac{\sum_{i=1}^{N}((X_i - \overline{X_i})(Y_i - \overline{Y_i}))}{\sqrt{((\sum_{i=1}^{N}((X_i - \overline{X_i})^2)((\sum_{i=1}^{N}((Y_i - \overline{Y_i})^2)}} \tag{3}$$

$$SI = \frac{rms}{\frac{1}{N}\sum_{i=1}^{N} Y_i} \tag{4}$$

$$MPI = |1 - \frac{rms}{rms_{change}}| \tag{5}$$

$$rms_{change} = \sqrt{\frac{Y_i^2}{N}} \tag{6}$$

where X_i is the simulated wave parameter, Y_i the buoy wave quantity, N measurements. The use of several quantitative indices allow better classification, for example in some cases we may obtain a good bias, small SI and a moderate Model Performance Index (MPI). Hindcast parameters of H_{sig}, T_{peak} and T_{m02} are compared with buoy measurements.

Buoy data cover limited time duration and are used for validation and not for energy analysis. In addition, outliers and missing intervals from the buoys underwent quality control, and only reliable measurement are used (missing intervals removed). Interest is given to nearshore locations further in the study, since most oceanic models often cannot resolve nearshore conditions as well.

In case of no buoy data available, the corresponding location is marked with a n/a (non available). Comparison data exist from 2008 onwards, see Tables 4-5. In 2008 only the North Sea locations were available. Concerning the 2008 year the model shows good performance with low biases and rms errors. Correlation coefficient and model performance indices (MPI) are high throughout.

For Blackstone (B1) the comparison with buoy measurements provide high correlation and good performance (see Fig. 2). Scattering appears lower at the Western locations for which higher levels of energy. This is supported by the low scattering not exceeding 0.20-0.25 for T_{peak}, T_{m02} and H_{sig}. At Eastern locations while the biases and mean rms erros are lower, scattering is significantly higher. This can be attributed to the inherit characteristics of numerical wave models (Campos & Guedes Soares, 2016; Cavaleri, 2009). SWAN tends to over-estimate low H_{sig} and under-estimate very high values. In these locations recorded H_{sig} are often very low accounting for the increased scattering. The model performance index (MPI) assesses the generation profile for each timestep, in all cases there is a good agreement with buoy and modelled data, with rms showing that majority of instances is close. Throughout the hindcast very low energy periods and wave heights have been over-estimated, while as expected under-estimations exist at very high waves.

3.1. *Resource Distribution*

The final distribution of wave power based on the hindcast satisfies minimum requirements of dataset duration, which propose a 10 year minimum as representative data for resource evaluation (Ingram et al., 2011; Smith & Maisondieu, 2014). In addition, evaluation of annual percentiles, mean H_{sig}, mean P_{wave} does not show significant variations over the years.

Higher P_{wave} concentrations are observed at West Scottish coastlines (see Fig. 3). This is due to incoming swells from the Atlantic Ocean that amplify levels of energy propagated. The Isle of Lewis, is exposed to high levels with intermediate and nearshore locations ranging from $40 - 60$ kW/m. On the North Side of the region, Shetland and Orkney islands obtain similar high levels in their Western coastlines. Wave groups "break" and reduce after the islands, due to diffraction, bottom friction, coastal interactions, reducing the resource which is propagated behind the islands significantly. On the East Side of Scotland, exposed to the North Sea, the absence of energetic swells and obstruction by the land mass of Scotland reduce the resource. Mostly wind generated wave can be accounted for in the region, nearshore coastal levels of wave power do not exceed 20kW/m.

The monthly average P_{wave} provides the spatial distribution of the resource, and can assist in the identification of consistent areas that can benefit from higher resolution studies. Furthermore, it offers a detailed monthly and seasonal evolution of spatial variability. Winter months, as expected, encompass higher energy levels while in the summer months P_{wave} reduces (see Fig. 4). During winter and autumn months (October-February), deep water power exceeds 90 kW/m while at late spring and summer months there is a dramatical decrease. Throughout January to March wave power reduces slowly, at the Isle of Lewis wave power resource levels are consistently within $40 - 70$ kW/m for intermediate and nearshore regions. At the Orkney island in Northern Scotland, wave power levels are ≈ 50 kW/m, while Eastern areas record lower resource within $\approx 15 - 20$ kW/m. From April to August there is a significant decrease at deeper waters, with less wave energy reaching the coastlines. The reduction at deep waters is almost half in regards to winter months, indicatively at Western coasts the range is $30 - 50$ kW/m. At the North Sea resources are $3 - 3.5$ times less with lower resources below 5 kW/m.

Wave resource levels are important in the identification of "energetic" locations planning purposes. However, standard deviation (STD) and percentile magnitudes complement and add to the decision making. Standard deviation provides with the necessary information concerning the deviation from mean values found in the area. Locations with higher STD are mostly based in the Western coastlines, where more alterations of the resource exist. At deeper locations STD reach their highest levels. The Isle of Lewis which has energetic resource has the highest STD levels throughout the hindcast, indicatively the average monthly STD values reach $\approx 40 - 60kW/m$. Moderate levels are recorded in the North central regions and the Orkney islands $\approx 30 - 50kW/m$, while North Sea coastal locations have the lowest $\approx 15 - 30kW/m$.

3.2. *Availability*

Availability is the percentage of time, for which the resource corresponds to operation for a wave energy converter (WEC). This study considers availability in terms of H_{sig}. For a WEC power is produced based on a specified combination of operational principles of significant wave height and wave period (varied). Like other renewable converters (i.e. wind), WECs have specific attributes concerning start of operation (H_{cut-in}) and end of operation (or survival mode) ($H_{sut-off}$). For wave energy applications resource availability has impact on the financial and technical performance (de Andres, Guanche, Vidal, & Losada, 2015; Guanche, De Andres, Losada, & Vidal, 2015).

WECs can be classified according to operational depths (deep, intermediate, nearshore, shoreline). With range of operation favouring low or higher resources. Usually minimum H_{cut-in} operation is set at 0.5-1m with $H_{cut-off}$ being the changing variable. For lower favouring WEC maximum production is achieved at H_{sig} of 2-3.5 meters, afterwards the converter is shifted to survival (no production) mode. For higher resources WECs the $H_{cut-off}$ increases to 5-7 meters (Babarit, 2015; Babarit et al., 2012). Obviously depending on the device at hand, availability for production will vary. For this reason, availability percentages are investigated given a Low and High scenario. Low availability scenario requires the sea state to have $H_{cut-in} \geq$ 1m and $H_{cut-off} \leq$ 4m. High availability scenario requires the sea state to have $H_{cut-in} \geq$ 1m and $H_{cut-off} \leq$ 6m. Finally, in order for this analysis to have applicability, we have applied a restriction on value displayed, based on current estimates for allowed deployable WEC depths (Carbon Trust & AMEC, 2012). Limiting deployment depth at $\leq$ 150m, any value above this depth limitation have been filtered out. For both scenarios, the monthly spatial distributions of operation allowed are shown in Figs. 5-6.

