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

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 CO_2 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.

44 This recently raised considerations towards the validity and over-estimations
45 it offers in comparison with third generation state-of-the-art models [11].
46   Under-estimations in most models have been reported [15, 16, 17, 18, 19],
47 while a discussion on the selection of input wind datasets and bathymetry
48 interaction can be see [20, 21]. In this study, a third generation phase-average
49 model is used to provide an 11-year high-resolution hindcast around Scot-
50 land and the North Sea region. Subsequently, the data are used to estimate
51 the wave energy resource and explore the opportunities for wave installa-
52 tions and site selection considerations. Previous studies for wave power in
53 the area involved either large scale oceanic models, which could not resolve
54 coastal approaches as well [22, 23, 24], or where run on limited spatial and/or
55 temporal terms [25, 11, 26].
56   Recent developments in the UK concerning renewable energy [27, 28] pro-
57 pose for adaptation of technologies that counteract systems variability and
58 enhance predictability [29, 30]. More specifically, UK agencies, governing
59 and research organizations have outlined the necessity of wave energy incor-
60 poration as a strong candidate for the combined exploitation of renewable
61 penetration. With the advantages of not only on energy security, diversifica-
62 tion, but also by establishing a strong industrial sector in the offshore marine
63 industry [30, 31].
64   Wave energy converters (WEC) have been developing over the last years
65 with variable levels of success, several models exist with some similarities in
66 the way kinetic energy is harnessed. Differences are predominately located
67 mainly in the PTO system utilised [7, 32, 33]. The Atlantic wave climate is
68 studied with the use of numerical wave models, by both operational forecast
69 organizations and research groups [34]. It has been underlined that variability
70 and uncertainty of waves, may act as a barrier of our understanding on the
71 resource [35].
72   The Isle of Lewis and Orkney areas are identified by the Crown Estate [36]
73 as regions with high interest for the offshore wave community (see Fig. 1).
74 For this reason additional information are extracted by the hindcast for these
75 locations in an attempt to quantify the results at near coastal terrains and
76 examine effects of high levels of energy in these areas.
77   In addition, a thorough examination of the Scottish coastline here presents
78 valuable information about the variation and distribution of wave energy
79 around all coastal areas, showing the annual energy content, providing addi-
80 tional information for future potential smaller hindcasts at areas of interest.
81 The numerical results are subsequently utilized for wave energy estimations,
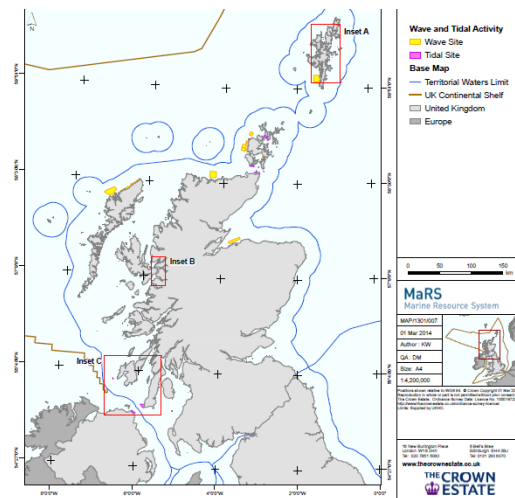
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Figure 1: The areas of interest for wave energy development (wave energy is yellow) as presented by the Crown Estate [36]

82 a wave development index, though additional use of such long-term data
83 includes wave climate, wave variability, and extreme analysis to name a few.
84   This study presents the validation of a third generation model, examines
85 the wave climate, wave power and potential for several areas that are of
86 interest for wave energy deployments In contrast to larger oceanic models
87 this study is able to represent coastal resources at higher degree, offering an
88 improvement in existing wave energy maps.
89   The results are coupled with published data of power matrices assessing
90 the potential energy benefits and the applicability of various WECs, pro-
91 viding robust estimations and insights on selection. The authors hope that
92 this study in combination with existing information and studies from other
93 models will prompt the examination of locations and increase awareness on
94 site selection for wave energy.

2. Model development

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

4

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° longitude and 6° 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.
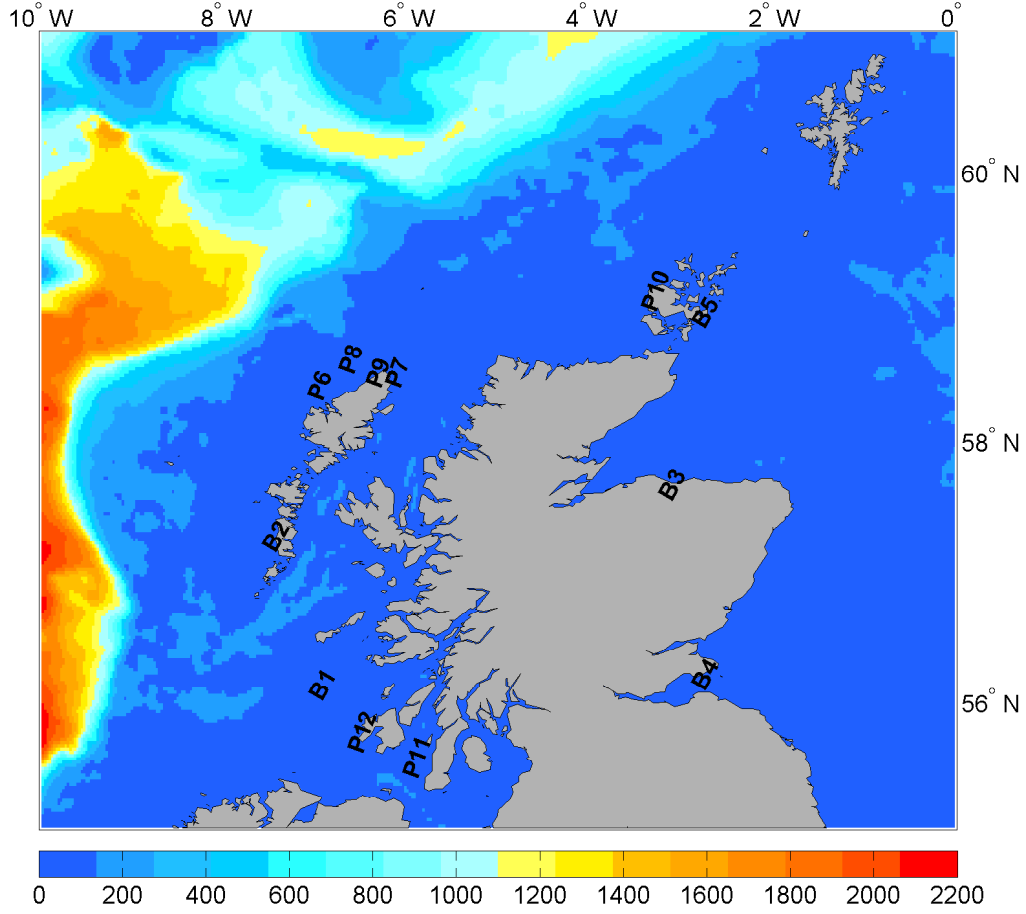
Figure 2: Computational domain of the hindcast, bathymetry of the area in meters

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

149 locations of interest are also extracted by the hindcast and are denoted as
150 SWAN not corresponding to buoys (see Table 1). Interest is given to coastal
151 shallow locations, since most oceanic models often cannot resolve nearshore
152 conditions as well [47]. All data recovered from the buoys underwent quality
153 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

