ANNEX II
Task 1.1 Generic and Site-related Wave Energy Data
September 2010

A report prepared by the RAMBOLL and LNEG to the OES-IA under the Annex II – Guidelines for Development and Testing of Ocean Energy Systems

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Generic and Site-related Wave Energy Data
Final Technical Report
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Author(s)

Kim Nielsen
Ramboll, Denmark
&
Teresa Pontes
LNEG, Portugal

Customer

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Annex II Task 1.1
Generic and Site-related Wave Energy Data

Kim Nielsen, Ramboll & Teresa Pontes, LNEG
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1 Introduction

The first part of Annex II was completed in 2003(1), focussing on tank test facilities and methodologies for testing wave power systems in model scales. In 2007 Annex II was extended to focus on guidelines for open sea testing of wave energy converters.

Task 1.1 of the extended Annex II proposes wave data to be used as reference data for preliminary evaluation and economic assessment of wave energy converters. Locations are chosen in the northern, middle and southern parts of the North-eastern Atlantic Ocean, as well as the fetch-limited North Sea. The offshore data presented will provide an upper estimate of the energy that can be produced in these areas compared to near shore data at specific locations, where directionality needs to be taken into account. However, the chosen data reflect different ocean conditions, which are seen from the presented bi-variate distributions of significant wave height (H_s) and energy period (T_e).

Guidelines for site-specific data that will enable designers to evaluate the dimensions and resources at a specific test site are given.

Examples of available data relating to selected test sites for testing Wave Power Converters are provided. Each site has different information available, which is presented in different formats.

The study has its main focus and most examples from Europe, but the methodology presented can be applied to any ocean area of the world.

2 Acknowledgement

The authors gratefully acknowledge the discussions and input from Fred Gardner, Jens Peter Kofoed, Jose Luis Villate Martinez, Tony Lewis and his team and Tom Denniss, as well as the financial contribution from the Danish Energy Agency, Ramboll and LNEG.

3 Generic and Site Specific Wave Energy Data

3.1 The Global Wave Energy Resource

Wave energy is a global resource as shown on the world map in Figure 1. The annual power levels range from 5kW/m in sheltered and closed seas and in tropical regions - to more than 60 kW/m in oceanic areas, such as found in the northern and southern hemispheres. The map shows that the oceans are most energetic at latitudes at about 50-60 deg. The blue and green colours indicate power levels below 20 kW/m and the yellow, red and brown colours indicate power levels above 20 kW/m up to more than 60 kW/m.