Depending on thresholds and scenario combinations, availability levels for potential production vary. The highest percentages are met when the High scenario is considered, in this case majority of most Western and North coastal locations record high availability percentages over $\approx$ 80%. The levels though change as the $H_{cut-off}$ is reduced for the Low scenario. In this case higher levels of availability for production are attained throughout certain months and periods of years.

For the Low scenario, highest levels are recorded in spring and summer months. For autumn and winter months availability levels reduce, mainly due to the upper threshold violated. In those periods H_{sig} and P_{wave} reach their highest levels. Thus, significant decrease in operational availability is recorded.

On the contrary, the High scenario has increased levels of availability. The higher upper limit favours such environments, and operation of a high $H_{cut-off}$ WECs and allows operation at higher percentages of time. Interestingly when comparing the two scenarios significant changes occur near the coasts. Specifically, at the Western coastlines and regions behind the Isle of Lewis, even at "shadowed" area behind the island exhibit higher levels of availability in contrast to Eastern coastlines. At the same time sheltering of the island front "protects" the area from extreme wave events. For the Low case, especially in the summer months availability is reduced to $\approx 30-40\%$, and reaches its peak during the winter months above 70%.

For the High scenario same locations have a much higher availability rate, indicating that they favour the operation of intermediate depth devices i.e. favouring waves from 2-5 meters, allowing to achieve higher levels of operation throughout the year, at potentially less capital expenditure. For example the sheltered region behind the Isle of Lewis in the High scenario, records over 15-20% more availability over the Low scenario. In overall, the Western ocean locations have constant higher availability rates (see Fig. 7).

At energetic waters enhanced levels of availability can be achieved by proper WEC selection. As seen in Section 3.1 higher resource often indicates larger waves. Hence, selection of a site has to be correlated with mean resource, but also with operational ranges by a potential WEC. For energetic wave environments, such as the one found in the Western coasts higher operational ranges will favour energy production, though at a higher cost of infrastructure capital due to exposure at harsher waves.

3.3. *Coastal quantification*

Additional nearshore locations for a more detail analysis have been extracted (denoted as P) (see Fig. 1). Selection of locations was made based on available maps (CrownEstates, 2014) and decision of the authors based on previous studies. The majority of the wave energy industry is considering installations at Western parts of Scotland, thus several locations from the region are chosen. This aids in an well-rounded analysis of wave power levels and differences found in the Atlantic and North Sea coastlines. SWAN allows skilled estimations at nearshore locations with enhanced physics, the additional points are extracted at shallow and intermediate depths. For example the lowest depth is 8.75 meters, with majority of locations is examined at depths from 40-60 m. Considering that operational depth deployments of WEC are advised to be made at depths $\leq 150m$ the analysis provides insights in areas of immediate interest for numerous WECs.

In Fig. 8, the annual variation in wave energy and the overall energy content are displayed. East coastlines (North Sea) locations, Moray Firth (B4) and Firth of Forth (B4) have the lowest resources. Northern locations are Point1 (P10) and Homlmsound (B5) presenting different levels for the same region. Orkney point is located at the West Side of Orkney open to the Atlantic Ocean, benefiting from high energy swells. On the other hand Homlmsound is at an encapsulated region of the island which dissipates energy by coastal and bottom breaking reducing its annual levels.

Remainder points are located the West coastlines where the resource assessment provided the highest levels (see Fig. 3). Hebrides 1-3 and Point1 represent Northern locations at Isle of Lewis, a region which has amongst the highest levels (see Section 3.1). Hebrides 1-3 are at intermediate depths ranging from 50-60 meter while Point1 at ≈ 8.75m, larger depths allow for higher energy propagated with locations having closely similar levels. Point1 is the shallowest it still records 30 kW/m which is almost 3.5 times higher than Eastern locations. Such high levels of energy at low depths are attractive for WEC potential installation, not only for the energy content but their distance from shore and high availability.

South Western locations are Blackstone (B1), West Hebrides (B2) and Polcoms 1-2 (P11-12). The West Hebrides and Blackstone are uninterrupted exposed to Atlantic swells, similar to the ones at Northern parts of Isle of Lewis. The remainder points have different levels available, with Polcoms1 recording the lowest energy content. Its positioning between surrounded coastlines enhances coastal interaction phenomena, reducing the energy reached.

In terms of expected fluctuations, Western location show decrease in their annual content in 2006 and 2010. Although, even at such events the content is above $35-40$ kW/m. Northern locations have similar reductions for same years with their magnitude much lower. Finally, Eastern and the encapsulated Homlmsound location, experiences lower annual variations. This implies that while the resource is lower it can be considered more reliable in terms of predictability. Fig. 9 provides with the probability levels for P_{wave} of the hindcast dataset. It is evident that the Western locations have higher wave energy content that the North and East, with exceedance probabilities at much higher percentages for high P_{wave} values.

In the West coastlines, particularly North at the Isle of Lewis, all locations record high wave energy. Most common joint occurrences are for H_{sig} within a range of $4-7$ meters, with several records exceed 8 meters, this means that most WEC shift to survival mode ($\geq 7m$). The period favours low frequency (high period) operation from $7-14$ seconds. On the lower Southern side of the West coast and the Isle of Lewis, similar range of H_{sig} are dominant with maximum values reaching over 8 meters, wave period components remains at similar levels, with high number of occurrences existing for high frequencies (lower periods), providing a wider range of operation from as low as 2 sec. At the Orkney Islands, the two locations show different characteristics, however as discussed their placement is different, one at open Atlantic front and the other in an enclosed environment. Orkney location shows higher population of occurrences in H_{sig} $3-5$ meters and T_e $6-11$ sec. On the other hand the Homlmsound has similar H_{sig} values, while at much smaller periods (higher frequencies), with majority located at $2-6$ sec. Finally, at East coastlines (North Sea) two low energy sites, Firth of Forth and Moray Firth, have H_{sig} not exceeding 3.5 meters and periods mostly located in the range of $2-6$ sec, Table 6 overall descriptive values are presented. While, energy content is important in the classification of a site, one must also account for the maximum H_{sig} levels which can prove catastrophic for any offshore activity.

West coast locations while they record high levels of energy content, they also acquire high maxima as seen in the H_{sig} and high percentile values. In terms of energy content this classifies them as energetic, although the higher levels may prove negative as are an additional cost consideration on WEC capital, in order to ensure survivability. Favouring range of WEC operation should be considered at H_{sig} of $4-6$ meters and T_e $8-10$ sec. WECs which attain their peak in those ranges will acquire higher operational rates. Availability levels, as seen in Section 3.2, depend not only on area but also on the threshold levels. In both scenarios (Low-High), Western locations achieve operational availability over $\approx 65\%$, the North Sea coast have $\approx 40\%$. At Orkney islands availability of operation depends on sitting, with Orkney point having values similar to the West coast and Homlmsound closer to East locations.

4. Discussion

Application of wave energy depends highly on the variability and characteristics of the resource, hence it is highly suggested that datasets used are ≥ 10 years (Ingram et al., 2011; Smith, 2014). This ensures that all intra-annual, seasonal and monthly variations are accounted for. Examination periods below this temporal threshold can not be confidently used for resource assessment.