154   The good level of confidence by our model was used for proper estimation
155 of wave energy in nearshore locations which other oceanic models cannot
156 hindcast locations at such depths [48, 49, 50]. Validation of results are given
157 in both tabular and selected figures, representative 2011 annual performance
158 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
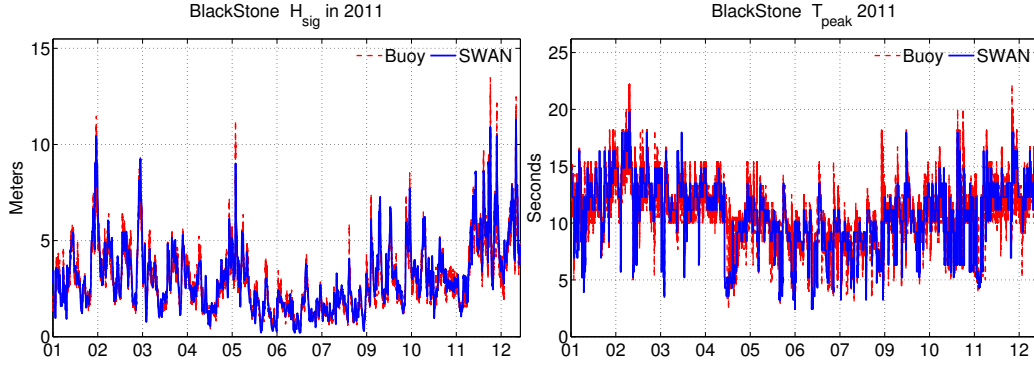
Figure 3: H_{sig} hindcast 2011
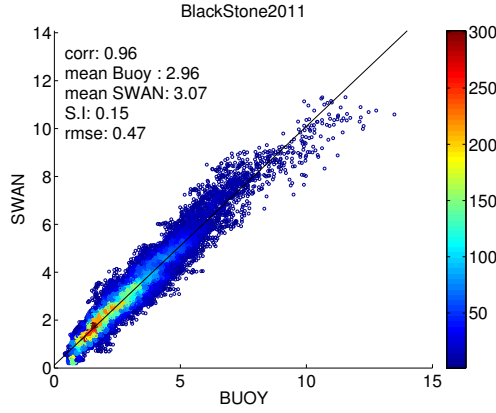

Figure 4: T_{peak} hindcast 2011

Figure 5: Scatter performance of the hindcast
for BlackStone 2011

159   Modelled data compared to buoy measurements are presented in Table 2
160 and compared modelled data are in good agreement with buoy measurements.
161 Eastern coastlines are exposed to lower resources, Moray Firth and Firth of
162 Forth average measured and simulated values have similar values with lower
163 coefficients of correlation and higher scattering. Though the results especially
164 at Moray Firth are of moderate accuracy, the overall bias expressed is low,
165 performance of the model for remaining time at Firth of Forth and Western
166 locations show that all quantities have good accuracy.
167   It has to be underlined, that due to the nature of wave numerical models,
168 some of the set up assumptions and numerical solutions within affect the level
169 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-
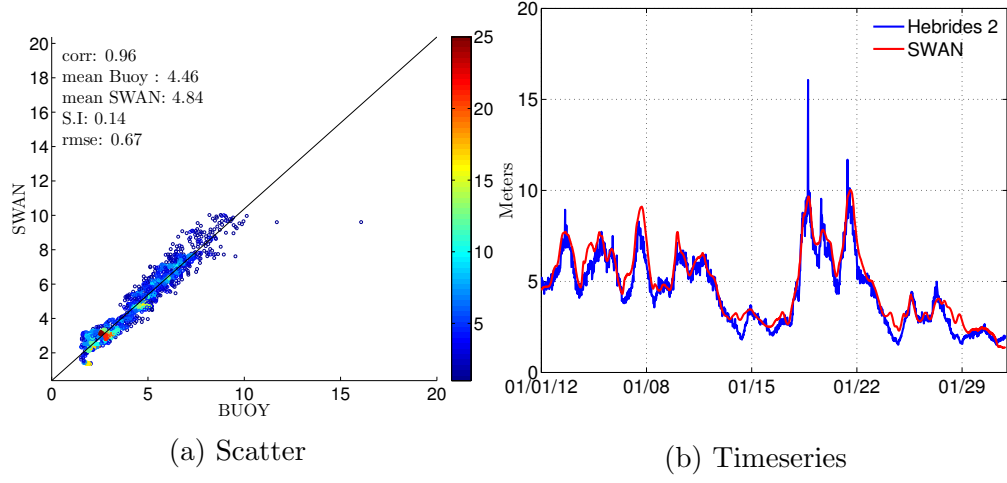
(a) Scatter

(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

206 tions of oceanic models are known, the validation allows presenting results
207 with confidence about the findings.
208   Wave energy flux is dependent on significant wave height (H_{sig}) and en-
209 ergy period (T_e), which represents the period of waves with sinusoidal form
210 and can be treated as ratio between the -1 moment and the zeroth moment
211 of the spectrum as:

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

212   With $m_0....m_n$ denoting the nth moment of the wave spectrum. For these
213 kind of locations and due to the fact that investigation is expressed for coastal

10

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

11

243 potential climate and wave fluctuations [55]. This was not the scope of this
244 study, though produced data can be also used to extreme value analysis and
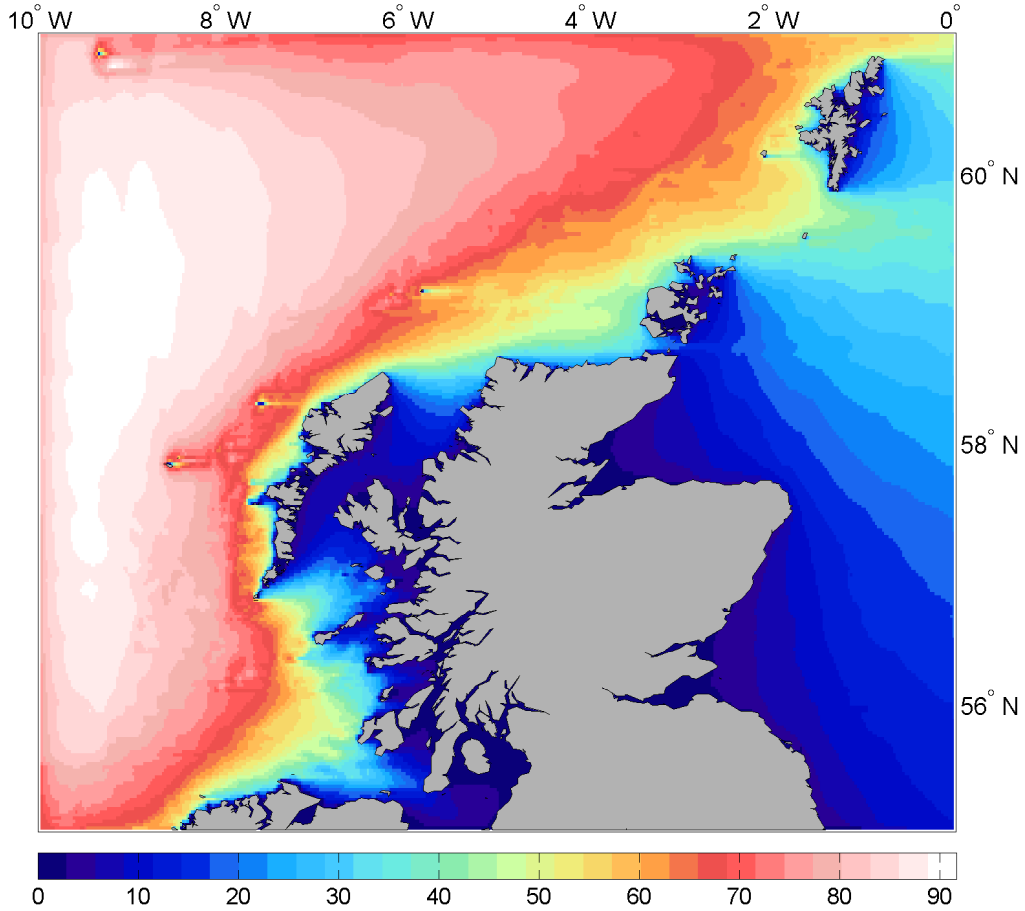245 decadal wave climate fluctuation in several locations.

Figure 7: Mean Wave Power over the $\approx$ 11 years period in kW/m

246   The contoured hindcast shows the energy flux of the region is extremely
247 high at deep-water regions, with previous published wave resource assess-
248 ments also reporting approximately 75-80 kW/m. The use of advanced nu-
249 merical solvers in SWAN for shallower areas, coastal locations are presented
250 fully allowing the application of a fine resolved bathymetry the first for such
251 a long-term study (see Fig. 7).
252   As shown by the maps both mean annual and overall, the interest ex-
253 pressed by many developers to place their device in the West and North

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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.

