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Wave energy extraction in Scotland through an improved nearshore Wave Atlas

George Lavidas^a, Vengatesan Venugopal^a, Daniel Friedrich^a

^a*The University of Edinburgh, Institute for Energy Systems, Faraday Building, King's Buildings, Colin MacLaurin Road, Edinburgh, EH9 3DW*

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 CO₂ and Green-House-Gases (GHG) [1]. Waves offer an abundant high energy density resource

*Corresponding author

Email address: G.Lavidas@ed.ac.uk (George Lavidas)

6 accessible by most countries in Europe. Though, energy levels and incom-
7 ing fluxes differ from country to country, the opportunities for significant
8 contribution to RE targets and energy independence are obvious.

9 United Kingdom (UK) and especially Scotland are exposed to some of
10 the most energetic waters in Europe with average annual resource exceeding
11 60-70 kW/m at mid-depth locations [2, 3]. While this is encouraging coastal
12 and more accessible resources are not always the same with different physical
13 terms affecting the final content. Gathering wave data is a cumbersome
14 process, which often does not allow overall estimation on the energy content
15 of an area. Buoy data have been used throughout the years for assessment
16 of the wave climate and lately of wave energy characterization [4]. This
17 however is not always feasible, since scarcity of buoys and lack of a long-
18 term monitoring installations do not allow long-term examination of the wave
19 climate and often coastal locations are overlooked.

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

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

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

41 The ABP MER [12] map has a very coarse resolution of $0.25^\circ \times 0.25^\circ$ (not
42 able to represent coastal locations), low number of frequency bins (13) and
43 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,

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.

95 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].

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

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

118 Initial conditions include set of direction and frequencies, minimum period
119 considered was 2 sec and maximum 24 sec with a logarithmic increment of
120 1.1, and the 25 directional bins. The wind generation is based and adapted
121 on Janssen’s [44] quasi theory with adjusted whitecapping coefficient and
122 diffusion scheme. Bottom friction uses the revised proposed approximation
123 of van Vledder et.al [45] with triads, refraction, diffraction also activated.
124 The quadruplet interactions are resolved as according to Discrete Interaction
125 Approximation (DIA) with a fully explicit solution per sweep of source terms
126 within the mesh.

127 The information of wind and boundary are given to the model and are
128 computed across the given domain shown in Fig.2, the domain size is 10° lon-
129 gitude and 6° latitude, which constitute nearly 100,000 points for which the
130 action balance is to be resolved at every timestep. The overall computational
131 requirements took over 30 days, thus use of the high performance comput-
132 ing facility of the Edinburgh University was necessary (EDDIE-ECDF) to
133 facilitate the run.

134 The outputs considered involve locations both at mid-depth for which
135 buoys are available by CEFAS [46], with additional multiple coastal nearshore
136 locations of wave energy interest. The point outputs are recorded every 30
137 minutes, while the overall mesh information was recorded every 3 hours due
138 to storage considerations and restrictions.

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

139 3. Validation of the model

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

146 Buoy data obtained by CEFAS [46] are used for model calibration and
 147 validation, it has to be noted that not all years have recordings. The locations which correspond to buoy are denoted as CEFAS, while additional
 148

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

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

170 over very high waves, and over-estimations at low wave heights [15, 51]. It has
171 been also suggested that the temporal resolution of wind affects the hindcast,
172 implying that a higher temporal resolution may increase the performance.
173 Such an analysis concerning two wind products and our domain can be found
174 in Lavidas et.al. [21], as well other recent studies which evaluated wave
175 hindcasts driven by different wind van Vledder et.al. [52].

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

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

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

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

203 4. Resource assessment

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

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:

$$T_e = \frac{m_{-1}}{m_0} \quad (1)$$

212 With $m_0, \dots, m_n$ denoting the n^{th} moment of the wave spectrum. For these
213 kind of locations and due to the fact that investigation is expressed for coastal

214 waters, the non-linear formulation of wave energy calculation is considered,
 215 representing wave energy for coastal locations as [54]. The energy contained
 216 within waves expressed, in W/m , which corresponds to the energy per crest
 217 unit length. In SWAN energy components are computed with a formulation
 218 appropriate for the realist representation of resource. Over the summation
 219 of very different wave numbers frequencies (f) and directions (θ).