Another issue that needs addressing are the physical attributes, calibration, and numerical wave model applicability. While for the Scottish region many models have been applied, most of them are oceanic. Extending to nearshore waters some appropriate models have been used, though their time duration restricts them for long-term consideration as according minimum requirements.

Scotland is one of the countries that has a significant interest in the development of wave energy farms. However, with wave energy converters at early stages of development it is vital to address and evaluate the wave power and availability levels. This ensures that regional wave farm consideration are based on properly resolved description of the wave resource.

Resource evaluation shows similar spatial distribution for metocean and wave power condition as in other studies that have hindcasted the area (Neill & Hashemi, 2013; Reguero et al., 2012; Venugopal & Nemalidinne, 2015). Higher levels of wave power and H_{sig} are found at West coastlines, with high energy swells originating from the Atlantic enhancing locally generated waves. At the East coastlines and upper North Sea, majority of resource is depending on wind-waves with smaller swells from the North East. Highest levels of energy content are met in the West coasts, with values reaching annually $\geq$ 50 kW/m at intermediate depths. In the North and East, wave power diminishes with levels almost three times less. Locations exposed to ocean waters have persistent higher number of events at larger H_{sig} and lower frequencies. Thus, when considering wave energy application, long term studies of energy levels and the dominant wave environment assists in the selection of WECs.

West coastlines experience higher levels of variation, larger maximum and percentiles values. In terms of energy production this is favourable, but such large events may jeopardise the structural safety of offshore devices. Highest wave recorded in the dataset exceed 14 meters, while highest percentiles of power exceeds 400 kW/m (potential storm conditions). The North Sea coast show less variation and maximum values. Depending on the region, selecting a WEC for installation should consider long-term databases of high temporal resolution. Solely examining the mean energy content, and not the highest values may prove catastrophic for the development of a non-mature technology as wave energy.

5. Conclusions

The study assessed metocean condition at the Scottish coastlines quantifying wave power resource and availability for WEC production. Selection of an appropriate model has to satisfy certain criteria. Janssen (2008) has extensively discussed the applicability of models and indicated that for nearshore estimates oceanic models are not suitable. Oceanic models offer significant advantages for larger domains and are often necessary for boundary conditions. Limitations on the previous wave power maps concerning the model used and resolution has been also discussed by Neill and Hashemi (2013). Our model is SWAN utilising a high resolution bathymetry and with all nearshore non-linear activated and tuned, ensuring confidence of coastal estimates.

Asides energy content which is one of the highest in the world, availability is a indicator that can assist in the selection not only of a location but also of WECs. Dedicated studies for availability in the Scottish region do not exist. Although, a previous long-term global wave hindcast study by Reguero et al. (2012) based on an oceanic model, offered important data. The metocean conditions from the database where subsequently used by Guanche et al. (2015), to assess the availability at a global scale. Although, they used different cut-in/off thresholds, the reported availability for the West Scottish coastlines was $\approx$ 85%. In the same study North Scotland and North Sea recorded over $\geq$ 90%.

Our analysis two scenarios were used, and determined the spatial and single location availability. Compared with the aforementioned study availability for the region is characterised high mainly at Western coasts, with the East side showing dramatically decrease in comparison. The Low scenario records $\approx\geq$ 70%, and the High $\approx\geq$ 80% for

Western coastlines. In both cases higher availability levels are achieved for Northern parts of Scotland. Eastern (North Sea) coast present a significant decrease $\approx 50\%$ in both cases. Suggesting that lower resource WEC operation is favourable on that side. Monthly maps indicate than during the low seasons/months (summer-spring), East coastlines do not satisfy the limit for initiation of operation. The Western coastlines present higher levels of availability, even at "shadowed" location i.e. behind the Isle of Lewis, maintaining a favourable level of resource.

Subsequently, several locations of immediate interest were extracted by the dataset. Their descriptive statistics and dominant metocean conditions are estimated, this allowed to investigate suitable range of WEC operations. For the Western coasts favourable operation ranges should be for high waves and low frequencies. On the East coastline, preferred application of WEC should account operation range within much lower waves approximately $2-4$ meters and periods $3-6$ sec.

Geolocation information

The manuscript is focused on Scotland with coordinates: 10^o West, 0^o East, 55^o South, 61^o North.

Disclosure

The authors disclose no conflict of interest

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Tables

Table 1.: Implementation of Atlantic wave models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
Europe-Atlantic	Pontes et al. (1996)	WAM	8 [1] & 3 [2]	$3^o x 3^o$ [1] & $0.5^o x 0.5^o$ [2]	Waves
Europe-Atlantic	Larsén, Kalogeri, Galanis, and Kallos (2015)	WAM	10	$0.05^o x 0.05^o$	Waves, Extremes
Europe-Atlantic	Caires and Sterl (2005)	WAM	45	$1.5^o x 1.5^o$	Waves, Climate Analysis, Extremes
Europe-Atlantic-UK	Neill and Hashemi (2013)	SWAN	7	$0.16^o x 0.16^o$ & $0.04^o x 0.04^o$	Waves, Wave Power
Europe-Atlantic-UK	Agarwal (2015)	WW3	140	$1^o x 1^o$ & $0.25^o x 0.25^o$	Waves, Climate Change, Extremes
Europe-Atlantic-UK	Venugopal and Nemalidinne (2015)	MIKE21	1	Unstructured	Wave Power
Europe-North East Atlantic	Pilar, Soares, and Carretero (2008)	WAM	44	$0.25^o x 0.25^o$	Waves
Europe-North East Atlantic	Dodet, Bertin, and Taborda (2010)	WW3	57	$0.5^o x 0.5^o$	Waves, Wave Climate
Europe-North East Atlantic	E. Rusu (2014)	WAM[3]	41	$0.5^o x 0.5^o$	Wave Power

Table 2.: Implementation of UK-Ireland wave models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
United Kingdom	MER (2014)	WAM	7	$0.25^o x 0.25^o$	Waves, Wave Power
Isle of Lewis-Scotland	Gleizon (2014)	SWAN	1	Unstructured	Waves, Wave Power
Isle of Lewis-Scotland	Gleizon et al. (2015)	SWAN	variable	Unstructured	Waves, Wave Power
United Kingdom	Agarwal (2015)	WW3	140	$1^o x 1^o$ & $0.25^o x 0.25^o$	Waves, Climate Change, Extremes
Scotland-North Sea	Lavidas (2015); Lavidas et al. (2017b)	SWAN	1	$0.025^o x 0.025^o$	Waves, Wave Power
Ireland	Gallagher et al. (2013)	WW3	10	$0.125^o x 0.125^o$	Wave Power
UK[4]	Neill and Hashemi (2013)	SWAN	7	$0.16^o x 0.16^o$ & $0.04^o x 0.04^o$	Waves, Wave Power
UK-Scotland	Venugopal and Nemalidinne (2015)	MIKE21	1	Unstructured	Wave Power
Ireland	Gallagher et al. (2014)	WW3	14	Unstructured	Wave Power
Scotland	Lavidas et al. (2017a)	SWAN	11	$0.025^o x 0.025^o$	Wave, Wave Power

