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Wave energy extraction in Scotland through an improved nearshore Wave Atlas

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Abstract

Wave energy is expected to play an important role in the forthcoming years for the de-carbonisation of Scottish and British electricity production. This study underlines the importance of resource assessment and attempts to improve the quantifiable wave power resource, with use of a validated numerical model. While levels of wave flux are high for an area that may not always constitute the best option for wave energy applications. In this study, a long-term hindcast for the Scottish coastlines run from 2004-2014 (11 years) improving the existing wave maps and resource estimations. Spatial and physical considerations of a third generation spectral model allow examination at locations of immediate interest for the ocean energy community. Utilising numerical wave models of finer resolution allows for the detailed coupling of potential wave energy converters (WECs) and site characterization. Such detail energy results allow for improved financial analysis that take into account the severity of local resource and its energy potential.

Keywords: Wave Energy, Resource Assessment, Capacity Factors, Site Characterization

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1. Introduction

Currently energy is of major concern to most countries, specific policies within the European Union (EU) include higher renewable energy (RE) into the electricity mix alongside a significant reduction of CO2 and Green-House-Gases (GHG) [1]. Waves offer an abundant high energy density resource

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accessible by most countries in Europe. Though, energy levels and incoming fluxes differ from country to country, the opportunities for significant contribution to RE targets and energy independence are obvious.

United Kingdom (UK) and especially Scotland are exposed to some of the most energetic waters in Europe with average annual resource exceeding 60-70 kW/m at mid-depth locations [2, 3]. While this is encouraging coastal and more accessible resources are not always the same with different physical terms affecting the final content. Gathering wave data is a cumbersome process, which often does not allow overall estimation on the energy content of an area. Buoy data have been used throughout the years for assessment of the wave climate and lately of wave energy characterization [4]. This however is not always feasible, since scarcity of buoys and lack of a long-term monitoring installations do not allow long-term examination of the wave climate and often coastal locations are overlooked.

Necessity of long-term data at coastal locations in which wave energy is eminently applicable has been underlined [5, 6, 7]. Long-term evaluation of wave data and wave energy should be the basis for analysis of energy production providing robust estimates on the opportunities at specific areas. In order to overcome the lack of data and buoy existence in several locations of interest use of numerical wave models has been proposed for climate change studies and analysis [8, 9, 10].

Numerical wave models offer an alternative for data gathering with their operation, development, calibration, validation, and errors identification being lengthy difficult process. There is no "quick" way for development of good models, considerations and processes taken into account by the modeller can improve results.

Several models have run in the North Atlantic for wave estimations, however wave energy resource assessments for Scottish waters are limited [11, 12]. One of the most common problems is the absence and inability of larger models to resolve and provide an accurate resource assessment at coastal regions. Most commonly used resource map for the region is from ABP MER [12]. At the time of its development offered some level of information but its hindcast time duration though limited to only 7 years. Recent developments and protocols suggesting at least 10 years of data for extraction of useful mid-term data [13, 14], and even longer desirable in analysis of extreme events.

The ABP MER [12] map has a very coarse resolution of $0.25^o \times 0.25^o$ (not able to represent coastal locations), low number of frequency bins (13) and directions (16) while the wave numerical model used was a second generation.

This recently raised considerations towards the validity and over-estimations it offers in comparison with third generation state-of-the-art models [11].

Under-estimations in most models have been reported [15, 16, 17, 18, 19], while a discussion on the selection of input wind datasets and bathymetry interaction can be see [20, 21]. In this study, a third generation phase-average model is used to provide an 11-year high-resolution hindcast around Scotland and the North Sea region. Subsequently, the data are used to estimate the wave energy resource and explore the opportunities for wave installations and site selection considerations. Previous studies for wave power in the area involved either large scale oceanic models, which could not resolve coastal approaches as well [22, 23, 24], or where run on limited spatial and/or temporal terms [25, 11, 26].

Recent developments in the UK concerning renewable energy [27, 28] propose for adaptation of technologies that counteract systems variability and enhance predictability [29, 30]. More specifically, UK agencies, governing and research organizations have outlined the necessity of wave energy incorporation as a strong candidate for the combined exploitation of renewable penetration. With the advantages of not only on energy security, diversification, but also by establishing a strong industrial sector in the offshore marine industry [30, 31].

Wave energy converters (WEC) have been developing over the last years with variable levels of success, several models exist with some similarities in the way kinetic energy is harnessed. Differences are predominately located mainly in the PTO system utilised [7, 32, 33]. The Atlantic wave climate is studied with the use of numerical wave models, by both operational forecast organizations and research groups [34]. It has been underlined that variability and uncertainty of waves, may act as a barrier of our understanding on the resource [35].

The Isle of Lewis and Orkney areas are identified by the Crown Estate [36] as regions with high interest for the offshore wave community (see Fig. 1). For this reason additional information are extracted by the hindcast for these locations in an attempt to quantify the results at near coastal terrains and examine effects of high levels of energy in these areas.

In addition, a thorough examination of the Scottish coastline here presents valuable information about the variation and distribution of wave energy around all coastal areas, showing the annual energy content, providing additional information for future potential smaller hindcasts at areas of interest. The numerical results are subsequently utilized for wave energy estimations,

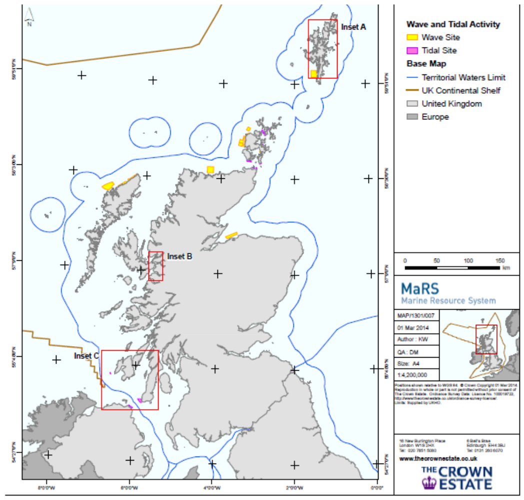


Figure 1: The areas of interest for wave energy development (wave energy is yellow) as presented by the Crown Estate [36]

a wave development index, though additional use of such long-term data includes wave climate, wave variability, and extreme analysis to name a few.

This study presents the validation of a third generation model, examines the wave climate, wave power and potential for several areas that are of interest for wave energy deployments In contrast to larger oceanic models this study is able to represent coastal resources at higher degree, offering an improvement in existing wave energy maps.

The results are coupled with published data of power matrices assessing the potential energy benefits and the applicability of various WECs, providing robust estimations and insights on selection. The authors hope that this study in combination with existing information and studies from other models will prompt the examination of locations and increase awareness on site selection for wave energy.

2. Model development

Recent wave assessments have been conducted with use of oceanic numerical models predominately for wave climate investigations and some for wave energy [37, 8, 2, 24, 10]. In addition, some coastal numerical models have also been applied in attempts to quantify the nearshore water environment of coastal areas but have been conducted for limited time-spans and/or often time limited to some individual areas [38, 39, 40, 11, 26].

The spectral model chosen to be used in this study is Simulating WAves Nearshore (SWAN) [41] 40.91ABC. The reason for this choice is the advanced coastal water mechanics solutions included in SWAN which are all activated and activated. Construction of the code itself consists of various considerations and input, thus both the physical assumptions and inputs chosen carefully. The bathymetry is constructed from data provided by Amante et.al. [42] and the final mesh has a resolution of $0.025^o \times 0.025^o$. Wind input used is extracted and converted from the ERA-Interim dataset with a temporal resolution of 6 hours and a spatial of $0.125^o \times 0.125^o$ [43].

Next is the assignment of boundary conditions, due to locale of the area high levels of swells and winds originate predominately from the West Atlantic front, and have to be included in the model. North Sea area is dominated by North winds travelling from the Pole and some swell components from North, less from the South and East Side. Outputs from the spectral wave model by ECMWF are extracted to construct boundary conditions for SWAN, with a temporal resolution os 6 hours.

Initial conditions include set of direction and frequencies, minimum period considered was 2 sec and maximum 24 sec with a logarithmic increment of 1.1, and the 25 directional bins. The wind generation is based and adapted on Janssen's [44] quasi theory with adjusted whitecapping coefficient and diffusion scheme. Bottom friction uses the revised proposed approximation of van Vledder et.al [45] with triads, refraction, diffraction also activated. The quadruplet interactions are resolved as according to Discrete Interation Approximation (DIA) with a fully explicit solution per sweep of source terms within the mesh.