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

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

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

$$P_{wave} = \sqrt{P_x^2 + P_y^2} \quad (4)$$

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

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

236 Recent studies with the same model were used by Neill et.al [11] and
 237 Gleizon et.al [39], although the first was using a nested scheme of several
 238 areas around the UK and was run for 7 years, while the latter used a small
 239 unstructured mesh approach for only the Isle of Lewis for one year. In order
 240 to evaluate the resource and assess additional climatological and extreme
 241 value indices a minimum duration of 10 years has been proposed [13, 14],
 242 this allows not only to examine a long trend series but also reveals any

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 ≈ 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

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

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

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

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

272 5. Wave Energy Development Index (WEDI)

273 Assessment tools for the level of severity at each location can be and ex-
 274 treme value analysis (EVA) and/or the corresponding Wave Energy Develop-

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.

$$WEDI = \frac{\overline{P_{wave}}}{J_{wave}} \quad (5)$$

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

Figure 9: WEDI annual examination for the multiple locations

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-

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

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 $\approx 30\text{kW/m}$ (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

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

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

$$E_o = P_o \times \Delta T \times CF \quad (7)$$

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

380 Four devices representing different PTO principals are selected, a floating
 381 two-body heaving (F2BH) converter similar to WaveBob [33]. A bottom
 382 fixed heave buoy with multiple arrays the WaveStar [61], a bottom fixed
 383 oscillating flap (BFXF) with close resemblance and inspired by the Oyster
 384 [33], and the attenuator of Pelamis [59, 62]. A more thorough look into
 385 the numerical methods of estimating the devices individual performance and
 386 power matrices can be found in [33, 63]. The matrices used are available from
 387 studies and published documentations [64, 33, 65, 66, 67, 68, 69, 70]. Each
 388 device taken into account uses its given power matrix, and only one device
 389 is considered as installed, meaning that the nominal installed capacity of
 390 each device corresponds to the nominal capacity given by the manufacturer
 391 and/or the representative power matrix in kW, see Fig.12-15.

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

403 a year, is able to provide us with a very close to reality approximation of ex-
404 pected production in the absence of information [71, 72, 73]. Use of the term
405 is utilized in numerical estimations on energy economics, energy production
406 assessment and provides the basis for a normalization and even comparison
407 of technologies. The CF is dependent on the total energy production and the
408 rated installed capacity, thus if a device achieves high utilization rates in a
409 year, with a smaller installed capacity then it has a higher the CF.

410 Indicative values in CF per technology are used by institutes, agencies for
411 calculations of energy productions in a location and economics [69, 74, 66, 75].
412 Concerning wave energy some studies have mentioned the use of proposed
413 CF numbers but based on limited amount of data or expected assumptions
414 [69, 76, 60, 77].

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

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

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

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 intermediate 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

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 $\leq$ 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-

495 ognize that the attenuator (Pelamis) option may not be applicable in Point
496 1, although a scaled down device in terms of dimension would expect to yield
497 similar capacity factors though different energy yields (reduced).

498 **7. Economic considerations**

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

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

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

524 Lifetime operation of the wave farm is 20 years, similar to other renewable
525 technologies such as wind and solar. Variable operational costs (VOC) have
526 not been included, due to limited information existing on the rate of failure
527 WECs. WEDI is taken into account as a factor increasing CAPEX, this will
528 be exhibited in the initial values for the economic estimation. The approach
529 used, based on a cumulative and present market values takes into account
530 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 £/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 £/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 .

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

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.

$$FC_n = m_{cost} \times I_{Co} \times \left[\frac{1+g}{1+i} + \dots + \left(\frac{1+g}{1+i} \right)^n \right] \quad (9)$$

$$C_n = I_{Co} + FC_n \quad (10)$$

546 As discussed new FITs and CfDs are not established, while suggestions
547 state the expected values are to range from 200-220 £/MWs for Ireland
548 [66]. O'Connor et.al. [69] explored a 330£/MWh financial scheme, the
549 authors chose to use an FIT of 200£/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.

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

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

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

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

637 of the primary modelling work must be adjusted, to provide accurate cal-
638 ibrated/validated data for energy applications. In this study a nearshore
639 model was used to estimate the metocean conditions in the highly energetic
640 coastlines of Scotland. The ability of the model to resolve nearshore mechan-
641 ics and the long duration of the hindcast allows robust energy estimates. To
642 date there is no long-term (≥ 10 years) conforming with suggested protocols
643 and practises [13].

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

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

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

672 While our model shows very good agreement with buoy data, improving
673 the knowledge for the area, much smaller isolated studies are necessary espe-
674 cially for devices that are intended for depths ≤ 20 m. Interaction of currents

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

711 assessed, with findings prompting site considerations. Preliminary financial
712 estimations display not only the energy viability of wave farms as investments
713 but also the financial opportunities that exist within the industry. Further
714 study of additional national plans of wave energy will benefit the policy
715 decision-making process. However, this should always be performed with
716 engineering considerations, improvements, and restrictions.

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