Table 3.: Location information

Point on Map	Depth	Name
B1	97	BlackStone
B2	100	West Hebrides
B3	54	Moray Firth
B4	65	Firth of Forth
B5	20	Homlmsound
P6	68	Hebrides 1
P7	55	Hebrides 2
P8	62	Hebrides 3
P9	8.75	Point1
P10	22	Orkney
P11	110	Polcoms 1
P12	73	Polcoms2

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[1] Atlantic

[2] Mediterranean

[3] Extracted by a custom database from Puertos del Estado, at 3-hour intervals

[4] Limited to specific high-resolution areas

[5] Distance from Shoreline $\approx Km$

Table 4.: Annual Indices (H_{sig}=in meters ,T_{peak} & T_{m02}=in seconds)

	2008											
	Moray Firth			Firth of Forth			West Hebrides			Blackstone		
	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}
R	0.92	0.78	0.73	0.94	0.76	0.81	n/a	n/a	n/a	n/a	n/a	n/a
RMS	0.43	3.41	1.23	0.33	2.88	1.11	n/a	n/a	n/a	n/a	n/a	n/a
MPI	0.98	0.94	0.94	0.98	0.91	0.94	n/a	n/a	n/a	n/a	n/a	n/a
Average Buoy	1.23	7.86	4.34	1.08	6.98	4.24	n/a	n/a	n/a	n/a	n/a	n/a
Average SWAN	1.24	6.96	4.2	1.09	6.86	4.32	n/a	n/a	n/a	n/a	n/a	n/a
bias	0.01	-0.89	-0.14	0.01	-0.1	0.07	n/a	n/a	n/a	n/a	n/a	n/a
SI	0.35	0.43	0.28	0.31	0.41	0.26	n/a	n/a	n/a	n/a	n/a	n/a
	2009											
	Moray Firth			Firth of Forth			West Hebrides			Blackstone		
	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}
R	0.91	0.73	0.79	0.94	0.74	0.81	0.96	0.85	0.85	0.97	0.83	0.89
RMS	0.38	3.2	1.02	0.3	2.73	1.09	0.62	2.02	1.34	0.44	2.33	1.09
MPI	0.99	0.94	0.96	0.99	0.94	0.96	0.97	0.91	0.94	0.97	0.91	0.94
Average Buoy	1.07	7.05	4.18	1.01	6.77	4.22	2.8	10.46	6.51	2.41	9.99	6.08
Average SWAN	0.97	6.47	3.97	0.95	6.77	4.29	2.5	10.24	5.87	2.5	9.66	5.89
bias	-0.1	-0.57	-0.2	-0.05	0	0.7	-0.29	-0.22	-0.63	0.09	-0.32	-0.19
SI	0.35	0.45	0.24	0.3	0.4	0.25	0.22	0.19	0.2	0.18	0.23	0.18
	2010											
	Moray Firth			Firth of Forth			West Hebrides			Blackstone		
	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}
R	0.94	0.69	0.77	0.96	0.754	0.81	0.94	0.78	0.82	0.96	0.79	0.85
RMS	0.37	3.2	1.13	0.32	2.64	1.18	0.62	1.41	1.39	0.44	2.56	1.17
MPI	0.99	0.94	0.96	0.99	0.94	0.96	0.98	0.91	0.94	0.98	0.92	0.95
Average Buoy	1.13	7.37	4.37	1.15	7.11	4.54	2.3	10.27	6.32	2.05	9.96	5.97
Average SWAN	1.07	7.1	4.28	1.09	7.51	4.75	2.04	9.98	5.69	2.1	9.43	5.69
bias	-0.05	-0.26	-0.08	-0.05	0.39	0.21	-0.26	-0.29	-0.62	0.05	-0.53	-0.28
SI	0.33	0.43	0.25	0.28	0.37	0.26	0.27	0.23	0.22	0.21	0.25	0.19

Figures

(1) Domain indicating depths and location assessed (B=buoys, P=additional points)
(2) Model Overview Performance for 2012 at (B1), x-axis is the month's number
(3) P_{wave} distribution (kW/m)
(4) Monthly P_{wave} for all years
(5) Low scenario as a % of time
(6) High scenario as a % of time
(7) Availability Scenarios
(8) Energy Content of locations
(9) Exceedance Probability, x-axis in the % probability and y-axis P_{wave} in kW/m

Table 5.: Annual Indices (continuation)

	2011											
	Moray Firth			Firth of Forth			West Hebrides			Blackstone		
	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}
R	0.87	0.71	0.7	0.92	0.68	0.75	0.96	0.89	0.85	0.98	0.89	0.9
RMS	0.47	3.95	1.4	0.32	3.4	1.19	0.69	1.78	1.4	0.47	1.88	1.1
MPI	0.99	0.94	0.97	0.99	0.95	0.96	0.97	0.91	0.94	0.97	0.91	0.94
Average Buoy	0.98	6.93	3.9	0.9	6.36	4	3.33	11.17	7.04	2.95	10.88	6.74
Average SWAN	0.97	6.67	3.87	0.89	6.78	4.17	3.04	11.16	6.27	3.07	10.79	6.52
bias	-0.01	-0.26	-0.02	-0.01	0.42	0.17	-0.28	-0.001	-0.76	0.11	-0.09	-0.21
SI	0.44	0.57	0.36	0.35	0.53	0.29	0.2	0.16	0.19	0.15	0.17	0.16
	2012											
	Moray Firth			Firth of Forth			West Hebrides			Blackstone		
	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}
R	0.92	0.69	0.78	0.95	0.72	0.83	0.97	0.89	0.87	0.96	0.87	0.89
RMS	0.38	3.44	1.01	0.32	2.74	1.04	0.64	1.87	1.34	0.44	2.19	1.11
MPI	0.99	0.94	0.96	0.99	0.94	0.96	0.97	0.92	0.95	0.98	0.92	0.95
Average Buoy	1.1	7.16	4.22	1.02	6.79	4.27	2.83	10.51	6.55	2.5	10.2	6.21
Average SWAN	1.04	6.49	4.03	0.95	6.75	4.36	2.49	10.08	5.74	2.55	9.71	5.84
bias	-0.06	-0.67	-0.18	-0.07	-0.04	0.09	-0.34	-0.42	-0.81	0.05	-0.48	-0.37
SI	0.35	0.48	0.24	0.3	0.4	0.24	0.22	0.17	0.2	0.17	0.21	0.17
	2013											
	Moray Firth			Firth of Forth			West Hebrides			Blackstone		
	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}
R	0.94	0.69	0.8	0.96	0.72	0.86	0.97	0.86	0.85	0.97	0.87	0.9
RMS	0.36	3.4	0.96	0.31	2.79	0.89	0.73	2.17	1.44	0.48	2.47	1.14
MPI	0.99	0.94	0.96	0.99	0.95	0.96	0.977	0.91	0.94	0.96	0.87	0.92
Average Buoy	1.05	6.82	4.11	1.05	6.41	4.17	3.01	10.92	6.77	2.76	10.8	6.46
Average SWAN	0.99	6.19	3.82	0.99	6.32	4.1	2.64	10.29	5.95	2.83	10.08	5.93
bias	-0.06	-0.62	-0.28	-0.06	-0.08	-0.07	-0.36	-0.6	-0.81	0.06	-0.7	-0.52
SI	0.34	0.5	0.23	0.3	0.43	0.2	0.24	0.19	0.21	0.17	0.22	0.17
	2014											
	Moray Firth			Firth of Forth			West Hebrides			Blackstone		
	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}
R	0.92	0.74	0.81	0.95	0.68	0.84	0.96	0.85	0.83	n/a	n/a	n/a
RMS	0.5	3.34	1.16	0.37	2.82	1.03	0.75	2.21	1.65	n/a	n/a	n/a
MPI	0.98	0.9	0.94	0.98	0.9	0.94	0.95	0.85	0.91	n/a	n/a	n/a
Average Buoy	1.36	7.43	4.53	1.32	7.17	4.61	3.52	12.03	7.45	n/a	n/a	n/a
Average SWAN	1.15	6.56	3.96	1.18	6.85	4.39	3.21	11.49	6.42	n/a	n/a	n/a
bias	-0.21	-0.86	-0.56	-0.14	-0.32	-0.22	-0.31	-0.54	-1.02	n/a	n/a	n/a
SI	0.37	0.45	0.25	0.28	0.39	0.22	0.2	0.18	0.22	n/a	n/a	n/a