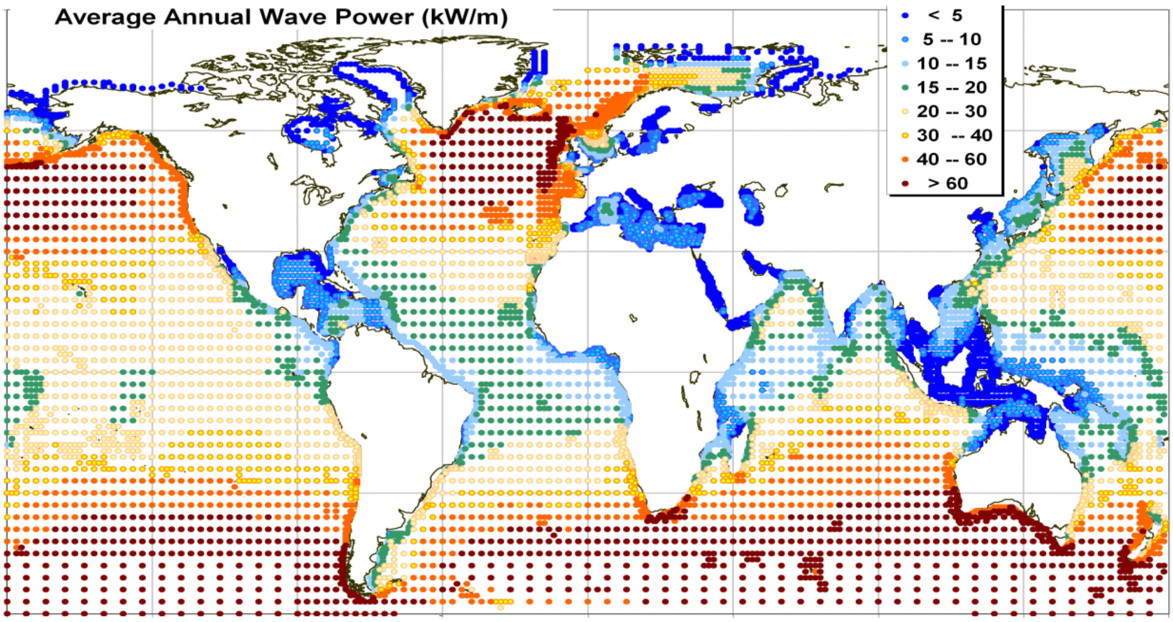


Figure 1 Ocean Wave Energy resource indicated in kW/m "The data originate from the ECMWF (European Centre for Medium-Range Weather Forecasts) WAM model archive and are calibrated and corrected (by OCEANOR) against a global buoy and Topex satellite altimeter database."

The highest power levels more than 60 kW/m are found offshore along the coastlines of southern Chile, Africa, Australia, New Zealand, Northwest Canada, west of Scotland (UK) and Ireland.

The data presented on Figure 1 are based on 10-year / 6-hourly time-series of wave energy at each point, the model data being validated and calibrated against 10 years of Topex satellite altimeter data for each point, as well as buoy data where available. The points are all offshore and do not reflect the coastal wave climate, which will normally be very different due to various shallow water effects and coastal sheltering. Different software can be used to derive the near shore wave climate from open-ocean, e.g., the Worldwaves package, as well as various shallow-water models such as the SWAN model.

In addition to wave power levels, other design criteria are important such as the maximum wave height, design current and wind velocity, the intervals between storms (for maintenance and installation), the water depth and water level variations from tidal action and storm surges and the distance to the coast and infrastructure for installation of devices and power transmission.

Information such as seasonal wave power maps (variation of energy through the year) and maps of the ratio of average wave height (this is indicative of the income from a wave power device) and the extreme wave height (indicating the design costs for the wave power plant - or the expenditure) can be obtained from the database. The areas of the world with a good stable resource and low extremes can also be pinpointed using the global database WorldWaves data/OCEANOR/ECMWF.

3.2 The Nature of Wind-Generated Ocean Waves

Ocean waves are generated by winds blowing over its surface. If the wind is blowing from the shore, one will observe that initially waves are just ripples; with a trained eye from the ripples you can assess the strength and direction of the wind.

Imagine you sit in a boat drifting with the wind further and further to shore. You will observe that the waves are growing in height and length; short waves break as they become too steep and form longer waves that travel faster. After drifting to a certain distance (fetch) the waves do not become larger – they have reached equilibrium with the wind speed and the sea is said to be “fully developed”.

The Energy Spectrum of fully developed sea was proposed by Pierson & Moskowitz(2) expressed by the wind speed (U). measured 19.5 metres above the sea level as:

$$S(f,U) = \frac{\alpha}{(2\pi^4)} g^2 f^{-5} e^{-\beta\left(\frac{f(U)o}{f}\right)^4} \tag{1}$$

where the constants involved are

$$\alpha = 0{,}0081$$
$$\beta = 0{,}74$$
$$f(U)_0 = \frac{g}{2\pi U}$$

Later variations of this spectrum have been used to describe the energy distribution in frequency in an irregular sea surface. Also spreading functions $f(\theta)$ have been proposed.

$$S(f,\theta) = S(f) * f(\theta) \tag{2}$$

More information on the spectra and their derivatives can be found in the Annex II report from 2003, (1).

For practical purposes, the sea state is characterized by the energy period T_e and the significant wave height H_s and the mean direction of propagation.

In deep water, the global power level (from all directions) of a sea state is given by:

$$Pw(H_s, T_e) = \frac{\rho g^2}{64\pi} H_s^2 T_e \cong 0{,}49 H_s^2 T_e \tag{3}$$

P_w is expressed in (kW/m) if the significant wave height (H_s) is expressed in metres and the energy period (T_e) in seconds.

Table 1 below indicates at different wind speeds the corresponding significant wave height, periods and power levels for fully developed seas, as well as the minimum fetch and duration required to generate fully developed seas. For comparison the distance across the North Sea from west coast of Denmark to the east coast of the UK is about 600 km.