The information of wind and boundary are given to the model and are computed across the given domain shown in Fig.2, the domain size is 10^o longitude and 6^o latitude, which constitute nearly 100,000 points for which the action balance is to be resolved at every timestep. The 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.

The outputs considered involve locations both at mid-depth for which buoys are available by CEFAS [46], 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.

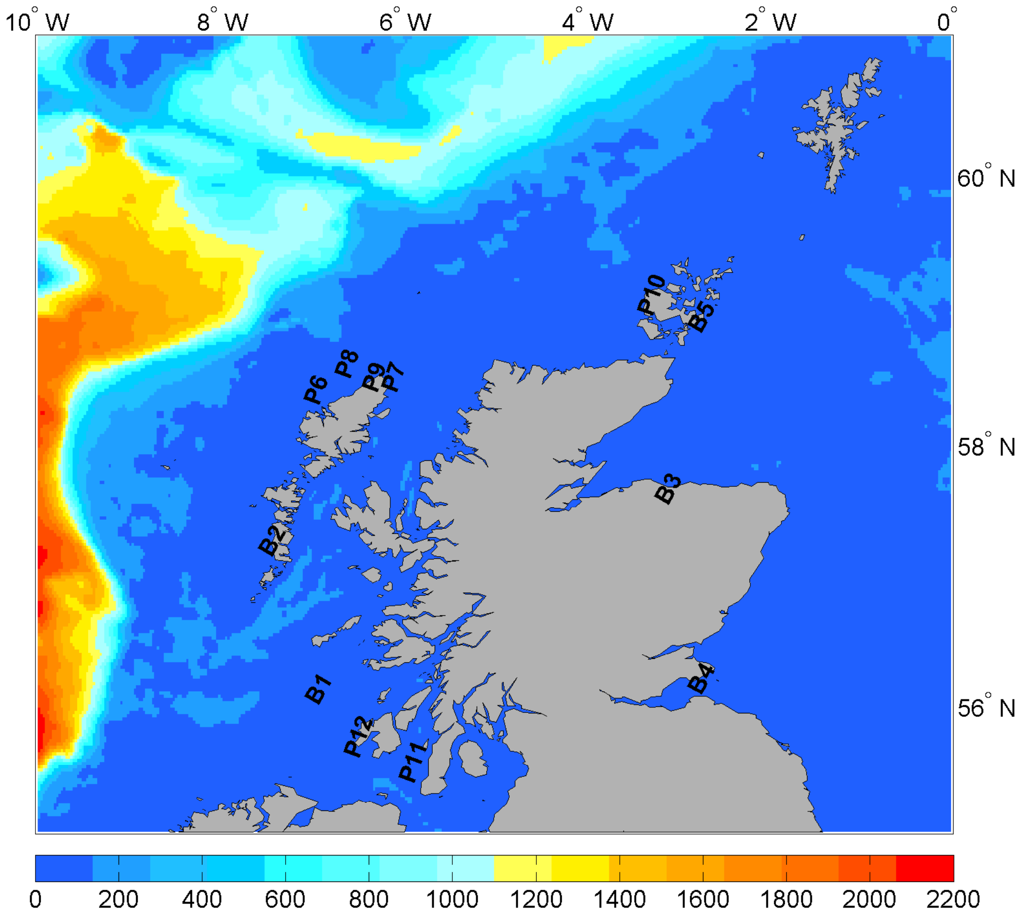


Figure 2: Computational domain of the hindcast, bathymetry of the area in meters

3. Validation of the model

The model run for approximately 11 years, with a "hot" start configuration to alleviate ramp up periods and obtain better results from the first recording. Due to the amount of hindcasted data, validation information are provided for selected years with the overall indices performance are discussed and presented in tabular form. Various statistical indices for model assessment were taken into account more thoroughly discussed in [21].

Buoy data obtained by CEFAS [46] are used for model calibration and validation, it has to be noted that not all years have recordings. The locations which correspond to buoy are denoted as CEFAS, while additional locations of interest are also extracted by the hindcast and are denoted as SWAN not corresponding to buoys (see Table 1). Interest is given to coastal shallow locations, since most oceanic models often cannot resolve nearshore conditions as well [47]. All data recovered from the buoys underwent quality control that identified missing intervals and removed them.

Table 1: Buoys locations denoted as CEFAS and additional points extracted for analysis denoted as SWAN

Origin	Coordinates	Name	Depth ($\approx m$)
B1–CEFAS	56.03 N–7.03 W	BlackStone	97
B2–CEFAS	57.17 N–7.54 W	West Hebrides	100
B3–CEFAS	57.57 N–3.20 W	Moray Firth	54
B4–CEFAS	56.11 N–2.84 W	Firth of Forth	65
B5–CEFAS	58.86 N–2.84 W	Homlmsound	20
P6–SWAN	58.30 N–7.04 W	Hebrides 1	68
P7–SWAN	58.40 N–6.19 W	Hebrides 2	55
P8–SWAN	58.50 N–6.70 W	Hebrides 3	62
P9–SWAN	58.40 N–6.40 W	Point 1	8.75
P10–SWAN	58.97 N–3.39 W	Orkney	22
P11–SWAN	55.4 N–6 W	Polcoms 1	110
P12–SWAN	55.6 N–6.6 W	Polcoms 2	70

The good level of confidence by our model was used for proper estimation of wave energy in nearshore locations which other oceanic models cannot hindcast locations at such depths [48, 49, 50]. Validation of results are given in both tabular and selected figures, representative 2011 annual performance is given in Table 2 and visual comparison are given in Figs. 3-5.

Table 2: 2011 indices comparisons with H_{sig} is in meters and wave periods (T_{peak}, T_{m02}) in seconds

	West Hebrides			Blackstone			Moray Firth			Firth of Forth		
	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	0.96	0.89	0.85	0.98	0.89	0.9	0.87	0.71	0.7	0.92	0.68	0.75
RMS	0.69	1.78	1.4	0.47	1.88	1.1	0.47	3.95	1.4	0.32	3.4	1.19
MPI	0.97	0.91	0.94	0.97	0.91	0.94	0.99	0.94	0.97	0.99	0.95	0.96
Av. Buoy	3.33	11.17	7.04	2.95	10.88	6.74	0.98	6.93	3.9	0.9	6.36	4
Av. SWAN	3.04	11.16	6.27	3.07	10.79	6.52	0.97	6.67	3.87	0.89	6.78	4.17
bias	-0.28	-0.001	-0.76	0.11	-0.09	-0.21	-0.0	1 -0.26	-0.02	-0.01	0.42	0.17
SI	0.2	0.16	0.19	0.15	0.17	0.16	0.44	0.57	0.36	0.35	0.53	0.29

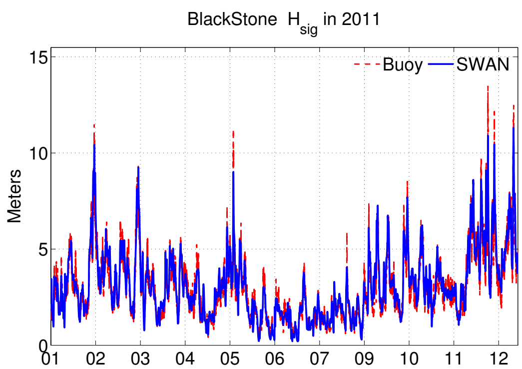


Figure 3: H_{sig} hindcast 2011

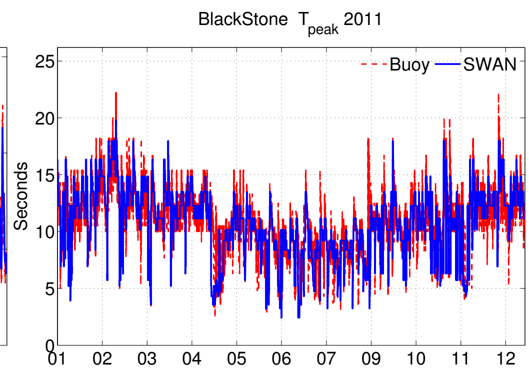


Figure 4: T_{peak} hindcast 2011

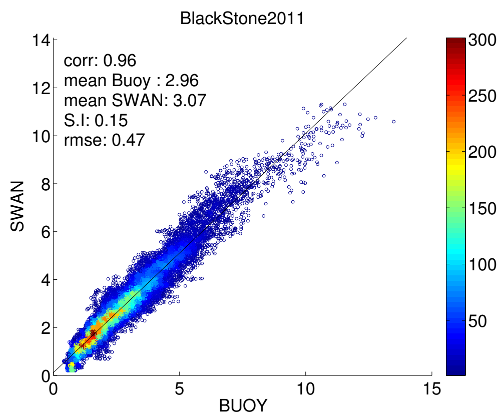


Figure 5: Scatter performance of the hindcast for BlackStone 2011

Modelled data compared to buoy measurements are presented in Table 2 and compared modelled data are in good agreement with buoy measurements. Eastern coastlines are exposed to lower resources, Moray Firth and Firth of Forth average measured and simulated values have similar values with lower coefficients of correlation and higher scattering. Though the results especially at Moray Firth are of moderate accuracy, the overall bias expressed is low, performance of the model for remaining time at Firth of Forth and Western locations show that all quantities have good accuracy.