Table 6.: Description of Locations

	Max H_{sig} m	P_{wave} kW/m	$P_{95^{th}}$ kW/m	$P_{99^{th}}$ kW/m	P_{kDir}	Avail High	Avail Low	Depth $\approx m$	$\approx Km$ [5]
Point 1	4.38	30.23	94.34	121.28	255.55^o	84.55%	81.70%	8.75	6
BlackStone	12.68	53.71	210.43	415.51	266.02^o	82.76%	69.21%	97	48
Firth of Forth	6.41	4.80	19.35	45.79	107.34^o	38.20%	37.91%	65	17
Hebrides 1	13.72	61.17	214.68	407.58	224.05^o	90.47%	73.55%	68	15
Hebrides 2	14.74	60.36	215.62	420.24	222.69^o	90.21%	73.96%	55	7.5
Hebrides 3	14.68	58.86	212.13	413.24	221.95^o	90.09%	74.35%	62	14.5
Homlmsound	6.60	6.55	28.86	70.16	122.77^o	42.03%	41.15%	20	11
Moray Firth	6.39	4.68	19.06	43.67	113.10^o	40.78%	40.53%	54	31
Orkney	8.80	30.80	115.94	203.51	279.57^o	77.58%	69.73%	22	17.4
Polcoms 1	7.74	18.01	74.54	154.87	266.22^o	64.47%	61.17%	110	7
Polcoms2	9.55	37.84	156.39	321.33	267.54^o	78.22%	69.37%	73	26
West Hebrides	7.35	53.93	232.95	335.80	269.70^o	81.79%	67.97%	100	32

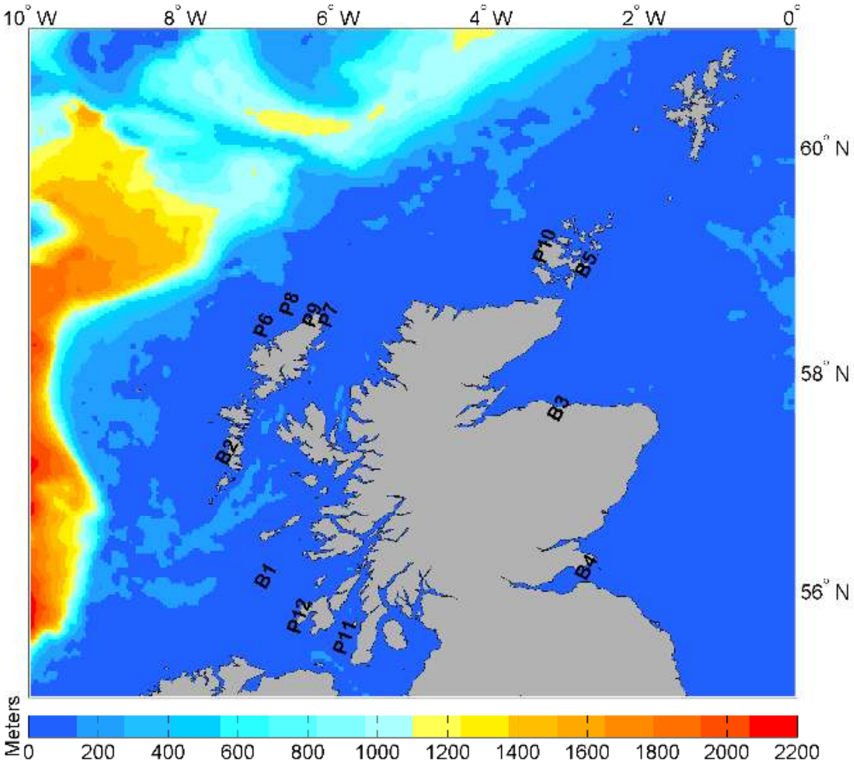
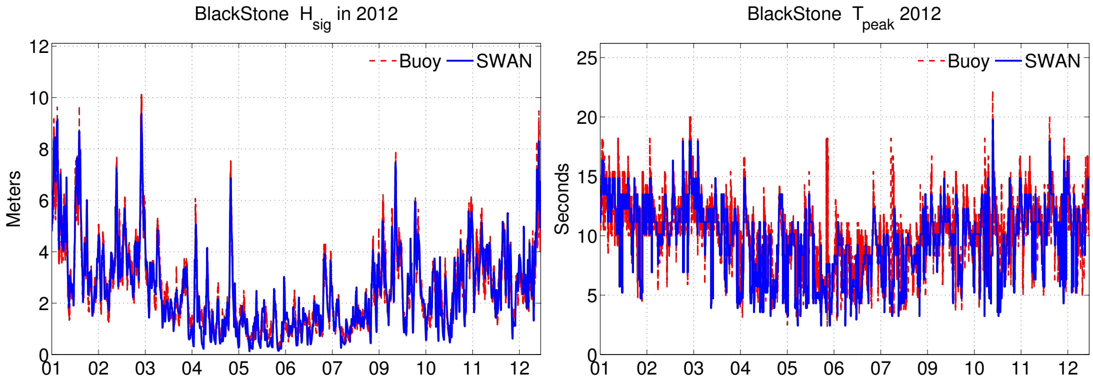
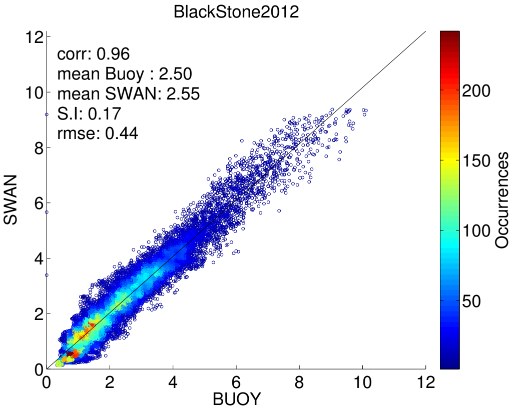


Figure 1.: Domain indicating depths and location assessed (B=buoys, P=additional points)