Table 1 - Values of Wave Integral Parameters for Fully Developed Seas

Wind speed (m/s)	5	7,5	10	12,5	15
Minimum duration [hours]	2,4	6	10	15	20
Min Fetch [km]	19	62	138	269	458
H_s (m)	0,5	1,2	2,1	3,3	4,8
T_z (s)	2,6	3,9	5,2	6,5	7,8
T_e (s)	3,1	4,7	6,3	7,9	9,4
T_p (s)	3,6	5,5	7,3	9,1	10,9
P_w (kW/m)	0,4	3,2	13,1	41,2	103,2

Various wave period parameters are used in addition to the energy period T_e. The most traditional one is the zero crossing period T_z (or T_{02} when computed from wave spectra) and also peak period T_p (period with maximum spectral energy) is sometimes used. Depending on the spectral shape different relations are found between T_p, T_z and T_e.

The following relations can be used to compute T_e from the two other period parameters assuming the Pierson-Moskowitz spectral shape

$T_e = 1,2\ T_z$
$T_e = 0,857\ T_p$

4 Generic Ocean Wave Data

Generic wave data for wave energy systems evaluation was discussed in the first Workshop of the CA-OE project (Coordinated Action on Ocean Energy, EC Contract Contract N°: 502701, 2004-2007) in Aalborg in March 2005. Teamwork Technology presented the wave data information from WERATLAS(3) and showed how four different zones could be defined. The generic scatter diagrams are described in the paper presented at the 6th EWTEC conference in Glasgow in 2006(4).

It appears that there are specific trends in terms of the energy content in the waves and typical annual distribution of T_e and H_s in different areas of the North-eastern Atlantic.

The wave energy resource is generated by the wind and the wind fields are related to the depressions passing from west to east. Ireland and the UK are more frequently hit by strong depressions compared to more southern regions like Portugal. To illustrate the trends four different locations have been chosen as illustrated on the Google map below.

The locations are:
1. **North-eastern North Atlantic**, Norwegian Sea, Haltenbanken, Norway, 42 kW/m
2. Fetch limited conditions as in the **North Sea**, AUK, 20 kW/m
3. **North-eastern Central Atlantic** conditions Belmullet, Ireland, 72 kW/m
4. **South Atlantic** conditions illustrated by Lisboa, PT, 37 kW/m

Figure 2 The four locations chosen in order to show generic trends in the distribution of sea states and their Wave Energy contribution.

The highest average power level is found in the Atlantic Ocean west of Ireland and off Scotland (UK), it being higher than 70 kW/m. In the most northern and southern European Atlantic sites, power levels are found to be of similar magnitude (around 40 kW/m). However, the distribution of wave period shows that waves of longer periods are more common at the Lisboa location compared to Haltenbanken in Norway. The power levels around 20 kW/m occur in the fetch limited central region of the North Sea where wind-sea is predominant thus shorter wave periods are found.

The annual distribution of energy period T_e at the four selected sites is shown on the Figure 3 below (all directions).