It has to be underlined, that due to the nature of wave numerical models, some of the set up assumptions and numerical solutions within affect the level of accuracy. Numerical wave models usually tend to have under-estimations over very high waves, and over-estimations at low wave heights [15, 51]. It has been also suggested that the temporal resolution of wind affects the hindcast, implying that a higher temporal resolution may increase the performance. Such an analysis concerning two wind products and our domain can be found in Lavidas et.al. [21], as well other recent studies which evaluated wave hindcasts driven by different wind van Vledder et.al. [52].

From our analysis in Lavidas et.al. [21] ECMWF produces the best numerical wave data when compared with buoys. That study used different wind products one of high temporal resolution and one of high spatial, the increase in temporal resolution lead to higher peak simulations while the overall scattering was increased [21]. On the other hand, a high spatial resolution increases the computational requirements although it ensures that the wind wave generation is adequately resolved by the hindcast. Finally, several authors also consider the suitability of various datasets, with their performance reportedly subjected to alterations according to locations and Hemispheres [53].

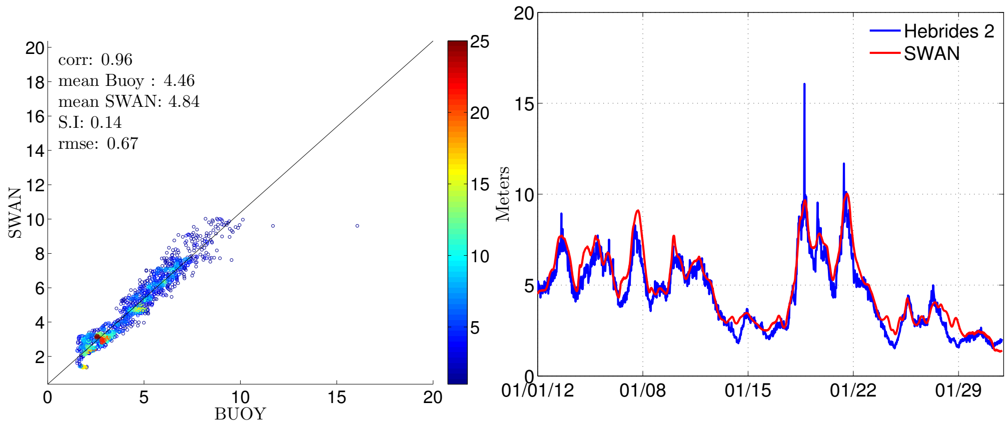
Though SWAN is able to record most values, limitations on storm events exist in all models. Rapid alterations in wave heights are hard to simulate by the model see Fig. 3 where the correlation between measurements and hindcast are given. With extreme storms often under-appreciated, usually to the temporal input resolution of the wind inputs.

To examine the performance of SWAN, one has to look into the comparison of results at coastal locations, and local environment interactions. For this purpose specific proprietary data for the month of January 2012 were kindly provided by Arne Vogler [4], and one month is compared (see Fig. 6). The Hebrides 2 site is of immediate interest to the wave energy community, for deployment and development of wave energy at the site [38, 26].

In addition, latest measurements from 2014 are given in Table 3, and allow to confidently consider the hindcast as appropriate to be of further use. Though extreme storm events are not easily captured as shown in the previous year, representation of the sea state is of high quality, which allows us to expand the findings, improve wave resource assessment of the area, and add to the knowledge for potential energy fluxes in coastal locations.

4. Resource assessment

Main concern of the dataset produced is the examination of coastal wave energy resource, since limitations with previous efforts exist and the limita-



(a) Scatter

(b) Timeseries

Figure 6: Hebrides 2 comparison for H_{sig} in meters

Table 3: 2014 indices comparisons with H_{sig} is in meters and wave periods (T_{peak},T_{m02}) in seconds

	West Hebrides			Firth of Forth			Moray Firth		
	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}	H_{sig}	T_{peak}	T_{m02}
Correlation	0.96	0.85	0.83	0.95	0.68	0.84	0.92	0.74	0.81
RMS	0.75	2.21	1.65	0.37	2.82	1.03	0.5	3.34	1.16
MPI	0.95	0.85	0.91	0.98	0.9	0.94	0.98	0.9	0.94
Average Buoy	3.52	12.03	7.45	1.32	7.17	4.61	1.36	7.43	4.53
Average $SWAN$	3.21	11.49	6.42	1.18	6.85	4.39	1.15	6.56	3.96
bias	-0.31	-0.54	-1.02	-0.14	-0.32	-0.22	-0.21	-0.86	-0.56
SI	0.2	0.18	0.22	0.28	0.39	0.22	0.37	0.45	0.25

tions of oceanic models are known, the validation allows presenting results with confidence about the findings.

Wave energy flux is dependent on significant wave height (H_{sig}) and energy period (T_e), which represents the period of waves with sinusoidal form and can be treated as ratio between the -1 moment and the zeroth moment of the spectrum as:

$$T_e = \frac{m_{-1}}{m_0} \tag{1}$$

With $m_0....m_n$ denoting the n^{th} moment of the wave spectrum. For these kind of locations and due to the fact that investigation is expressed for coastal waters, the non-linear formulation of wave energy calculation is considered, representing wave energy for coastal locations as [54]. The energy contained within waves expressed, in W/m, which corresponds to the energy per crest unit length. In SWAN energy components are computed with a formulation appropriate for the realist representation of resource. Over the summation of very different wave numbers frequencies (f) and directions (θ).

$$P_x = \rho g \int \int C_{gx} E(f, \theta) df d\theta \tag{2}$$

$$P_y = \rho g \int \int C_{gy} E(f, \theta) df d\theta \tag{3}$$

where $E(f, \theta)$ the energy density spectrum over an x (longitude) y (latitude) system. C_g are the components of absolute group velocities, water density (ρ), g gravitational acceleration. Total wave power is estimated in kW/m:

$$P_{wave} = \sqrt{P_x^2 + P_y^2} \tag{4}$$

The calculated resource is expressed in kW/m for presented maps; exhibit the mean average energy that is encountered for each year. This allows to quickly establish the areas for which wave energy is the highest and are to be considered for future developments. Western coastlines are exposed highest wave resource and our findings correspond well with other studies [26, 11]. The difference is that most of the models used are oceanic and even the widely used based on an larger outdated model 2nd generation model [12], which restricts full representation of coastal information.

The 1 year study by Venugopal et.al. [26] used a highly skilled spectral model for the same area, though based on a commercial product which is not commonly accessed. In addition the physical aspects of the action balance equation are resolved on a unstructured grid.

Recent studies with the same model were used by Neill et.al [11] and Gleizon et.al [39], although the first was using a nested scheme of several areas around the UK and was run for 7 years, while the latter used a small unstructured mesh approach for only the Isle of Lewis for one year. In order to evaluate the resource and assess additional climatological and extreme value indices a minimum duration of 10 years has been proposed [13, 14], this allows not only to examine a long trend series but also reveals any potential climate and wave fluctuations [55]. This was not the scope of this study, though produced data can be also used to extreme value analysis and decadal wave climate fluctuation in several locations.