H_{sig} T_{peak}



Scatter plot BlackStone 2012

Figure 2.: Model Overview Performance for 2012 at (B1), x-axis is the month's number

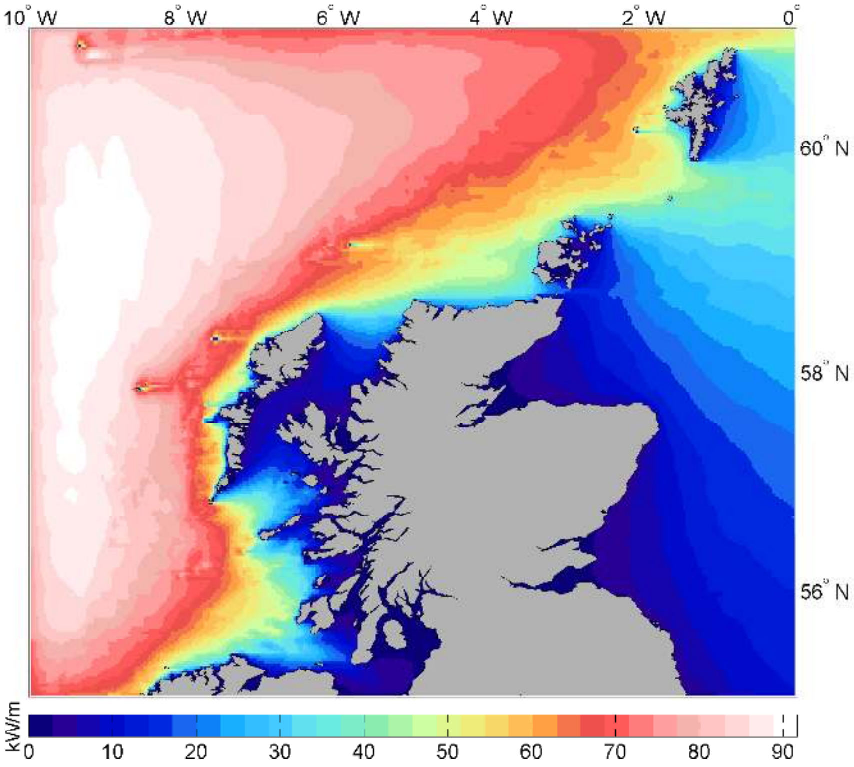
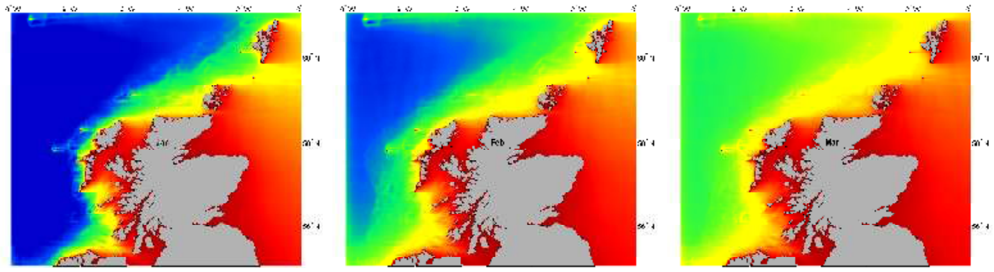
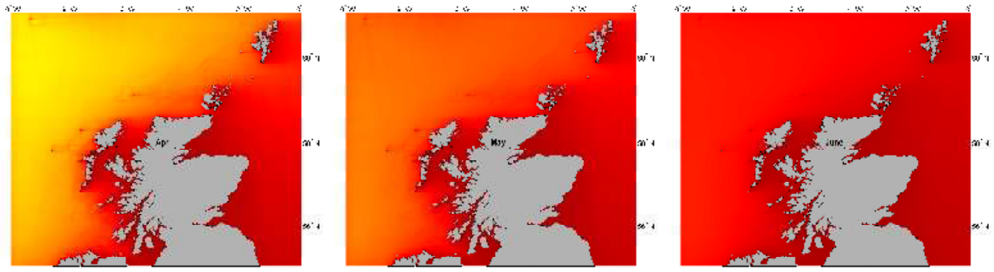


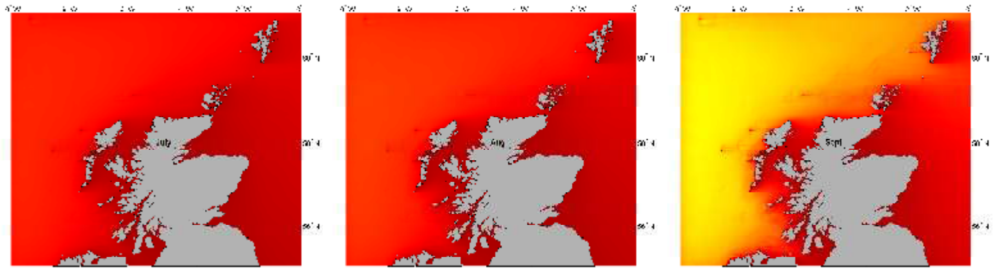
Figure 3.: P_{wave} distribution (kW/m)



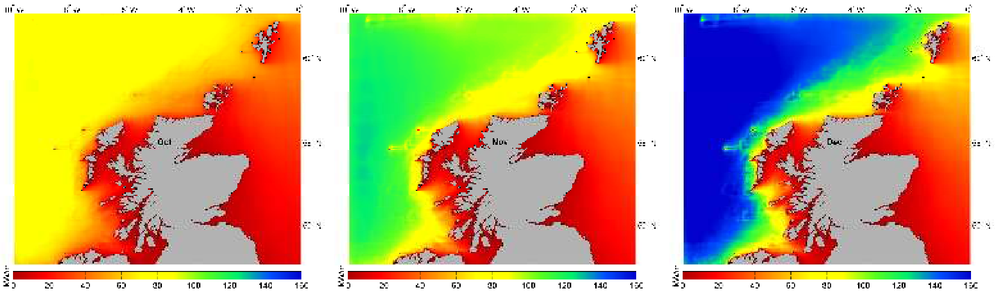
January February March



April May June

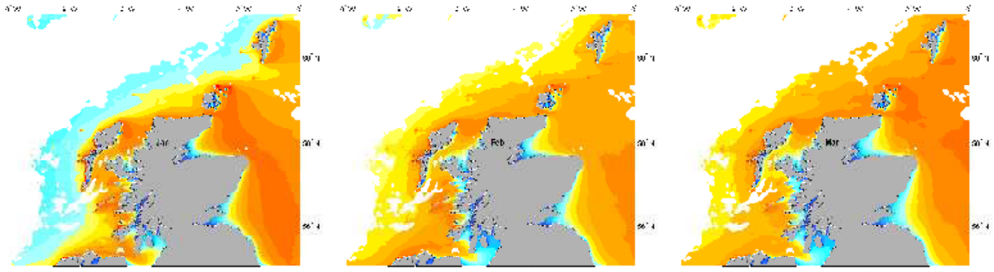


July August September



October November December

Figure 4.: Monthly P_{wave} for all years



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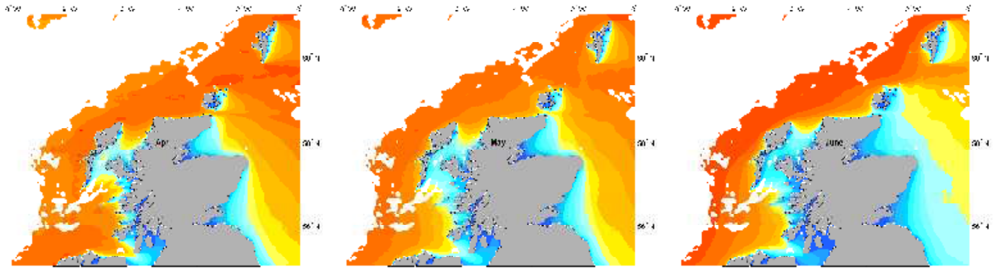