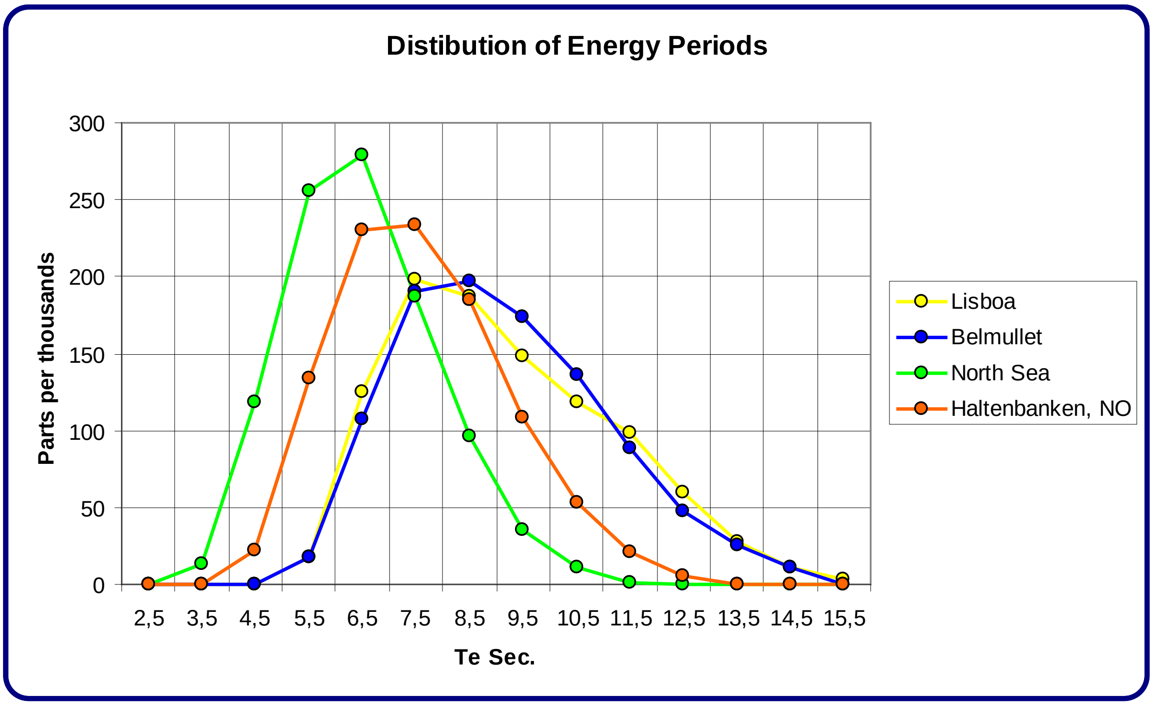


Figure 3 Distribution of energy periods at the four sites

To evaluate the relationship between significant wave height H_s and the average energy period T_e, the best linear fit between H_s and average $T_{e\ ave}$ has been determined from the scatter diagrams (in WERATLAS) for each site as follows:

$T_{e\ ave} = A*H_s + B$ [sec]

The position of the site, the annual average power level and the four distinct relations between average H_s and $T_{e\ ave}$ are shown in Table 2, as well as the respective period of observations.

Table 2 Key data from four selected sites

Location	Position	P_{ave} (kW/m)	$T_{e\ ave}$	Observation period
Haltenbanken, Norway	65,1° N, 7,4° E	42	0,75*Hs + 5,65	1980 - 88
AUK, North Sea	56,23° N, 2,03° E	20	0,75*Hs + 4,98	1984 - 94
Belmullet,Ireland	54° N, 12° W	72	0,90*Hs + 6,34	1987 - 94
Lisboa, Portugal	39° N, 12° W	37	1,09*Hs + 6,47	1987 - 94

The relations between H_s and $T_{e\ ave}$ are plotted on a common graph shown on Figure 4.