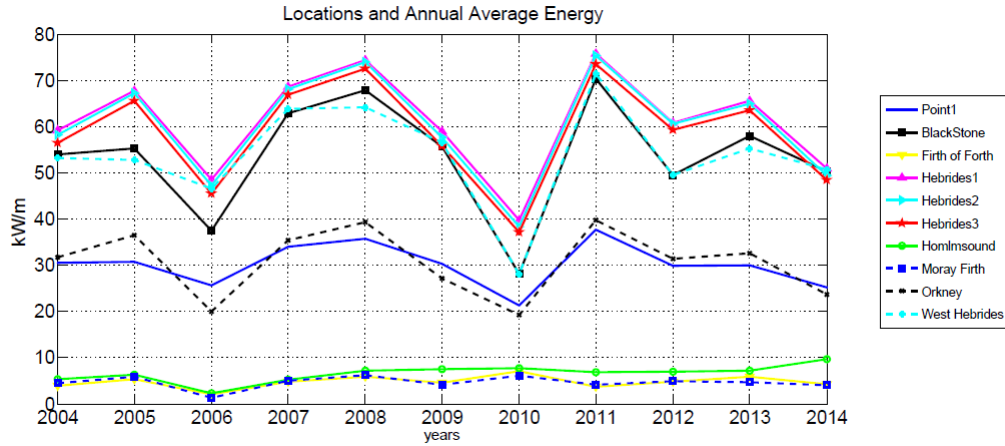Figure 8: Mean Annual Power at each of the locations in kW/m

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 Develop-

13

275 ment Index (WEDI). The use of EVA returns the probabilities of exceedance
276 and return periods of wave height within a year, allow proposing the extreme
277 events that may occur, this will not be investigated in this study.

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

278   The index is the ratio of annual average wave power (P_{wave}) to the max-
279 imum storm wave power (J_{wave}) that every offshore device or structure will
280 have to absorb. Devices are usually placed based on mean power content.
281 Depending on both the mean and maximum power potential influences on
282 the wave energy of the location can be attributed, measuring severity and
283 penalising areas with a high index, that is discussed in Hagerman [56].
284   The focus of our approach is the evaluation of WEDI in comparison with
285 the available wave energy at the locations of interest. The WEDI takes into
286 account the maximum wave energy content that occurs throughout the pe-
287 riod of any dataset. This allows us to examine severity of the wave resource
288 in direct comparison with a locations wave energy content. The index is pro-
289 posed to be used to estimate the stress on moorings, machine dependencies
290 (components) and potential losses of utilization [56, 57, 58]. A higher WEDI
291 indicates considerations about the economic feasibility of locations. Since
292 the highest extremes might pose additional economic requirements for the
293 secure operation of devices, the WEDI variation and annual trend can be
294 combined and assess potential WEC deployments, see in Fig.9.
295   Proper sitting selections ensures not only maximum output of energy but
296 also minimise effects by metocean events on the devices, reducing capital cost,
297 operation and maintenance. The calculation takes into account extreme val-
298 ues of waves estimated during the SWAN hindcast, leading to the estimation
299 of highest energy flux. The model has performed well and the amount of
300 data allow for a good representation of the decadal offshore environment,
301 especially since coastal locations are hindcasted with high confidence.
302   A high-recorded WEDI will lead to an increase in maintenance and oper-
303 ational costs, thus to strengthen the notion of optimal candidate locations,
304 estimations about the energy annual content for the sites are also calculated.
305 This is done to establish the performance of devices and expected increases
306 in cost. The assessment in energy terms allows a direct comparison for the
307 drawbacks and benefits encountered at each location.
308   WEDI as shown directly correlates with "extreme" energy content of loca-
309 tions (see Figs. 9-10). This stresses out the fact that wave energy converters
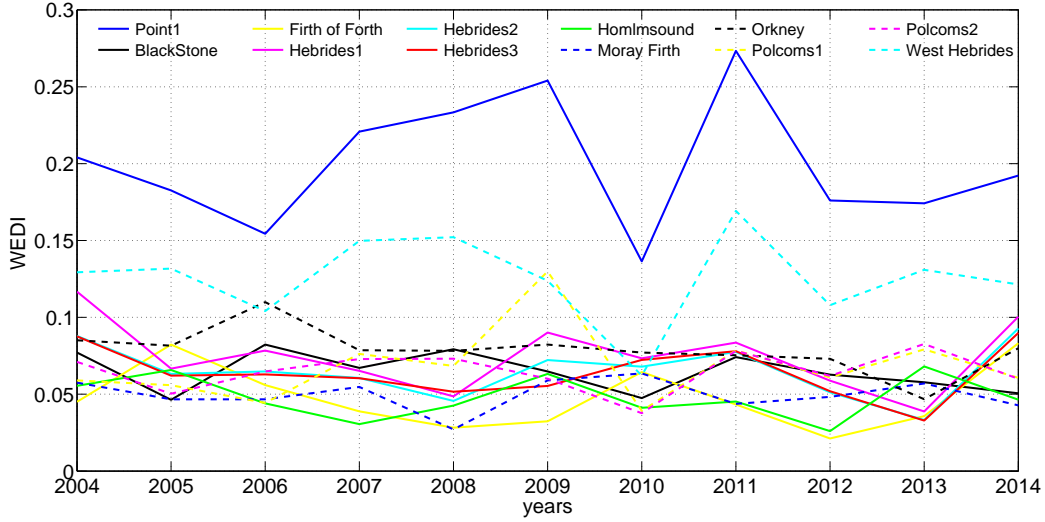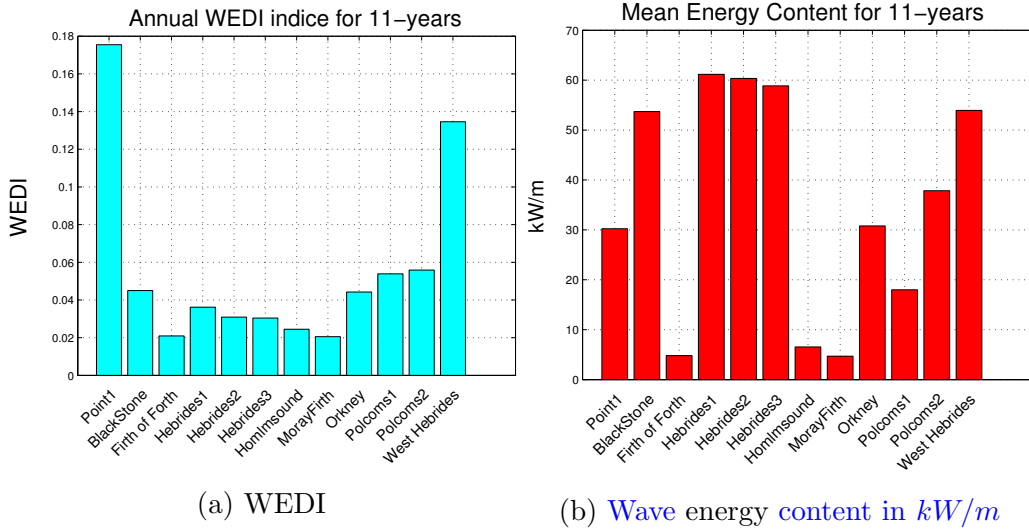
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Figure 9: WEDI annual examination for the multiple locations

(a) WEDI

(b) Wave energy content in kW/m

Figure 10: WEDI and wave power for locations of interest

310 have to operate and "survive" under extreme (potential storm) conditions.
311 Point 1 has the highest index, while as expected Eastern locations present
312 lower values. One has to bear in mind, that the index is a direct comparison
313 of the individual location and its characteristics, thus actually most severe
314 wave heights are not occurring at Point 1 but at deeper locations. Since def-

15

315 inition of the index revolves around extreme influx of energy at a location,
316 it is helpful to consider the annual average wave energy as it occurs in every
317 location (see Fig. 8).