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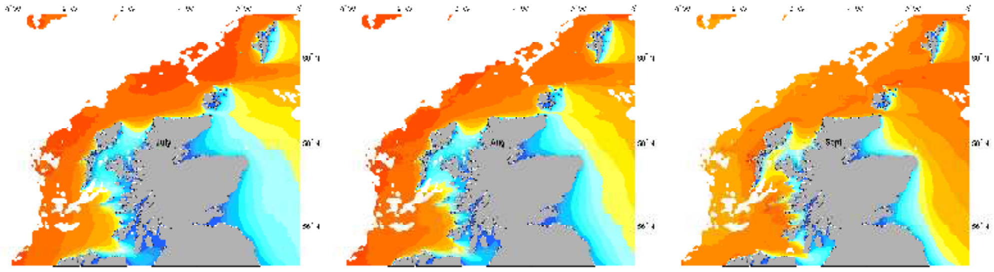
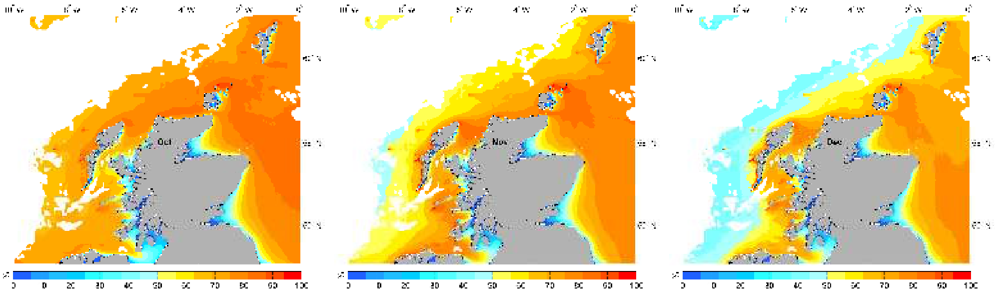
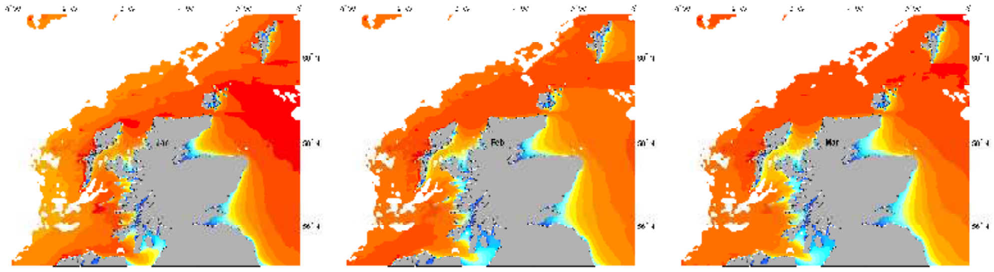