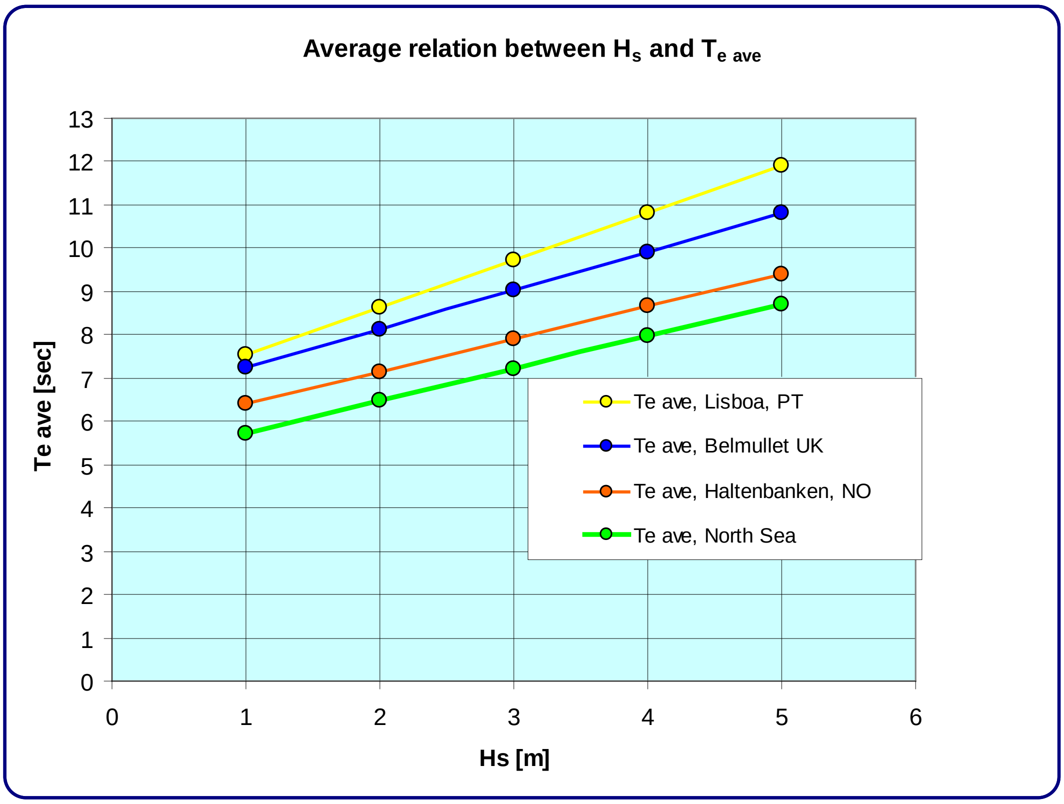
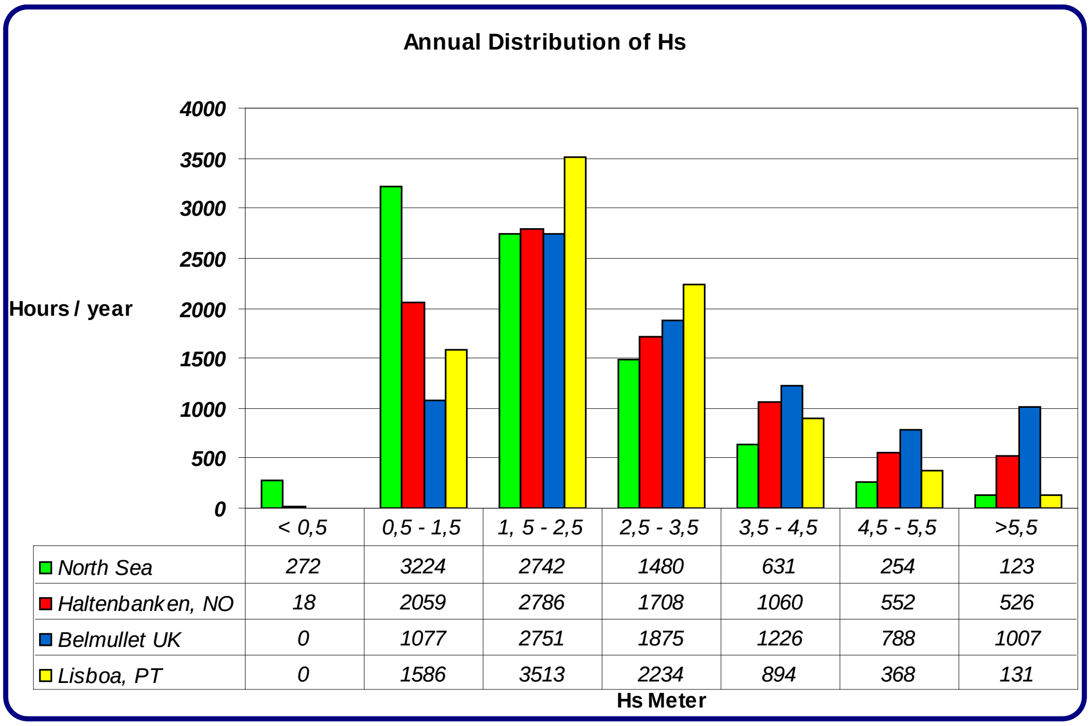


Figure 4 - Linear Relationship between H_s and $T_{e\ ave}$ for the Selected Sites

In Figure 4 it should be noted that the average energy period is about 2 to 3 seconds larger at the Lisboa site compared to the North Sea site for the same significant wave height H_s. This is due to the fact that in the North Sea wind-sea conditions are dominant, while in Lisboa swell prevails.

It appears from Figure 4 that different linear relations can be used to describe the most likely wave energy period T_e for the different locations as a function of the significant wave height H_s.

Such relations can be useful, e.g., if it is desired to present and evaluate the most likely performance curve of a wave power converter based on its performance matrix. In this way the three-dimensional performance matrix is simplified to a two dimensional power curve related to a generic location.