318   In Fig. 11 an iterative process was used to estimate the index for all loca-
319 tions around the region, providing a graphical overview of the area. Combi-
320 nation of WEDI with the mean annual resource, allows expanding upon and
321 further investigate sites that present good opportunities.
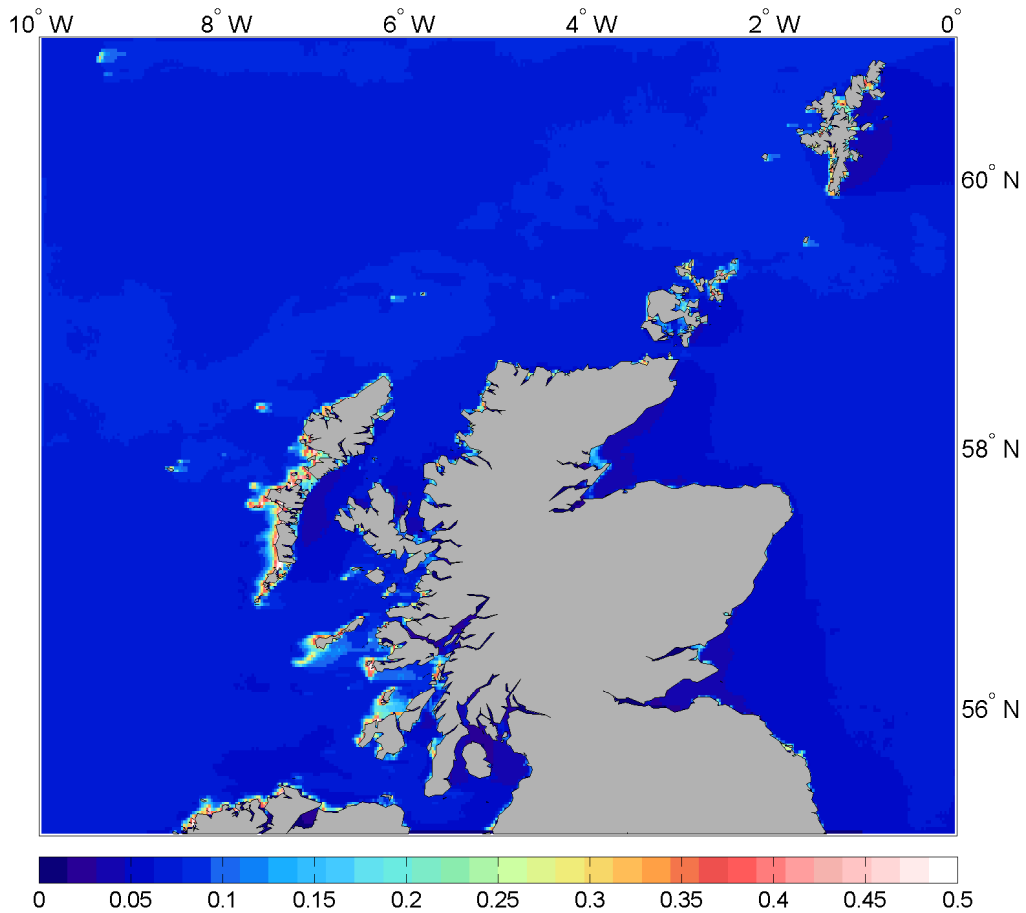

Figure 11: WEDI index established for the mesh based on the gridded data for every point over the 11 year period

322   The Hebrides 1-3 locations present the most interesting locales with both
323 low WEDI and highest mean energy potential, on the other hand West He-
324 brides, located at the South of Isle of Lewis present similar levels of wave

16

325 energy though its development index is almost three times more. As the
326 hindcast indicated, the location is exposed to storm events that may com-
327 promise operation of devices and reduce utilization rate, due to sea states
328 occurring outside the span of useful device operation. BlackStone is located
329 on the South of West Hebrides has similar levels of energy while at same
330 depth and a reduced index, favouring as well the further investigation for
331 wave deployments.

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

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

6. Energy capturing and performance of wave energy converters

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

359 This of course translates into the variability of bivariate distribution that
360 has to be estimated as we investigate the resource potential and extractable

17

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.

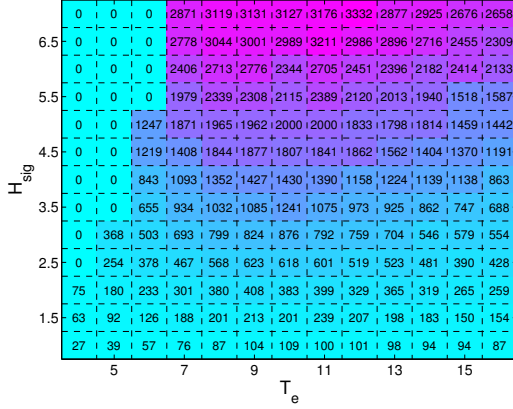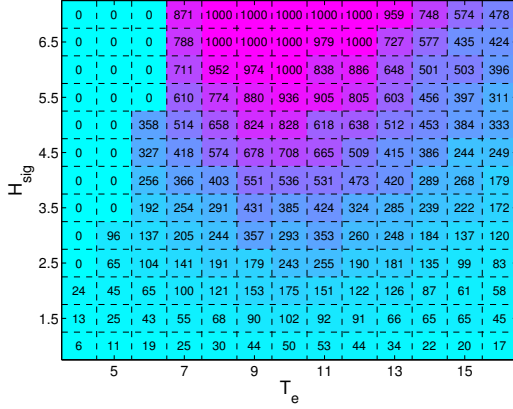Figure 12: Bottom fixed flap(BFXF)

Figure 13: Power matrix for the Pelamis
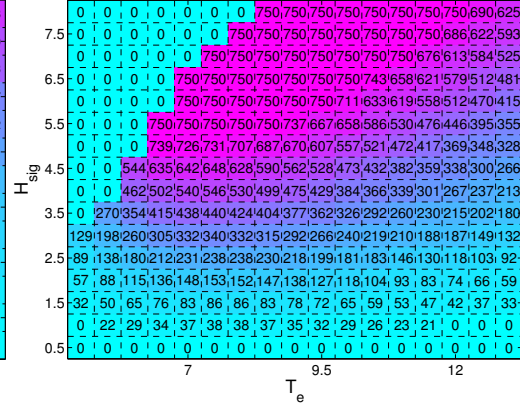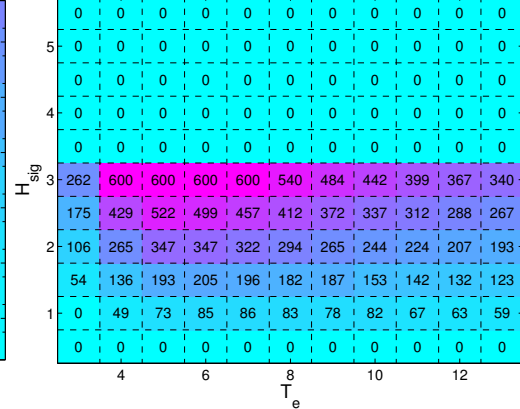

Figure 14: Heave buoy(F2BH)

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

19

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

20

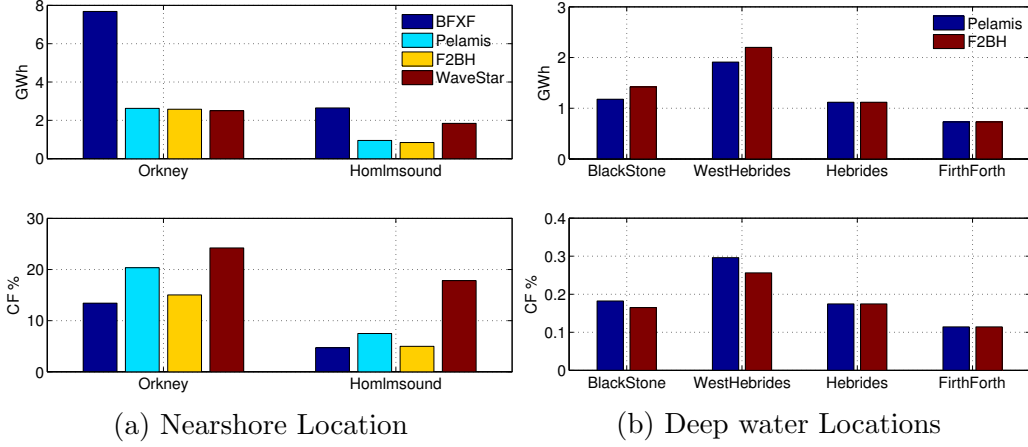| (a) Nearshore Location | (b) Deep water Locations |

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 ≈ 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

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464 rated capacities, extraction of energy and active span of production based
465 on resource, the CF allowed to compare them regardless assessing potential
466 capacity factor per device that can be used in the future at locations and
467 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%