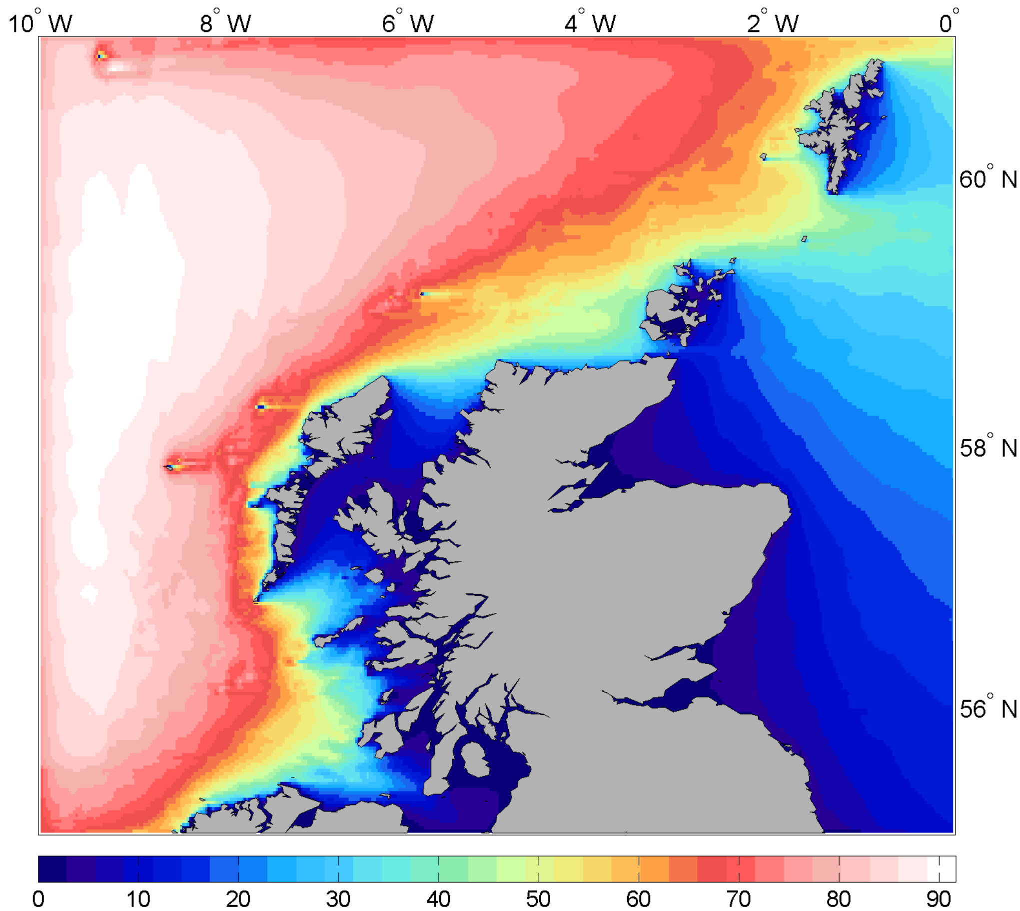


Figure 7: Mean Wave Power over the ≈ 11 years period in kW/m

The contoured hindcast shows the energy flux of the region is extremely high at deep-water regions, with previous published wave resource assessments also reporting approximately 75-80 kW/m. The use of advanced numerical solvers in SWAN for shallower areas, coastal locations are presented fully allowing the application of a fine resolved bathymetry the first for such a long-term study (see Fig. 7).

As shown by the maps both mean annual and overall, the interest expressed by many developers to place their device in the West and North

West parts is supported by the high mean energy flux, though this is not the only component that has to be taken into account. High levels of propagated waves mean additional stress and higher components fatigue for the devices, thus examination of interactions between resource and device have to be investigated.

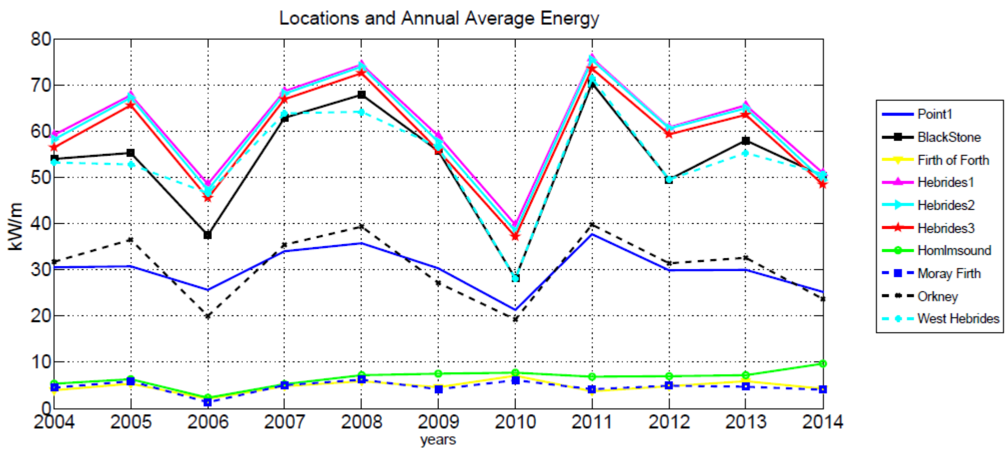


Figure 8: Mean Annual Power at each of the locations in kW/m

The variability and annual fluctuation associated with the wave resource for both deep and coastal locations given in Fig. 8. It is noticeable that the three lower resource locations correspond to Moray and Firth of Forth, while the third corresponds to shallow waters at Orkney islands at depth of 18m. They present similar levels of energy content while they latter one is located in an encapsulated area thus providing some insight on the available high level or resource.

Majority of other locations are exposed to the West wave front and are situated at depths ranging from 45-90m, Point1 and Orkney locations share similar levels of energy with the latter having higher energy variations. The data indicate that there might be a correlation and cyclic event of wave energy variance; although for safer assumptions and climate, trend identification a more extensive, longer over 30 years dataset is required.

5. Wave Energy Development Index (WEDI)

Assessment tools for the level of severity at each location can be and extreme value analysis (EVA) and/or the corresponding Wave Energy Development Index (WEDI). The use of EVA returns the probabilities of exceedance and return periods of wave height within a year, allow proposing the extreme events that may occur, this will not be investigated in this study.

$$WEDI = \frac{\overline{P_{wave}}}{J_{wave}} \tag{5}$$

The index is the ratio of annual average wave power (P_{wave}) to the maximum storm wave power (J_{wave}) that every offshore device or structure will have to absorb. Devices are usually placed based on mean power content. Depending on both the mean and maximum power potential influences on the wave energy of the location can be attributed, measuring severity and penalising areas with a high index, that is discussed in Hagerman [56].

The focus of our approach is the evaluation of WEDI in comparison with the available wave energy at the locations of interest. The WEDI takes into account the maximum wave energy content that occurs throughout the period of any dataset. This allows us to examine severity of the wave resource in direct comparison with a locations wave energy content. The index is proposed to be used to estimate the stress on moorings, machine dependencies (components) and potential losses of utilization [56, 57, 58]. A higher WEDI indicates considerations about the economic feasibility of locations. Since the highest extremes might pose additional economic requirements for the secure operation of devices, the WEDI variation and annual trend can be combined and assess potential WEC deployments, see in Fig.9.

Proper sitting selections ensures not only maximum output of energy but also minimise effects by metocean events on the devices, reducing capital cost, operation and maintenance. The calculation takes into account extreme values of waves estimated during the SWAN hindcast, leading to the estimation of highest energy flux. The model has performed well and the amount of data allow for a good representation of the decadal offshore environment, especially since coastal locations are hindcasted with high confidence.

A high-recorded WEDI will lead to an increase in maintenance and operational costs, thus to strengthen the notion of optimal candidate locations, estimations about the energy annual content for the sites are also calculated. This is done to establish the performance of devices and expected increases in cost. The assessment in energy terms allows a direct comparison for the drawbacks and benefits encountered at each location.

WEDI as shown directly correlates with "extreme" energy content of locations (see Figs. 9-10). This stresses out the fact that wave energy converters