	< 0,5	0,5 - 1,5	1, 5 - 2,5	2,5 - 3,5	3,5 - 4,5	4,5 - 5,5	>5,5
North Sea	272	3224	2742	1480	631	254	123
Haltenbanken, NO	18	2059	2786	1708	1060	552	526
Belmullet UK	0	1077	2751	1875	1226	788	1007
Lisboa, PT	0	1586	3513	2234	894	368	131

Figure 5 - Annual Distributions of H_s (hours per year) for the Four Selected Sites

In Figure 5 sea states with H_s between 1,5 meter and 2,5 meter occur at all sites for more than 2,500 hours per year. Sea states with H_s between 2,5 meter and 3,5 meter occur more than 1,500 hours per year. At the Lisboa site and in the North Sea, the significant wave height H_s exceeds 5,5 meter about 125 hours per year (5 days per year). In the north, at Haltenbanken in the Norwegian Sea, this level is exceeded more than 500 hours per year (20 days per year) and at the Belmullet site more than 1,000 hours per year (41 days per year).

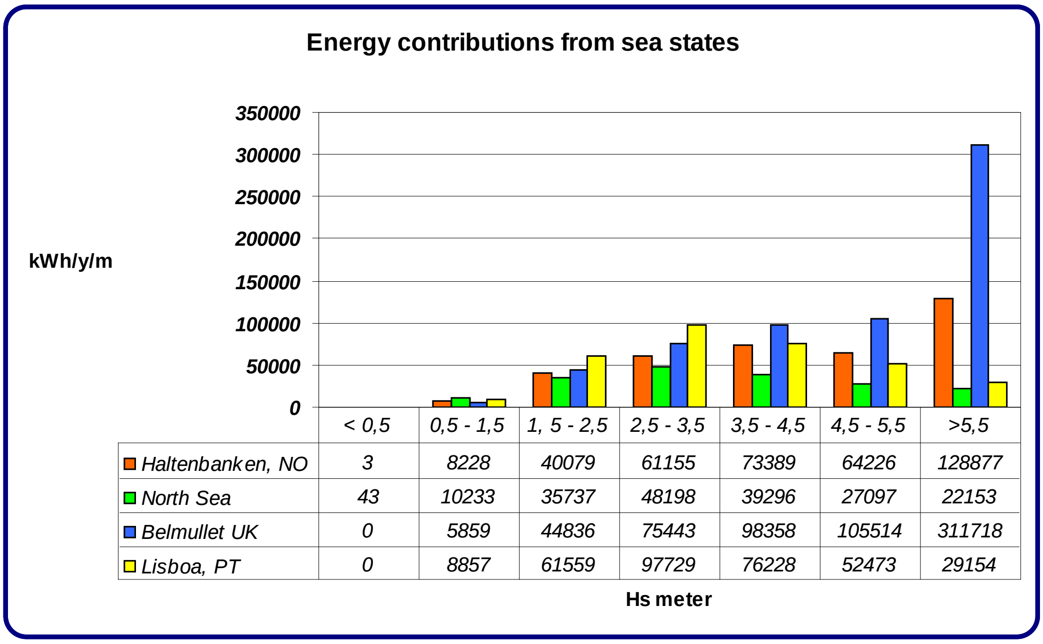


Figure 6 - Annual Energy Contribution for each Sea State at the Four Locations.

Figure 6 shows the annual energy contribution from each sea state characterized by H_s, and one can notice that up to H_s = 3,5 meter the wave conditions at Lisboa provide most energy. For sea states with H_s above 3,5 metres the north and central East-Atlantic locations Haltenbanken and Belmullet respectively provide most energy. Further almost half of the energy at Belmullet comes from seas states above 5,5 metres. Tables 3 to 6 below show how many hours per year five sea states (H_s from 1 metre to 5 metres) occur and for each $H_{s,}$ the most likely energy period T_e and the energy contribution per meter per year.