468   The capacity factors calculated have been given to every mid-depth and
469 coastal locations, though the author feels that for the West Scottish coastline
470 shallow locations can characterized by capacity factor of $20 - 30\%$ (device
471 dependent) with Orkney and North coastlines acquiring $\approx$ 8-15% (device
472 dependent). For example in case of WaveStar dominant metocean conditions
473 reduce its CF and production, because it is favourable to be adapted in less
474 energetic environments of coastal waters such as the Mediterranean or the
475 North Sea.
476   Concerning intermediate and deep locations, the performance of WECs
477 led us to apply a capacity factor within the range of average $20 - 30\%$,
478 though deeper locations are exposed to resource that is far more energetic
479 they also increase the occurrences of extreme and storm waves, which re-
480 duce the operational time of the devices, usually for survivability reasons.
481 The performance of converters favours WEC operating at lower metocean
482 conditions (low energy).
483   The outcome of CFs is and will be variable for every location, as we
484 move towards lower longitudes the resource decreases, though in search of
485 economic viability, projections have to based on energy assumptions. With
486 use of such an extensive dataset of hindcast data, the projected behaviour
487 of devices examined provides a look into the actual expected energy benefits
488 and utilization times.
489   The authors would like to point out simulated production considered is
490 based on existing non-customized devices, with available information lim-
491 ited. In addition, for the first time consideration at coastal-shallow location
492 of depth ≤ 10 meters is attempted, while the applicability of all converters
493 may not be feasible there, the conditions extending from depths 10-20 meters
494 are not expected to be significantly different. For example, the authors rec-

ognize 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.

531   A 10 MW installed capacity (P_o) was considered based on the recommen-
532 dations and expectations about reducing cost by increasing WECs [69]. The
533 cost of a WEC is suggested to be varying from 2,000,000-4,000,000 $\pounds/MW$
534 [80, 28, 66] while some studies indicate higher levels of cost [82, 83]. In this
535 preliminary analysis we considered an approximately 3,000,000 $\pounds/MW$ The
536 cost of the device excludes installation works cost, which will be attributed
537 in order to calculate the final CAPEX, as in every renewable technology this
538 is assigned and expected to vary for wave energy [84, 85, 69].
539   The energy calculated and the annual revenue stream for the financial
540 estimation is based on the proposed method by [84]. With initial capital I_{Co}
541 (CAPEX) including the I_{Cn} (works) cost and installed capacity P_o.

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

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

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

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

546   As discussed new FITs and CfDs are not established, while suggestions
547 state the expected values are to range from 200-220 $\pounds/MWs$ for Ireland
548 [66]. O'Connor et.al. [69] explored a $330\pounds/MWh$ financial scheme, the
549 authors chose to use an FIT of $200\pounds/MWh$ which seems more realistic to
550 the existing and previous scheme for RE technologies that have been used in
551 similar emerging technologies around Europe [80, 86, 70].
552   The potential annual revenues are estimated by adapting the CF with
553 installed capacity over one year period providing the annual energy (E_o),
554 with the finalized earnings of each year adapted to current prices, while in
555 Table 5 the economic set-up model is presented with the indicative indices
556 used.

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

557   The final amortization periods, i.e. "break-even" scenarios are estimated
558 by the accumulated gains/revenues R_n of each year adjusted to current prices,
559 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%

560   The additional cost of the WEDI index is represented, by an increase of
561 15% for the CAPEX based on expected extreme conditions in the area. This
562 is to assess the strengthening works associated with several components to
563 ensure stable operation of the device. Increased M&O costs are associated
564 with the increase of volatile conditions expected, while no additional estima-
565 tion of weather windows and accessibility levels performed in this study, with
566 these expected to increase especially for locations with higher energy influx
567 level.
568   Finally, the capacity factors used in this study are derived by our energy
569 analysis (see Section 6). It is obvious that several converters favour some lo-
570 cations due to their operational characteristics. From the current approach,
571 we established a general characterization for any WEC device (treated as
572 generic) and then its associated costs and amortization periods are given.
573 For all three cases examined the amortization periods do not vary signifi-
574 cantly, the West Hebrides location is determined to payback its associated
575 cost at 9.5 years, the Hebrides at 9 years, and the Orkney location at 10.5
576 years. Although, similar capital returns are in place, the expenditure for
577 annual costs associated with each location is significantly higher with the
578 West Hebrides presenting a 31% higher required fixed cost expenditure. The
579 CAPEX difference increased only 8% percent for the West Hebrides, while

580 the energy production difference is 17%. Finally, the cost of energy for the
581 locations and devices, established via the production estimates and overall
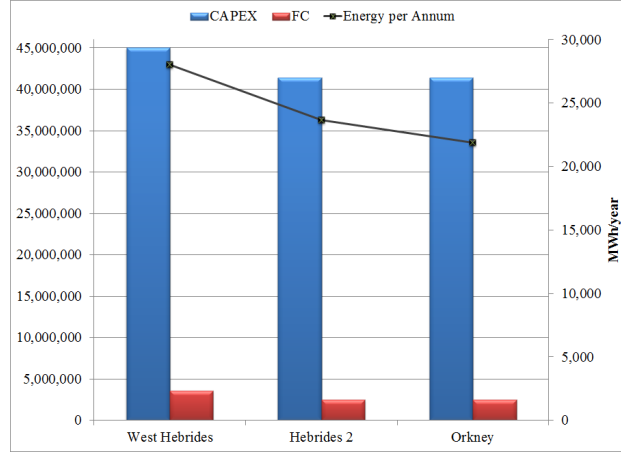582 costs see Fig. 17.

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

583   As it is obvious there is a significant sensitivity concerning the selling cost
584 of electricity to the grid and overall I_{Cn} of the device, based on experience
585 gained by installations. However, this was tested but not recorded in the
586 study; reductions in the amortization periods are expected. Scaled down
587 devices and increase in power production have been mentioned by appro-
588 priately adjusting the WECs operation to specific sea states [74]. Findings
589 are encouraging, since the CF exhibit that wave energy potential are simi-
590 lar to established technologies. The cost of wave converters is high due to
591 the lack of installation and heavily dependent on several technological and
592 components factors, which are expected to be reduced in the future, as more
593 installation come into effect [81].
594   Moreover, custom power matrices for locations or even wider areas can
595 also increase the CF and utilization rates that will also add to financial
596 attractiveness of the technology. Authors believe that even at such early
597 stage WECs are competent to provide both energy and financial gains to
598 investors and grid operators.
599   Additional investigation is eminent to associate annual F_{Cn} cost and
600 CAPEX to availability and accessibility of the locations. Energy content
601 as expected, is higher for deeper locations, shallower and coastal application

602 are considered to have significant less financial requirements, though more
603 information about the cost associated have to be shared by the community
604 in order to maximise accuracy of calculations.

605 8. Discussion

606   Scotland is exposed to some of the highest wave resources in the world,
607 and is currently considered as one of the most promising region for wave en-
608 ergy applications. Wave energy converters (WECs) are one option to extract
609 energy from waves. During the past years several ideas, configurations of
610 WECs have been proposed with the number ever increasing [32, 33]. While,
611 a higher number of potential WECs can seem as beneficial, for development
612 of the industry, at the same time it is a serious disadvantage for the wave
613 energy industry.
614   In order to allow WECs to be take part in the competitive market of
615 renewable energy, their performance has to be properly assessed and quan-
616 tified. This raises significant issues concerning data availability. To date
617 majority of the wave resource studies for Scotland, are extracted by previous
618 model generation, larger oceanic runs and/or limited duration studies which
619 are not suitable to be used for nearshore quantification [11]. Nearshore wave
620 energy assessments are limited for Scotland, with their absence limiting the
621 energy and cost considerations. Most studies propose the use of Levelised
622 Cost of Electricity (LCOE) for wave energy [87, 88], however the LCOEs
623 estimated are often widely varied and encompass high uncertainties [82].
624 While, uncertainty in capital costs is a factor another higher significance rea-
625 son is often overlooked, the expected energy production. Most studies, use
626 "rule-of-thumbs" coefficient to estimate energy production and thus examine
627 economic parameters. This is highly obvious in the work of Farrell et.al [89]
628 where the large range of LCOE in wave energy is discussed.
629   Estimating wave energy by multiple WECs allows not only to assess and
630 compare performance and adaptability of numerous devices, but also un-
631 derstand the economic implications and payback (amortisation) periods for
632 every choice. While LCOE is a metric, the final decision is the economic
633 survivability of a WEC and its payback periods. This information are often
634 absent, on the reason that wave energy is still in immature stages.
635   To support and enhance energy modelling and economics of wave energy,
636 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

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675 and tides at such depths is expected to alter the final wave energy resource.
676 Such consideration must come at a cost of either regional outreach, accu-
677 racy and computational cost. With no information on the nearshore environ-
678 ment of Scotland, our model offers suitable long-term information of wave
679 power. Identifying "hot-spot" areas which can benefit from future investiga-
680 tions at higher degree.