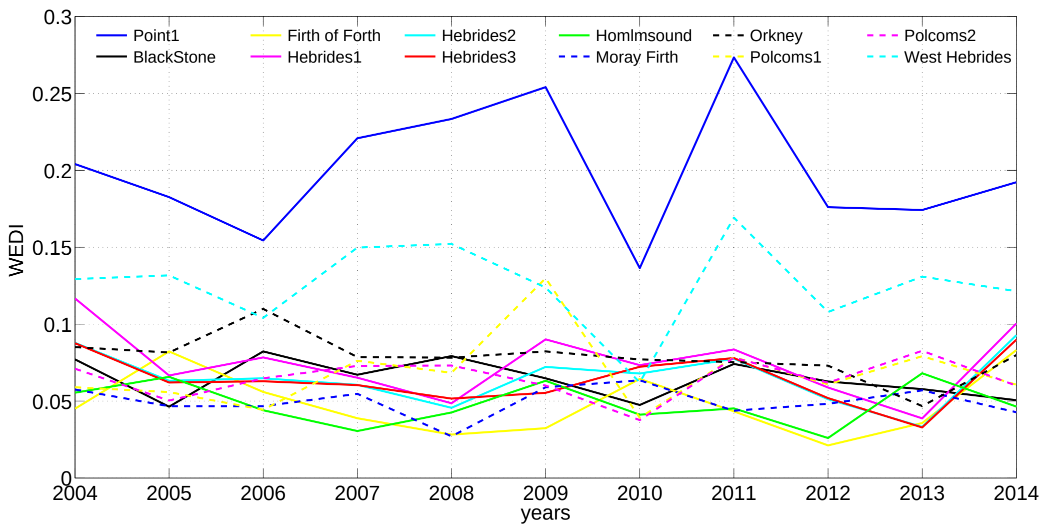
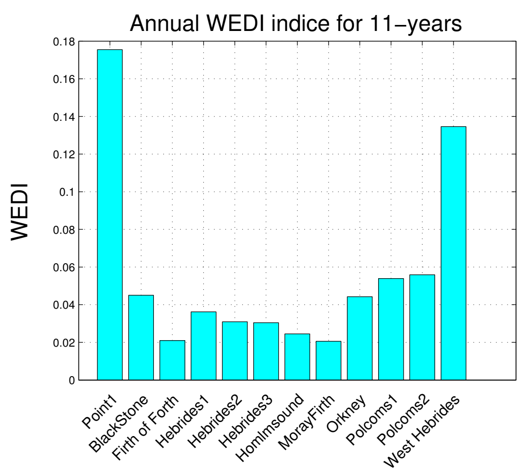
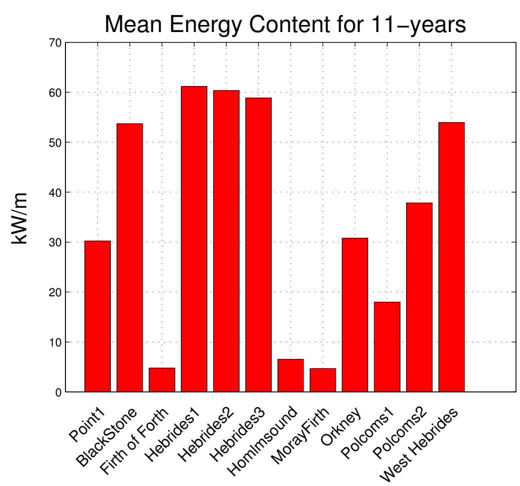


Figure 9: WEDI annual examination for the multiple locations



(a) WEDI



(b) Wave energy content in kW/m

Figure 10: WEDI and wave power for locations of interest

have to operate and "survive" under extreme (potential storm) conditions. Point 1 has the highest index, while as expected Eastern locations present lower values. One has to bear in mind, that the index is a direct comparison of the individual location and its characteristics, thus actually most severe wave heights are not occurring at Point 1 but at deeper locations. Since definition of the index revolves around extreme influx of energy at a location, it is helpful to consider the annual average wave energy as it occurs in every location (see Fig. 8).

In Fig. 11 an iterative process was used to estimate the index for all locations around the region, providing a graphical overview of the area. Combination of WEDI with the mean annual resource, allows expanding upon and further investigate sites that present good opportunities.

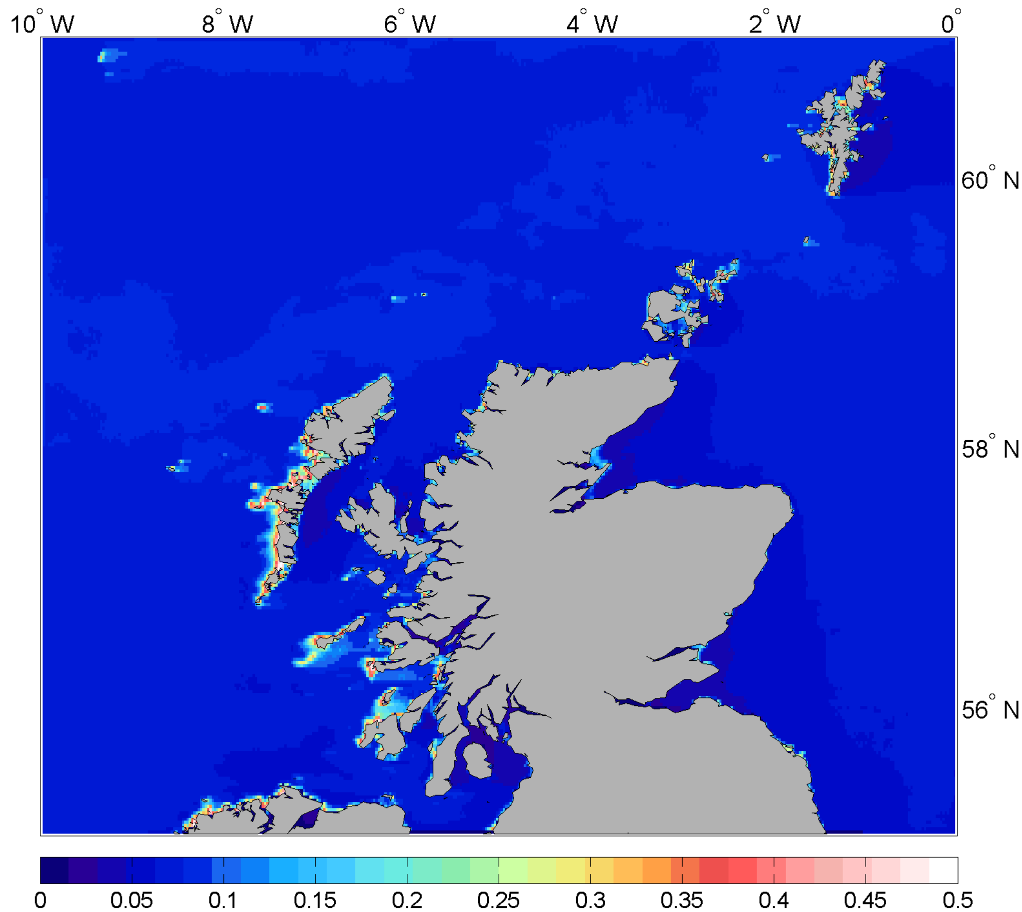


Figure 11: WEDI index established for the mesh based on the gridded data for every point over the 11 year period

The Hebrides 1-3 locations present the most interesting locales with both low WEDI and highest mean energy potential, on the other hand West Hebrides, located at the South of Isle of Lewis present similar levels of wave energy though its development index is almost three times more. As the hindcast indicated, the location is exposed to storm events that may compromise operation of devices and reduce utilization rate, due to sea states occurring outside the span of useful device operation. BlackStone is located on the South of West Hebrides has similar levels of energy while at same depth and a reduced index, favouring as well the further investigation for wave deployments.

At the Orkney region, two locations Homlmsound and Orkney show that although located at neighbouring regions, effects on survivability are completely different. From the two, Orkney location has almost three times the available resource while the WEDI is higher than Homlmsound. The index though is at similar levels with Hebrides 1-3 locations while its depth is almost half, indicating that even smaller wave heights and smaller periods exist. The content of wave energy utilized is significant and can be used for further exploration with a more detailed bathymetry to express coastal interactions better.

Point 1 has the smallest depth, and is near the Hebrides 1-3 is exposing it to energetic conditions, content of the locale is highly promising though the average index shows that stress forces are expected higher. It has to be noted though, that if the depth is taken into consideration extreme events are not expected to surpass safety limits of most devices, since depth breakage will act as a limitation to the developing of waves.

6. Energy capturing and performance of wave energy converters

The volatility of wave parameters is a major factor affecting potential energy generation, can be observed in Fig. 8, the variation of H_{sig} affects the energy content to a greater extend as it is appropriately noticed in the wave energy equation. Locations with greater depths have usually higher energy. At coastal locations breaking of waves because of bottom friction and non-linear interactions reduce H_{sig} and increase frequency. Making waves travelling at shorter time-periods, reducing H_{sig} thus energy flux reaching the devices. With exception of locations at Eastern coasts Moray Firth and Firth of Forth, remainder locations display high levels of energy availability with even shallowest points recording mean wave energy potential over $\approx$ 30kW/m (see Fig. 8 and Fig. 10).