July August September

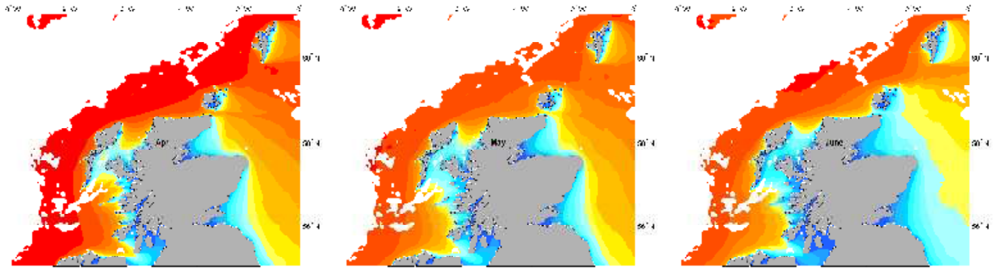


October November December

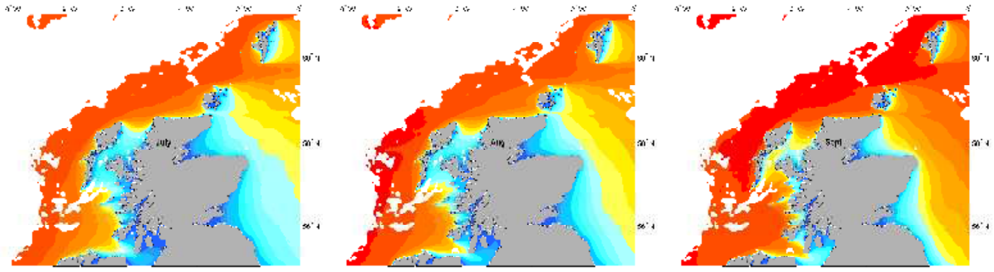
Figure 5.: Low scenario as a % of time



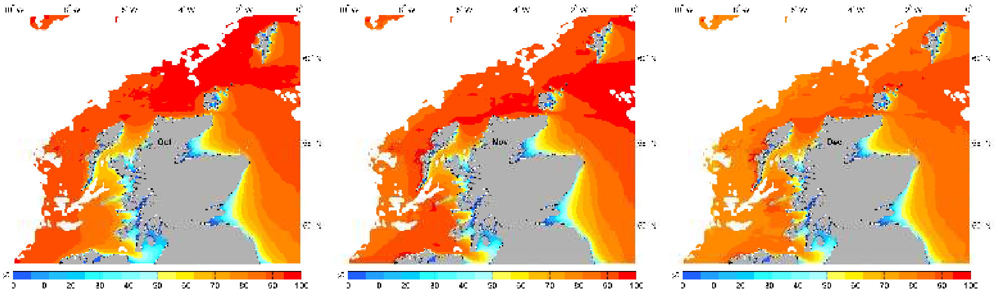
January February March



April May June

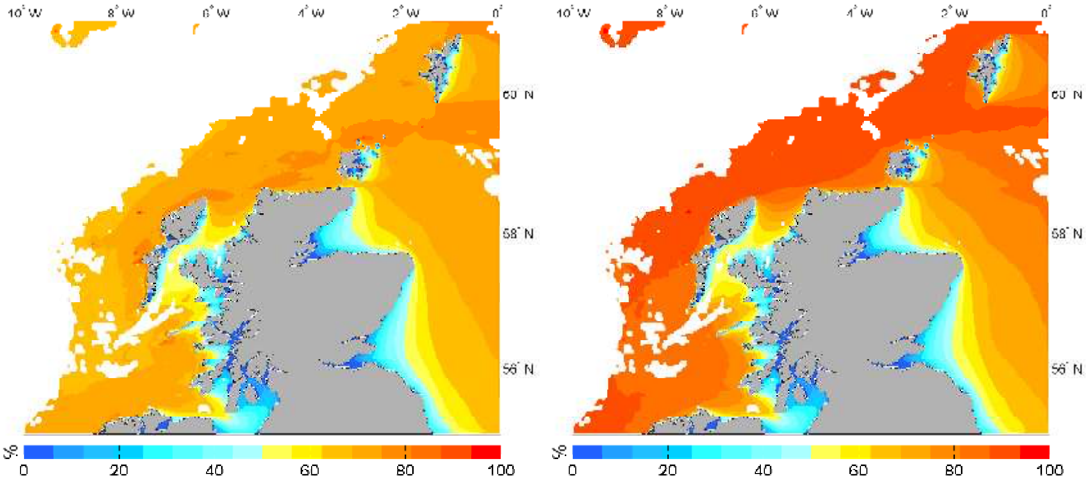


July August September



October November December

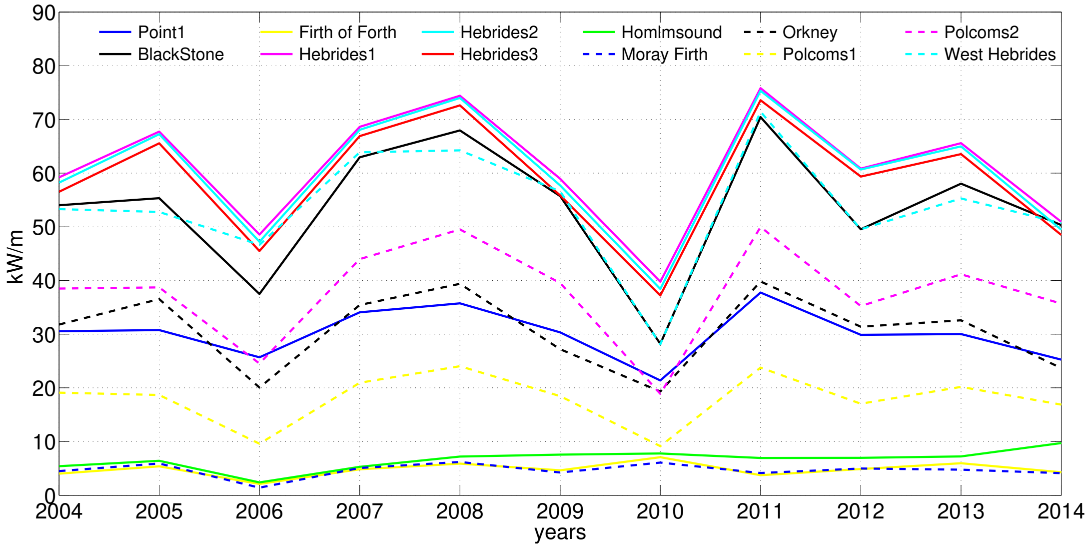
Figure 6.: High scenario as a % of time



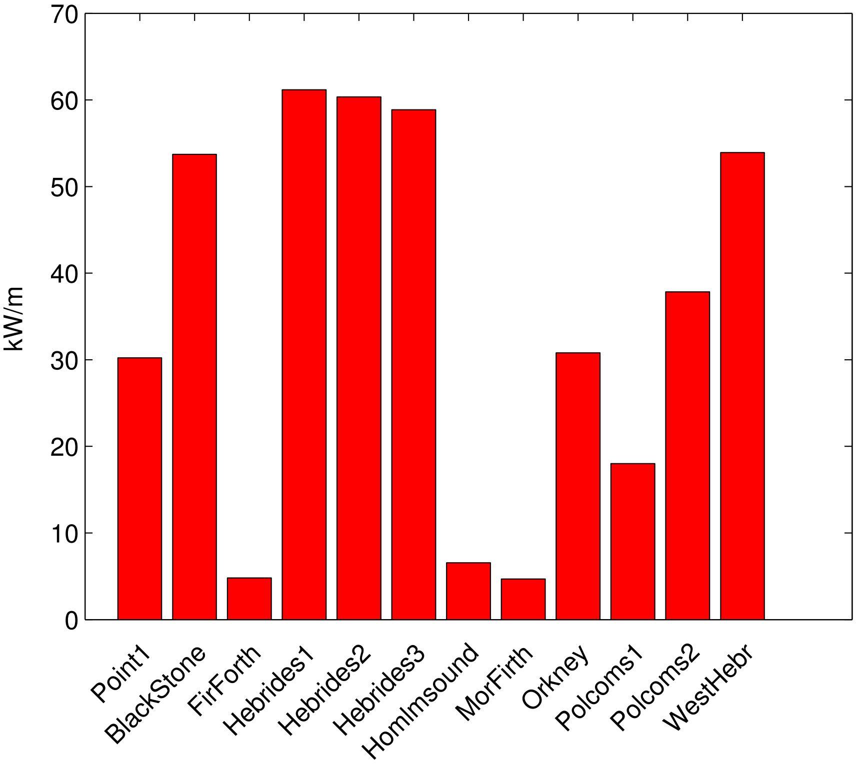
Low Scenario

High Scenario

Figure 7.: Availability Scenarios

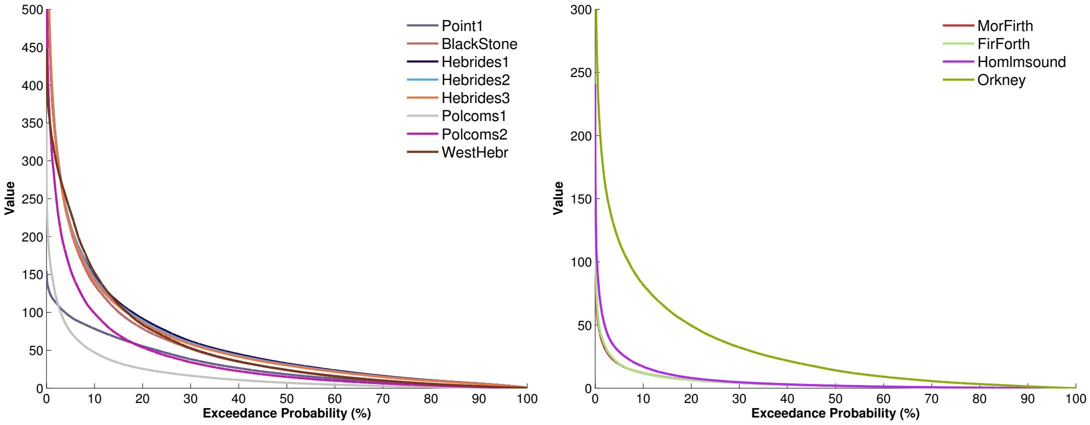


Mean annual P_{wave}, exhibiting year to year variations



Mean P_{wave} over the hindcast

Figure 8.: Energy Content of locations



West sites

North and East sites

Figure 9.: Exceedance Probability, x-axis in the % probability and y-axis P_{wave} in kW/m