681 **9. Conclusions**

682 A third generation high-resolution spectral model was used to examine
683 and hindcast the Scottish coastline. Results provided span from 2004 to
684 November 2014, providing one of the most up-to-date studies on the cur-
685 rent wave energy flux and perspectives. The model development and set-up
686 presented fully, while a detail examination and validation.
687 The final maps and overall resource constitutes the latest improvement
688 in wave resource estimation around the region, with model used being highly
689 skilled at coastal location. The mesh resolution used in combination with
690 the extended period, allowed to examined not only very shallow regions but
691 also include in results the intra-annual and decade variation of wave energy.
692 Several locations extracted by the final maps are compared with buoy
693 recordings for separate years examining and discussing the models perfor-
694 mance and limitations. The model has missed extreme storm events, al-
695 though such behaviour expected as stated in previous literature. The annual
696 indices are represented very good by the model, with small biases, even at
697 the occurrence of high storms that are common in the Atlantic areas.
698 Through the validation process, high levels of confidence to the results,
699 allowed for the construction of annual wave energy maps indicating the re-
700 source in coastal locations around Scotland. In accordance with expressed
701 interest by the wave industry and the Crown Estates leases for wave deploy-
702 ments, several locations examined for available wave energy. In addition, the
703 effect of maximum wave resource to potential sites mentioned and assessed,
704 in the form of an index. The WEDI presents not only the opportunities for
705 wave energy but the potential stresses that a device may be exposed to, al-
706 lowing for further additional dissemination of wave energy assessments and
707 adding an informative criterion in the appropriate selection of a wave site.
708 The examination of data presented the annual mean fluctuations of wave
709 energy allowing observations the level of high and low energy content per year
710 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.

10. Acknowledgements

11. References

[1] E. Parliament, The European Parliament. Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources amending and subsequently repealing directives 2001/77/ec and 2003/30/ec., Tech. rep. (2009).

[2] A. M. Cornett, A Global Wave Energy Resource Assessment, Proc. Eighteenth Int. Offshore Polar Eng. Conf. Vancouver,BC,Canada July 6-11 8 (2008) 318–326.

[3] J. Cruz, Ocean Wave Energy: Current Status and Future Perspectives, 2008.

[4] A. Vögler, V. Venugopal, OMAE2012-83658 Hebridean Marine Energy Resources: Wave-Power Characterisation Using a Buoy Network, in: ASME (Ed.), Proc. ASME 2012 31st Int. Conf. Ocean. Offshore Arct. Eng. June10-15,Rio Janeiro, Brazil, Rio de Janeiro, Brazil, 2012, pp. 1–11.

[5] DECC (Department of Energy and Climate Change), Analysis of Renewables Growth to 2020, AEA Gr. Rep. (1).

[6] ORECCA, Off-shore Renewable Energy Conversion platforms Coordination Action (ORECCA) (2015).
URL http://www.orecca.eu/web/guest

[7] EMEC, Assessment of Performance of Wave Energy Conversion Systems, Marine Renewable Energy Guide (2009) 1–28.

[8] S. Caires, A. Sterl, 100-year return value estimates for ocean wind speed and significant wave height from the ERA-40 data, J. Clim. 18 (7) (2005) 1032–1048. doi:10.1175/JCLI-3312.1.

[9] A. Sterl, S. Caires, Climatology, variability and extrema of ocean waves: The web-based KNMI/ERA-40 wave atlas, Int. J. Climatol. 25 (7) (2005) 963–977. doi:10.1002/joc.1175.

[10] A. Agarwal, A long-term analysis of the wave climate in the North East Atlantic and North Sea, Ph.d thesis, University of Edinburgh, Edinburgh (2015).

[11] S. P. Neill, M. R. Hashemi, Wave power variability over the northwest European shelf seas, Appl. Energy 106 (2013) 31–46. doi:10.1016/j.apenergy.2013.01.026.

[12] MER, WEBvision - Renewable (wave) (2014).
URL http://vision.abpmer.net/renewables/

[13] D. Ingram, G. Smith, C. Bittencourt-Ferreira, H. Smith, EquiMar: Protocols for the Equitable Assessment of Marine Energy Converters, no. 213380, 2011. doi:978-0-9508920-3-0.

[14] H. Smith, Best Practice Guidelines for Wave and Current Resource Assessment Task 1 . 6 of WP3 from the MERiFIC Project A report prepared as part of the MERiFIC Project " Marine Energy in Far Peripheral and Island Communities " (June) (2014) 1–16.

[15] L. Cavaleri, Wave Modeling-Missing the Peaks, J. Phys. Oceanogr. 39 (11) (2009) 2757–2778. doi:10.1175/2009JPO4067.1.

[16] L. Bertotti, J.-R. Bidlot, C. Bunney, L. Cavaleri, L. Delli Passeri, M. Gomez, J.-M. Lefèvre, T. Paccagnella, L. Torrisi, A. Valentini, A. Vocino, Performance of different forecast systems in an exceptional storm

in the Western Mediterranean Sea, Q. J. R. Meteorol. Soc. 138 (662) (2012) 34–55. doi:10.1002/qj.892.

[17] L. Bertotti, L. Cavaleri, Wind and wave predictions in the Adriatic Sea, J. Mar. Syst. 78 (2009) S227–S234. doi:10.1016/j.jmarsys.2009.01.018.

[18] T. Soukissian, N. Gizari, D. Fytilis, A. Papadopoulos, G. Korres, A. Prospathopoulos, Wind and Wave Potential in Offshore Locations of the Greek Seas, in: Proc. Twenty-second Int. Offshore Polar Eng. Conf. June 17-22, Vol. 4, 2012, pp. 525–532.

[19] D. Peres, C. Iuppa, L. Cavallaro, A. Cancelliere, E. Foti, Significant wave height record extension by neural networks and reanalysis wind data, Ocean Model. 94 (2015) 128–140. doi:10.1016/j.ocemod.2015.08.002.

[20] G. Lavidas, V. Venugopal, Influence of Computational Domain Size on Wave Energy Assessments in Energetic Waters, in: Proc. 11th Eur. Wave Tidal Energy Conf. 6-11th Sept 2015, Nantes, Fr., EWTEC, Nantes, 2015, pp. 1–8.

[21] G. Lavidas, V. Venugopal, D. Friedrich, Sensitivity of a numerical wave model on wind re-analysis datasets, Dynamics of Atmospheres and Oceans 77 (2017) 1 – 16. doi:10.1016/j.dynatmoce.2016.10.007.

[22] K. Gunn, C. Stock-Williams, Quantifying the global wave power resource, Renew. Energy 44 (2012) 296–304. doi:10.1016/j.renene.2012.01.101.

[23] S. Barstow, G. Mørk, L. Lønseth, J. P. Mathisen, WorldWaves wave energy resource assessments from the deep ocean to the coast, Fugro Ocean. AS (2009) 149–159.

[24] B. G. Reguero, M. Menéndez, F. J. Méndez, R. Mínguez, I. J. Losada, A Global Ocean Wave (GOW) calibrated reanalysis from 1948 onwards, Coast. Eng. 65 (2012) 38–55. doi:10.1016/j.coastaleng.2012.03.003.

[25] S. Gallagher, R. Tiron, F. Dias, OMAE2013-10719 A detailed investigation of the nearshore wave climate and the nearshore wave energy

804   resource on the west coast of Ireland, in: ASME 2013 32nd Int. Conf.
805   Ocean. Offshore Arct. Eng. OMAE2013, June 9-14, Nantes,France, 2013,
806   pp. 1–12.