This of course translates into the variability of bivariate distribution that has to be estimated as we investigate the resource potential and extractable content. From the bivariate distributions we calculated the probabilities of occurrences and applied the WECs to estimate production levels, as shown in [59, 60]. The probability of occurrences for every sea-state then used to estimate the extractable energy levels. The proven ability of SWAN, to produce high level hindcasts nearshore, allows to estimate production yields as valid with confidence. The annual variability reveals that in contrast with the sharp deviations in H_{sig}, the final annual production does not deviate as much. In addition, another outcome from this study that helps to disseminate the overall performance of the devices in annual terms, is the capacity factor (CF).

$$E_o = \frac{1}{100} \sum_{i=1}^{n_T} \sum_{i=1}^{n_{H_{sig}}} p_{i,j} P_{i,j} \tag{6}$$

$$E_o = P_o \times \Delta T \times CF \tag{7}$$

with E_o being the annual wave power produced by the coupling of resource with corresponding power matrix, see Eq. 6. In order to quantify this value, the percentage of occurrences of H_{sig} and wave period (T) must be combined with the power matrix. The parameter $p_{i,j}$ represents the energy percentage corresponding to the bin assigned. $P_{i,j}$ is the electrical expected output by the same bin as state by the power matrix. The column is denoted j, and the row as i. The capacity factor (CF) takes into account the nominal rated capacity P_o, the hours in a year (ΔT) and E_o energy produced. Its estimation can be used by Eq. 7.

Four devices representing different PTO principals are selected, a floating two-body heaving (F2BH) converter similar to WaveBob [33]. A bottom fixed heave buoy with multiple arrays the WaveStar [61], a bottom fixed oscillating flap (BFXF) with close resemblance and inspired by the Oyster [33], and the attenuator of Pelamis [59, 62]. A more thorough look into the numerical methods of estimating the devices individual performance and power matrices can be found in [33, 63]. The matrices used are available from studies and published documentations [64, 33, 65, 66, 67, 68, 69, 70]. Each device taken into account uses its given power matrix, and only one device is considered as installed, meaning that the nominal installed capacity of each device corresponds to the nominal capacity given by the manufacturer and/or the representative power matrix in kW, see Fig.12-15.

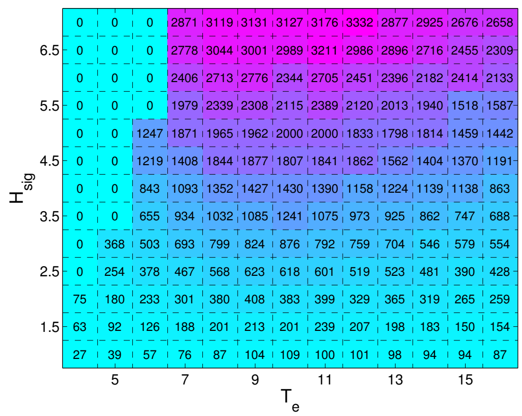


Figure 12: Bottom fixed flap(BFXF)

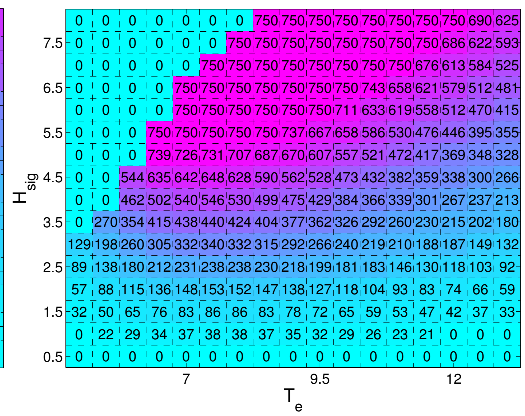


Figure 13: Power matrix for the Pelamis

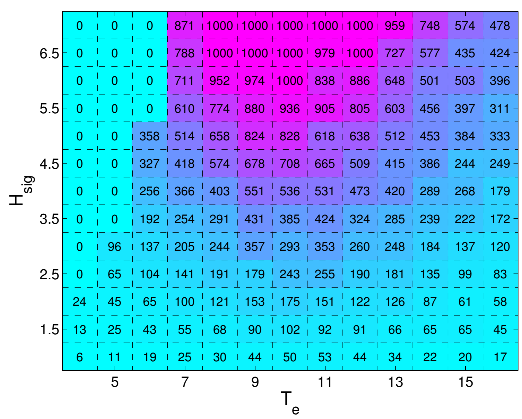


Figure 14: Heave buoy(F2BH)

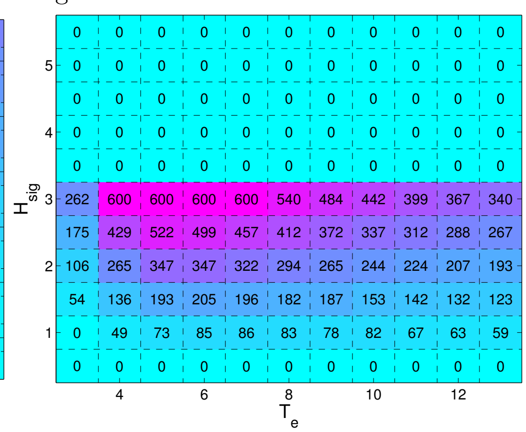


Figure 15: Power matrix for the WaveStar

The power matrices combined with the 11-year power hindcast evaluate the performance in terms of overall energy production. The results estimate production levels and capacity factor of each device at specific points, allowing a readily available, usable capacity factor in future studies. For energy estimations, and economic evaluation of wave power expected annual revenues as in other renewable industries, i.e. solar, wind. Notion of the capacity factor (CF), although "crude" helps identify the potential production by resource better, is an extremely helpful terms that has been developed and used throughout the year.

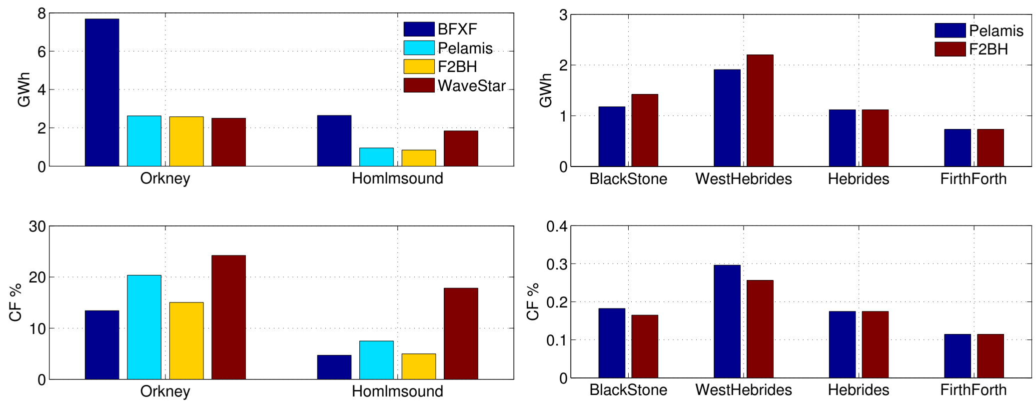
The CF examines is that the produced power annually, in combination with the nominal rated capacity of the device and hours of operation within a year, is able to provide us with a very close to reality approximation of expected production in the absence of information [71, 72, 73]. Use of the term is utilized in numerical estimations on energy economics, energy production assessment and provides the basis for a normalization and even comparison of technologies. The CF is dependent on the total energy production and the rated installed capacity, thus if a device achieves high utilization rates in a year, with a smaller installed capacity then it has a higher the CF.

Indicative values in CF per technology are used by institutes, agencies for calculations of energy productions in a location and economics [69, 74, 66, 75]. Concerning wave energy some studies have mentioned the use of proposed CF numbers but based on limited amount of data or expected assumptions [69, 76, 60, 77].

Based on their characteristics and previously mentioned resource, the WECs under question are adapted to the location and assessed, based on their installation characteristics. Nearshore water locations examined by all four available WECs while mid-depth, due to installation restrictions are comparing only the attenuator and heave buoy systems, where installation deemed "easier" for such depths. All the figures concerning overall annual performance presented in GWh per annum, while capacity factors are in percentages.

Although we have to note that use of Point 1 is only considered as a representative case, due to limitations in the indices used for the bathymetry construction, extraction of points is as accurately as possible. While only some devices operate at such shallow depths, the information provided at Point 1 may be used at depths of 15-20 meters were a wider variety of WEC is applicable. The energy production will change as we move to different depths, however the final capacity factor is not expected to deviate much.

Annual yields are given at Fig.16, reveal that even single devices can amount significant contributions in renewable energy contribution, shallow water locations although obtain less of the broken wave heights, favour the operation of WEC. According to energy yields, the BFXF due to its higher nominal installed capacity attains almost twice the amount of energy production, other devices expressing similar installed capacities deliver same amounts of energy throughout the years explored. Homlmsound and Orkney are located in similar coordinates and exhibit alike yields, however Point 1 at the Isle of Lewis shows that even at shallow locations WEcs deliver twice as much as the two other shallow locations with suitable WECs. Intermediate depths show similar behaviour of performance for both devices, while even



(a) Nearshore Location (b) Deep water Locations

Figure 16: Mean production in GWh for the hindcast period and capacity factors (CF)

the least energetic location at the Firth of Forth contributing considerable amounts of energy to the overall yield.

The energy yield calculations took into account the nominal installed capacity, in order to have a broader estimation of performance for similar longitude and latitude the CF can act as an index to offer information concerning the decision making and future economic considerations of wave energy applications. This levels the field and reveals the operational situation for any given device at these locations. The estimation of these capacity factors pose an improvement to the so far perception of wave devices performance. Due to the amount of data and production data, CFs give the overall performance of the device. From the above Fig. 16 it is observed that regardless of the annual yield the CF at Orkney favours the WaveStar, which although yielded less than the BFXF exhibits a higher capacity factor. Point 1 clearly shows that in such highly energetic waters as the one found in the open Atlantic coasts, the BFXF device provides significant energy and CF $\approx$ 33%. On the other hand, WaveStar achieves only 18.34% this performance closely relates to the operational conditions expressed for each device as given by the power matrices (see Fig. 12-15) surprisingly the F2BH and Pelamis attenuator amounts with higher utilization rates (see Table 4).

For intermidiate depth locations the two WECs have similar CFs, it is noticeable that the range at which the attenuator (Pelamis) operates, allows it to extract more operational time within a year even at the least energetic location at Firth of Forth. All the devices presented, have differences in their rated capacities, extraction of energy and active span of production based on resource, the CF allowed to compare them regardless assessing potential capacity factor per device that can be used in the future at locations and surrounding areas for energy information.

Table 4: Capacity Factor for Locations

	BlackStone	WestHebrides	Hebrides 2	Firth of Forth	Homlmsound	Orkney	Point1
Pelamis	17.36%	15.61%	14.45%	12.97%	7.48%	20.35%	43.12%
F2BH	13.35%	22.66%	12.87%	5.72%	4.98%	15.02%	34.82%
BFXF	N/A	N/A	N/A	N/A	4.70%	13.42%	31.20%
Wavestar	N/A	N/A	N/A	N/A	17.82%	24.22%	18.34%

The capacity factors calculated have been given to every mid-depth and coastal locations, though the author feels that for the West Scottish coastline shallow locations can characterized by capacity factor of $20 - 30\%$ (device dependent) with Orkney and North coastlines acquiring $\approx$ 8-15% (device dependent). For example in case of WaveStar dominant metocean conditions reduce its CF and production, because it is favourable to be adapted in less energetic environments of coastal waters such as the Mediterranean or the North Sea.

Concerning intermediate and deep locations, the performance of WECs led us to apply a capacity factor within the range of average $20 - 30\%$, though deeper locations are exposed to resource that is far more energetic they also increase the occurrences of extreme and storm waves, which reduce the operational time of the devices, usually for survivability reasons. The performance of converters favours WEC operating at lower metocean conditions (low energy).

The outcome of CFs is and will be variable for every location, as we move towards lower longitudes the resource decreases, though in search of economic viability, projections have to based on energy assumptions. With use of such an extensive dataset of hindcast data, the projected behaviour of devices examined provides a look into the actual expected energy benefits and utilization times.

The authors would like to point out simulated production considered is based on existing non-customized devices, with available information limited. In addition, for the first time consideration at coastal-shallow location of depth ≤ 10 meters is attempted, while the applicability of all converters may not be feasible there, the conditions extending from depths 10-20 meters are not expected to be significantly different. For example, the authors recognize that the attenuator (Pelamis) option may not be applicable in Point 1, although a scaled down device in terms of dimension would expect to yield similar capacity factors though different energy yields (reduced).

7. Economic considerations

From the detailed long-term dataset at our disposal we established the utilization factors, and adapt them to 10 MW proposed wave farm to the following locations identified, Hebrides 1-3 (as Hebrides), West Hebrides and Orkney.

For all three locations, we have considered the calculated capacity factor over a long-term period, while the components used are discussed and assigned based on the WEDI index as seen in the previous section, see Section 5. Because limited data exists on the cost of the overall capital expenditure (CAPEX) and operation (OPEX), our assigned values are attributed based on literature and published estimations. Moreover, at the time of writing this study no comprehensive feed-in-tariff (FIT) is established nor the Contracts for Difference (CfD) are published we have also considered a FIT alongside the literature and government lines. Finally, the use of Renewable Obligations Certificates (ROC), have been considered though with the values as proposed by the United Kingdom Scheme and not Scottish Parliament proposals [78], thus considering two ROC for every MWh.

Though several studies have considered the Levelized Cost of Energy (LCOE) [79, 80, 28, 81], the authors have chosen to minimize assumptions for energy estimations by coupling multiple devices with the validated data. We utilized published power matrices of both generic and established devices in order to obtain the optimal and most accurate estimates. The highly temporal nature of the wave conditions ensure better approximation of operations and non-operation conditions which the wave energy converters are expected to encounter. The 11-year data incorporate the seasonal and intra-annual variations that affect the production levels.

Lifetime operation of the wave farm is 20 years, similar to other renewable technologies such as wind and solar. Variable operational costs (VOC) have not been included, due to limited information existing on the rate of failure WECs. WEDI is taken into account as a factor increasing CAPEX, this will be exhibited in the initial values for the economic estimation. The approach used, based on a cumulative and present market values takes into account cost of money, inflation and return on investments.

A 10 MW installed capacity (P_o) was considered based on the recommendations and expectations about reducing cost by increasing WECs [69]. The cost of a WEC is suggested to be varying from 2,000,000-4,000,000 $£/MW$ [80, 28, 66] while some studies indicate higher levels of cost [82, 83]. In this preliminary analysis we considered an approximately 3,000,000 $£/MW$ The cost of the device excludes installation works cost, which will be attributed in order to calculate the final CAPEX, as in every renewable technology this is assigned and expected to vary for wave energy [84, 85, 69].

The energy calculated and the annual revenue stream for the financial estimation is based on the proposed method by [84]. With initial capital I_{Co} (CAPEX) including the I_{Cn} (works) cost and installed capacity P_o.

$$I_{Co} = [(I_{Cn} \times inst_{cost}) + I_{Cn}] \times P_o \tag{8}$$

The annual Fixed Cost (FC_n) for $M\&O$ calculated by assigned percentage of maintenance, and values calculated for the current money price, over the years (n). The annual (FC_n) expenditure allows to calculate the cost to benefit (C_n) of the wave farm.

$$FC_n = m_{cost} \times IC_o \times \left[\frac{1+g}{1+i} + \cdots + \left(\frac{1+g}{1+i}\right)^n\right] \tag{9}$$

$$C_n = IC_o + FC_n \tag{10}$$

As discussed new FITs and CfDs are not established, while suggestions state the expected values are to range from 200-220 $£/MWs$ for Ireland [66]. O'Connor et.al. [69] explored a 330$£/MWh$ financial scheme, the authors chose to use an FIT of 200$£/MWh$ which seems more realistic to the existing and previous scheme for RE technologies that have been used in similar emerging technologies around Europe [80, 86, 70].

The potential annual revenues are estimated by adapting the CF with installed capacity over one year period providing the annual energy (E_o), with the finalized earnings of each year adapted to current prices, while in Table 5 the economic set-up model is presented with the indicative indices used.

$$R_n = E_o \times c_o \times \left[\frac{1+e}{1+i} + \cdots + \left(\frac{1+e}{1+i}\right)^n\right] \tag{11}$$

The final amortization periods, i.e. "break-even" scenarios are estimated by the accumulated gains/revenues R_n of each year adjusted to current prices, and the C_n of the wave farm.

Table 5: Economic considerations and indices used in the study

Components	% of IC_o ("One-Off")
Cabling	5%
Mooring	10% (low) 20% (high)
Installation	20%
Construction Management	3%
Components	Maintenance and Operations FC_n % of IC_o (annual)
M&O FC_n	6% (low) 8% (high)
	Economic Indices
Inflation (g)	4%
Energy Escalation Rate (e)	3%
Discount rate (r)	10%
Return rate of investment	10%
Cost of Money (ic)	5%
ROC value (croc)	40 /MWh
Feed-in-Tariff (FIT) (co)	200/MWh
CF Hebrides	27%
CF West Hebrides	32%
CF Orkney	25%

The additional cost of the WEDI index is represented, by an increase of 15% for the CAPEX based on expected extreme conditions in the area. This is to assess the strengthening works associated with several components to ensure stable operation of the device. Increased M&O costs are associated with the increase of volatile conditions expected, while no additional estimation of weather windows and accessibility levels performed in this study, with these expected to increase especially for locations with higher energy influx level.