807 [26] V. Venugopal, R. Nemalidinne, Wave resource assessment for Scottish
808   waters using a large scale North Atlantic spectral wave model, Renew.
809   Energy 76 (2015) 503–525. doi:10.1016/j.renene.2014.11.056.

810 [27] G. Wood, S. Dow, What lessons have been learned in reforming the
811   Renewables Obligation? An analysis of internal and external failures in
812   UK renewable energy policy, Energy Policy 39 (5) (2011) 2228–2244.
813   doi:10.1016/j.enpol.2010.11.012.

814 [28] Carbon Trust, AMEC, Carbon Trust Foreword to UK Wave Resource
815   Study ., Tech. Rep. October (2012).

816 [29] F. Hervás Soriano, F. Mulatero, EU Research and Innovation (R&I) in
817   renewable energies: The role of the Strategic Energy Technology Plan
818   (SET-Plan), Energy Policy 39 (6) (2011) 3582–3590. doi:10.1016/j.
819   enpol.2011.03.059.

820 [30] J. Tipping, The benefits of marine technologies within a diversified re-
821   newables mix. A report for the British Wind Energy Association, Tech.
822   rep., Redpoint Energy Ltd. (2009).

823 [31] J. Taylor, R. Wallace, J. Bialek, Matching Renewable Electricity Gen-
824   eration with Demand, Scottish Exec. (February).

825 [32] A. F. D. O. Falcão, Wave energy utilization: A review of the tech-
826   nologies, Renew. Sustain. Energy Rev. 14 (3) (2010) 899–918. doi:
827   10.1016/j.rser.2009.11.003.

828 [33] A. Babarit, J. Hals, M. Muliawan, A. Kurniawan, T. Moan, J. Krokstad,
829   Numerical benchmarking study of a selection of wave energy converters,
830   Renew. Energy 41 (2012) 44–63. doi:10.1016/j.renene.2011.10.002.

831 [34] ECMWF, ERA Interim (2014).
832   URL http://www.ecmwf.int/

833 [35] E. B. Mackay, A. S. Bahaj, P. G. Challenor, Uncertainty in wave energy
834   resource assessment. Part 2: Variability and predictability, Renew. En-
835   ergy 35 (8) (2010) 1809–1819. doi:10.1016/j.renene.2009.10.027.

836 [36] CrownEstates, The Crown Estates-Energy and Infrastructure (2014).
837   URL http://www.thecrownestate.co.uk/energy-infrastructure/

838 [37] A. Sterl, G. J. Komen, P. D. Cotton, Fifteen years of global wave hind-
839   casts using winds from the European Centre for Medium-Range Weather
840   Forecasts reanalysis: Validating the reanalyzed winds and assessing the
841   wave climate, J. Geophys. Res. 103 (1998) 5477–5492.

842 [38] C. E. Greenwood, V. Venugopal, D. Christie, J. Morrison, A. Vogler,
843   OMAE2013-11356 Wave modelling for potential wave energy sites
844   around the outer Hebrides, in: ASME 2013 32nd Int. Conf. Ocean.
845   Offshore Arct. Eng. OMAE2013, June 9-14, Nantes,France, 2013, pp.
846   1–9.

847 [39] P. Gleizon, Modelling wave energy in archipelagos-case of northern scot-
848   land, in: EIMR2014-968, no. May, 2014, pp. 1–4.

849 [40] P. Gleizon, F. J. Campuzano, P. C. García, B. Gomez, A. Martinez,
850   Wave energy mapping along the European Atlantic coast, in: Proc. 11th
851   Eur. Wave Tidal Energy Conf. 6-11th Sept 2015, Nantes, Fr., 2015, pp.
852   1–9.

853 [41] T. Delft, Scientific and technical documentation SWAN cycle III version
854   40.91ABC, 2013.
855   URL http://swanmodel.sourceforge.net/

856 [42] C. Amante, B. Eakins, ETOPO1 1 Arc-Minute Global Relief Model:
857   Procedures, Data Sources and Analysis. NOAA Technical Memorandum
858   NESDIS NGDC-24 (2014).
859   URL http://maps.ngdc.noaa.gov/viewers/wcs-client/

860 [43] D. P. Dee, S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli,
861   S. Kobayashi, U. Andrae, M. A. Balmaseda, G. Balsamo, P. Bauer,
862   P. Bechtold, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann,
863   C. Delsol, R. Dragani, M. Fuentes, A. J. Geer, L. Haimberger, S. B.
864   Healy, H. Hersbach, E. V. Holm, L. Isaksen, P. Kallberg, M. Kohler,
865   M. Matricardi, A. P. Mcnally, B. M. Monge-Sanz, J. J. Morcrette, B. K.
866   Park, C. Peubey, P. de Rosnay, C. Tavolato, J. N. Thepaut, F. Vitart,
867   The ERA-Interim reanalysis: Configuration and performance of the data

868   assimilation system, Q. J. R. Meteorol. Soc. 137 (656) (2011) 553–597.
869   doi:10.1002/qj.828.

870 [44] P. A. Janssen, Quasi-Linear theory of Wind-Wave Generation applied
871   to wave forecasting, J. Phys. Oceanogr. 6 (1991) 1631–1642.

872 [45] G. van Vledder, M. Zijlema, L. Holthuijsen, Revisiting the JONSWAP
873   bottom friction formulation, in: Proc. 32nd Conf. Coast. Eng. Shanghai,
874   China, 2010, Proceedings of the International Conference on Coastal
875   Engineering; No 32, 2010, pp. 1–8.

876 [46] Center for environment fisheries & aquaculture science.
877   URL http://www.cefas.defra.gov.uk/home.aspx

878 [47] T. Delft, User manual SWAN Cycle III version 40.91ABC, Delft
879   University of Technology Faculty of Civil Engineering and Geosciences
880   Environmental Fluid Mechanics Section, 2013.
881   URL   http://www.fluidmechanics.tudelft.nl/swan/index.
882   htmhttp://www.fluidmechanics.tu

883 [48] A. W. Ratsimandresy, M. G. Sotillo, J. C. Carretero Albiach, E. Álvarez
884   Fanjul, H. Hajji, A 44-year high-resolution ocean and atmospheric
885   hindcast for the Mediterranean Basin developed within the HIPOCAS
886   Project, Coast. Eng. 55 (11) (2008) 827–842.   doi:10.1016/j.
887   coastaleng.2008.02.025.

888 [49] P. Pilar, C. G. Soares, J. C. Carretero, 44-year wave hindcast for the
889   North East Atlantic European coast, Coast. Eng. 55 (11) (2008) 861–
890   871. doi:10.1016/j.coastaleng.2008.02.027.

891 [50] B. Cañellas, A. Orfila, F. Méndez, M. Menéndez, J. Tintoré, Application
892   of a POT model to estimate the extreme significant wave height levels
893   around the Balearic Sea (Western Mediterranean), J. Coast. Res. Spec.
894   Issue 50 (50) (2007) 329–333.
895   URL   http://costabalearsostenible.com/PDFs/
896   ICS2007{_}final3{_}.pdf

897 [51] A. Akpinar, M. . Kömürcü, Assessment of wave energy resource of the
898   Black Sea based on 15-year numerical hindcast data, Appl. Energy 101
899   (2013) 502–512. doi:10.1016/j.apenergy.2012.06.005.

[52] G. P. Van Vledder, A. Akpinar, Wave model predictions in the Black Sea: Sensitivity to wind fields, Appl. Ocean Res. 53 (2015) 161–178. doi:10.1016/j.apor.2015.08.006.
URL http://linkinghub.elsevier.com/retrieve/pii/S0141118715001121

[53] J. E. Stopa, K. F. Cheung, Intercomparison of wind and wave data from the ECMWF Reanalysis Interim and the NCEP Climate Forecast System Reanalysis, Ocean Model. 75 (2014) 65–83. doi:10.1016/j.ocemod.2013.12.006.
URL http://linkinghub.elsevier.com/retrieve/pii/S1463500313002205

[54] V. Venugopal, T. Davey, F. Girard, H. Smith, L. Cavaleri, L. Bertotti, S. Mauro, Equitable testing and evaluation of Marine Energy Extraction Devices of Performance, Cost and Environmental Impact. Deliverable 2.4 Wave Model Intercomparison, Tech. rep. (2011).