Finally, the capacity factors used in this study are derived by our energy analysis (see Section 6). It is obvious that several converters favour some locations due to their operational characteristics. From the current approach, we established a general characterization for any WEC device (treated as generic) and then its associated costs and amortization periods are given. For all three cases examined the amortization periods do not vary significantly, the West Hebrides location is determined to payback its associated cost at 9.5 years, the Hebrides at 9 years, and the Orkney location at 10.5 years. Although, similar capital returns are in place, the expenditure for annual costs associated with each location is significantly higher with the West Hebrides presenting a 31% higher required fixed cost expenditure. The CAPEX difference increased only 8% percent for the West Hebrides, while the energy production difference is 17%. Finally, the cost of energy for the locations and devices, established via the production estimates and overall costs see Fig. 17.

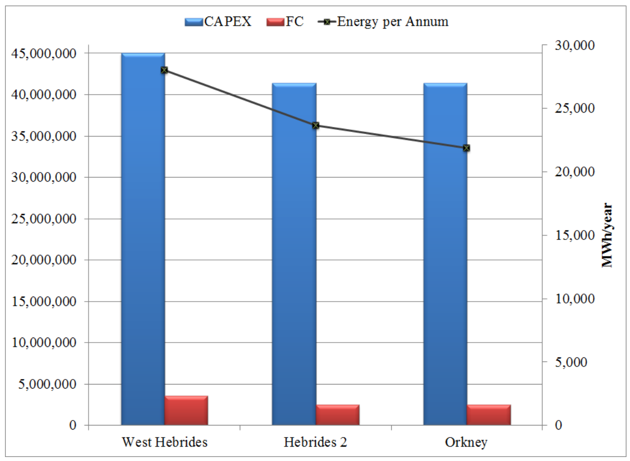


Figure 17: Estimated CAPEX, FC and produced energy per location for a generic wave energy device

As it is obvious there is a significant sensitivity concerning the selling cost of electricity to the grid and overall I_{Cn} of the device, based on experience gained by installations. However, this was tested but not recorded in the study; reductions in the amortization periods are expected. Scaled down devices and increase in power production have been mentioned by appropriately adjusting the WECs operation to specific sea states [74]. Findings are encouraging, since the CF exhibit that wave energy potential are similar to established technologies. The cost of wave converters is high due to the lack of installation and heavily dependent on several technological and components factors, which are expected to be reduced in the future, as more installation come into effect [81].

Moreover, custom power matrices for locations or even wider areas can also increase the CF and utilization rates that will also add to financial attractiveness of the technology. Authors believe that even at such early stage WECs are competent to provide both energy and financial gains to investors and grid operators.

Additional investigation is eminent to associate annual F_{Cn} cost and CAPEX to availability and accessibility of the locations. Energy content as expected, is higher for deeper locations, shallower and coastal application are considered to have significant less financial requirements, though more information about the cost associated have to be shared by the community in order to maximise accuracy of calculations.

8. Discussion

Scotland is exposed to some of the highest wave resources in the world, and is currently considered as one of the most promising region for wave energy applications. Wave energy converters (WECs) are one option to extract energy from waves. During the past years several ideas, configurations of WECs have been proposed with the number ever increasing [32, 33]. While, a higher number of potential WECs can seem as beneficial, for development of the industry, at the same time it is a serious disadvantage for the wave energy industry.

In order to allow WECs to be take part in the competitive market of renewable energy, their performance has to be properly assessed and quantified. This raises significant issues concerning data availability. To date majority of the wave resource studies for Scotland, are extracted by previous model generation, larger oceanic runs and/or limited duration studies which are not suitable to be used for nearshore quantification [11]. Nearshore wave energy assessments are limited for Scotland, with their absence limiting the energy and cost considerations. Most studies propose the use of Levelised Cost of Electricity (LCOE) for wave energy [87, 88], however the LCOEs estimated are often widely varied and encompass high uncertainties [82]. While, uncertainty in capital costs is a factor another higher significance reason is often overlooked, the expected energy production. Most studies, use "rule-of-thumbs" coefficient to estimate energy production and thus examine economic parameters. This is highly obvious in the work of Farrell et.al [89] where the large range of LCOE in wave energy is discussed.

Estimating wave energy by multiple WECs allows not only to assess and compare performance and adaptability of numerous devices, but also understand the economic implications and payback (amortisation) periods for every choice. While LCOE is a metric, the final decision is the economic survivability of a WEC and its payback periods. This information are often absent, on the reason that wave energy is still in immature stages.

To support and enhance energy modelling and economics of wave energy, resource assessments are vital. Depending on the analysis intended the scale of the primary modelling work must be adjusted, to provide accurate calibrated/validated data for energy applications. In this study a nearshore model was used to estimate the metocean conditions in the highly energetic coastlines of Scotland. The ability of the model to resolve nearshore mechanics and the long duration of the hindcast allows robust energy estimates. To date there is no long-term ($\geq$ 10 years) conforming with suggested protocols and practises [13].

Our results show that by producing and using higher resolution wave data, allows to estimate the energy flux and the potential energy production by numerous WEC for regions/locations where oceanic models have no adequate physical or spatial resolution. Our results show that depending on the region of Scotland different devices are more applicable than other. At Western coastlines, exposed to higher waves devices which attain peak performance at higher H_{sig} and lower frequencies display capacity factors of over 20%. However, the same devices if applied to a lower resource environment decrease their capacity factor almost threefold. Similar dependence on metocean conditions and capacity factors were also displayed in other world regions as shown in Rusu et.al [90].

The energy modelling results have significant implications on the economic analysis and financial viability. Proper energy quantification allows to determine the most suitable option for power production and thus enhance financial viability. Based on our long-term hindcast and energy estimates, we establish the performance of WECs accounting for multi-year variations. Leading to better sizing their potential annual energy production, subsequently the economic analysis considered the "best" performing devices and for a detail cost-benefit-analysis for wave energy is presented. While, some assumptions especially at general indices such as inflation, reflation of energy etc. have to be made our cost-benefit model is of higher fidelity since energy production is based on long-term data.

However, some limiting factors must also be discussed and presented. Our model, is based on a high fidelity nearshore, driven by six-hour winds with a customised numerical solution. In our consideration we have not considered currents and elevation impacts on the wave resource. This means that in areas of high currents and tides dependence, a higher resolution dedicated model should be run.

While our model shows very good agreement with buoy data, improving the knowledge for the area, much smaller isolated studies are necessary especially for devices that are intended for depths $\leq$ 20m. Interaction of currents and tides at such depths is expected to alter the final wave energy resource.

Such consideration must come at a cost of either regional outreach, accuracy and computational cost. With no information on the nearshore environment of Scotland, our model offers suitable long-term information of wave power. Identifying "hot-spot" areas which can benefit from future investigations at higher degree.

9. Conclusions

A third generation high-resolution spectral model was used to examine and hindcast the Scottish coastline. Results provided span from 2004 to November 2014, providing one of the most up-to-date studies on the current wave energy flux and perspectives. The model development and set-up presented fully, while a detail examination and validation.

The final maps and overall resource constitutes the latest improvement in wave resource estimation around the region, with model used being highly skilled at coastal location. The mesh resolution used in combination with the extended period, allowed to examined not only very shallow regions but also include in results the intra-annual and decade variation of wave energy.

Several locations extracted by the final maps are compared with buoy recordings for separate years examining and discussing the models performance and limitations. The model has missed extreme storm events, although such behaviour expected as stated in previous literature. The annual indices are represented very good by the model, with small biases, even at the occurrence of high storms that are common in the Atlantic areas.

Through the validation process, high levels of confidence to the results, allowed for the construction of annual wave energy maps indicating the resource in coastal locations around Scotland. In accordance with expressed interest by the wave industry and the Crown Estates leases for wave deployments, several locations examined for available wave energy. In addition, the effect of maximum wave resource to potential sites mentioned and assessed, in the form of an index. The WEDI presents not only the opportunities for wave energy but the potential stresses that a device may be exposed to, allowing for further additional dissemination of wave energy assessments and adding an informative criterion in the appropriate selection of a wave site.

The examination of data presented the annual mean fluctuations of wave energy allowing observations the level of high and low energy content per year for each of the location. Areas of imminent wave deployments discussed and assessed, with findings prompting site considerations. Preliminary financial estimations display not only the energy viability of wave farms as investments but also the financial opportunities that exist within the industry. Further study of additional national plans of wave energy will benefit the policy decision-making process. However, this should always be performed with engineering considerations, improvements, and restrictions.

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