[55] J. van Os, S. Caires, M. Gent, How to Carry Out Metocean Studies, Proc. Twenty-first Int. Offshore Polar Eng. Conf. 19-14 8 (2011) 290–297. doi:10.1115/OMAE2011-49066.

[56] G. Hagerman, Southern New England Wave Energy Resource Potential, in: Build. Energy, no. March, 2001.

[57] M. Saglam, E. Sulukan, T. S. Uyar, Wave Energy and Technical potential of Turkey, J. Nav. Sci. Eng. 6 (2) (2010) 34–50.

[58] A. Akpinar, G. P. van Vledder, M. . Kömürcü, M. Özger, Evaluation of the numerical wave model (SWAN) for wave simulation in the Black Sea, Cont. Shelf Res. 50-51 (2012) 80–99. doi:10.1016/j.csr.2012.09.012.

[59] D. Silva, E. Rusu, C. G. Soares, Evaluation of various technologies for wave energy conversion in the portuguese nearshore, Energies 6 (2013) 1344–1364. doi:10.3390/en6031344.

[60] L. Rusu, F. Onea, Assessment of the performances of various wave energy converters along the European continental coasts, Energy 82 (2015) 889–904. doi:10.1016/j.energy.2015.01.099.

932   URL   http://linkinghub.elsevier.com/retrieve/pii/
933   S0360544215001231

934 [61] WaveStar, WaveStar (2015).
935   URL http://wavestarenergy.com/

936 [62] F. Fusco, G. Nolan, J. V. Ringwood, Variability reduction through op-
937   timal combination of wind/wave resources-An Irish case study, Energy
938   35 (1) (2010) 314–325. doi:10.1016/j.energy.2009.09.023.

939 [63] A. Babarit, A database of capture width ratio of wave energy converters,
940   Renew. Energy 80 (2015) 610–628. doi:10.1016/j.renene.2015.02.
941   049.

942 [64] E. Rusu, C. Guedes Soares, Numerical modelling to estimate the spatial
943   distribution of the wave energy in the Portuguese nearshore, Renew. En-
944   ergy 34 (6) (2009) 1501–1516. doi:10.1016/j.renene.2008.10.027.
945   URL   http://linkinghub.elsevier.com/retrieve/pii/
946   S0960148108003935

947 [65] R. H. Hansen, M. M. Kramer, Modelling and Control of the Wavestar
948   Prototype, Proc. 9th Eur. Wave Tidal Energy Conf. (2011) 1–10.

949 [66] G. J. Dalton, R. Alcorn, T. Lewis, Case study feasibility analysis of the
950   Pelamis wave energy convertor in Ireland, Portugal and North America,
951   Renew. Energy 35 (2) (2010) 443–455. doi:10.1016/j.renene.2009.
952   07.003.

953 [67] F. Sharkey, E. Bannon, M. Conlon, K. Gaughan, Dynamic Electrical
954   Ratings and the Economics of Capacity Factor for Wave Energy Con-
955   verter Arrays, Proc. 9th Eur. Wave Tidal Energy Conf. (2011) 1–8.

956 [68] D. Dunnett, J. S. Wallace, Electricity generation from wave power in
957   Canada, Renew. Energy 34 (2009) 179–195. doi:10.1016/j.renene.
958   2008.04.034.

959 [69] M. O'Connor, T. Lewis, G. Dalton, Techno-economic performance of
960   the Pelamis P1 and Wavestar at different ratings and various locations
961   in Europe, Renew. Energy 50 (2013) 889–900. doi:10.1016/j.renene.
962   2012.08.009.

[70] R. Carballo, G. Iglesias, A methodology to determine the power performance of wave energy converters at a particular coastal location, Energy Convers. Manag. 61 (2012) 8–18. doi:10.1016/j.enconman.2012.03.008.

[71] J. Manwell, J. McGowan, A. Rogers, Wind Energy Explained: Theory, Design and Application, 2nd Edition, John Wiley & Sons Ltd., 2009.

[72] M. Sathyajith, Wind Energy Fundamentals,Resource Analysis and Economics, Springer-Verlag Berlin Heidelberg, 2006.

[73] J. Kaldellis, Stand-alone and hybrid wind energy systems: technology, energy storage and applications, woodhead p Edition, Woodhead Ltd., 2010.

[74] S. Bozzi, P. Milano, G. Passoni, MEDITERRANEAN SEA : COMPARISON AMONG DIFFERENT TECHNOLOGIES, in: ASME 2011 30th Int. Conf. Ocean. Offshore Arct. Eng. Vol. 5 Ocean Sp. Util. Ocean Renew. Energy Rotterdam, Netherlands, June 1924, 2011, 2011, pp. 1–6. doi:978-0-7918-4437-3.

[75] Energy Information Administation Agency U.S, Annual Energy Outlook 2014 (2014).
URL http://www.eia.gov/forecasts/aeo/electricity{_}generation.cfm

[76] E. D. Stoutenburg, N. Jenkins, M. Z. Jacobson, Power output variations of co-located offshore wind turbines and wave energy converters in California, Renew. Energy 35 (12) (2010) 2781–2791. doi:10.1016/j.renene.2010.04.033.

[77] J. P. Sierra, C. Mosso, M. Mestres, D. González-Marco, M. Grino, Assessment of the Wave Energy Resource around the Ria de Vigo (NW Spain), in: Proc. 11th Eur. Wave Tidal Energy Conf. 6-11th Sept 2015, Nantes, Fr., 2015, pp. 1–7.

[78] N. D. Rafferty, Renewable Obligation (Scotland) Statuatory Consultation, Tech. Rep. September, Renewables and Consents Policy Unit, Glasgow (2008).

[79] DTI, Quantifying the system cost of additional renewables in 2020, Tech. rep. (2002).

[80] G. Allan, M. Gilmartin, P. McGregor, K. Swales, Levelised costs of Wave and Tidal energy in the UK: Cost competitiveness and the importance of "banded" renewables obligation certificates, Energy Policy 39 (1) (2011) 23–39. doi:10.1016/j.enpol.2010.08.029.

[81] A. D. Andrés, A. Macgillivray, R. Guanche, H. Jeffrey, Factors affecting LCOE of Ocean energy technologies : a study of technology and deployment attractiveness, in: 5th Int. Conf. Ocean Energy, Halifax Factors, 2014, pp. 1–11.

[82] S. Astariz, G. Iglesias, The economics of wave energy: A review, Renew. Sustain. Energy Rev. 45 (2015) 397–408. doi:10.1016/j.rser.2015.01.061.

[83] OES, Annual Report Implementing Agreement on Ocean Energy Systems, Tech. rep. (2014). doi:10.1017/S0001972000001765.
URL http://www.ocean-energy-systems.org/

[84] J. Kaldellis, Stand-alone and hybrid wind energy systems.Technology, energy storage and applications, Woodhead Publishing Limited, Great Abington, Cambridge CB21 6AH, UK, 2011.

[85] D. Magagna, A. Uihlein, Ocean energy development in Europe: Current status and future perspectives, Int. J. Mar. Energy 11 (2015) 84–104. doi:10.1016/j.ijome.2015.05.001.

[86] D. Zafirakis, K. Chalvatzis, J. Kaldellis, "Socially just" support mechanisms for the promotion of renewable energy sources in Greece, Renew. Sustain. Energy Rev. 21 (2013) 478–493. doi:10.1016/j.rser.2012.12.030.

[87] Ocean Energy: Cost of Energy and Cost Reduction Opportunities, Tech. Rep. May (2013).
URL http://si-ocean.eu/en/upload/docs/WP3/CoEreport3{_}2final.pdf

[88] OES, International Levelised Cost Of Energy for Ocean Energy Technologies, Tech. Rep. May (2015).

1026 [89] N. Farrell, C. O. Donoghue, K. Morrissey, Quantifying the un-
1027   certainty of wave energy conversion device cost for policy ap-
1028   praisal: An Irish case study, Energy Policy 78 (2015) 62–77.
1029   doi:10.1016/j.enpol.2014.11.029.
1030   URL   http://www.sciencedirect.com/science/article/pii/
1031   S0301421514006375

1032 [90] E. Rusu, F. Onea, Estimation of the wave energy conversion efficiency
1033   in the Atlantic Ocean close to the European islands, Renew. Energy 85
1034   (2016) 687–703. doi:10.1016/j.renene.2015.07.042.