Table 3 - Haltenbanken Norway

H_s [m]	1	2	3	4	5	>5,5	Total
Energy period T_e [sec]	6,40	7,16	7,91	8,66	9,41	>9,79	
Hours per year	2059	2786	1708	1060	552	526	8707
Energy [kWh/m/year]	8228	40079	61155	73389	64226	128877	375957

Table 4 - North Sea (AUK)

H_s [m]	1m	2m	3m	4m	5m	>5,5m	Total
Energy period T_e [sec]	5,73	6,47	7,22	7,96	8,71	>9,08	
Hours per year	3224	2742	1480	631	254	123	8725
Energy [kWh/m/year]	10233	35737	48198	39296	27097	22153	182757

Table 5 – Belmullet, Ireland

H_s [m]	1m	2m	3m	4m	5m	>5,5m	Total
Energy period T_e [sec]	7,23	8,12	9,02	9,91	10,81	>11,26	
Hours per year	1077	2751	1875	1226	788	1007	8725
Energy [kWh/m/year]	5859	44836	75443	98358	105514	311718	641729

Table 6 - Lisboa, Portugal

H_s [m]	1m	2m	3m	4m	5m	>5,5m	Total
Energy period T_e [sec]	7,56	8,64	9,73	10,81	11,90	>12,44	
Hours per year	1586	3513	2234	894	368	131	8725
Energy [kWh/m/year]	8857	61559	97729	76228	52473	29154	325999

4.1 Data Preparation and Presentation

The wave data analysed have been obtained from the WERATLAS (3). Data for Belmullet and Lisboa are results from the ECMWF wind-wave WAM model, covering an 8-year period (1987-1994); for AUK (North Sea) and Haltenbanken, buoy data were used covering 1980-1988 and 1983-1994, respectively. The wave data analysed refers to all directions.

For each location a scatter table of H_s and T_e is shown. Each cell represents an interval that for the energy period T_e spans over 1 second and for H_s is 0,5 metre.

The value in each cell shows the relative frequency of occurrence of the respective combination (H_s, T_e).

For each row of H_s the average energy period $T_{e\ ave}$ is calculated and shown in the column ($T_{e\ ave}$) this value is the most likely energy period associated with the value of H_s. Central values of H_s and T_e for each bin are used assuming an even distribution within each bin.

The probability of each row is shown representing a specific level of H_s is shown in the column (sum), the accumulated probability in column (Acc) and the power contribution from this level of H_s in column (*dP*).

Summing up the power contributions (*dP)* for each row an estimate of the power resource in kW/m at the site is obtained as a sum of the column (*dP)*.

A plot of the average energy period T_e as a function of H_s is shown below at the corresponding scatter table. A trend line giving the best linear fit between the plotted points is shown; from the corresponding formula the linear coefficient and constant has been derived as showed for all sites in Table 2.

The probability of occurrence in each bin is given in parts per thousands without decimal points. This can be seen as the sum of occurrence is not 1,000. In the WEARATLAS the decimals are included when calculating the power levels for the four sites and this gives rise to slightly different values as shown in the table below. For practical purpose this difference is of minor importance.

Table 7 Comparison between calculations based on the truncated information to the original source WERATLAS

Location	WERATLAS P_{ave} (kW/m)	This Report P_{ave} (kW/m)
Haltenbanken, Norway	42	42
AUK, North Sea	21	20
Belmullet,Ireland	75	72
Lisboa, PT	39	37

4.2 Data from Haltenbanken Norway

Bivariate Frequency Table of (Hs,Te)

LOCATION: ATL.37 HALTENBANKEN (65,1° N ; 7,4° E)
DATA: Directional spectra from buoy measurements (1980 - 1988)
SEASON: Annual

Hs\Te	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	sum	Acc	Te ave	dP
0,25				1	1										2	2	6,00	0,00
0,75			9	28	24	9	2	1							73	75	6,09	0,12
1,25			11	53	57	28	10	3							162	237	6,39	0,80
1,75			2	36	57	47	22	5	2						171	408	6,93	1,79
2,25				14	51	44	25	9	3	1					147	555	7,34	2,70
2,75				2	27	37	27	12	4	1					110	665	7,83	3,21
3,25					11	32	24	11	4	2	1				85	750	8,21	3,64
3,75					2	22	24	13	5	2	1				69	819	8,60	4,12
4,25						11	21	13	5	2					52	871	8,85	4,10
4,75						3	14	11	4	2	1				35	906	9,24	3,60
5,25						1	10	10	5	1	1				28	934	9,43	3,59
5,75							4	7	4	2	1				18	952	9,89	2,90
6,25							2	6	3	1	1				13	965	9,96	2,50
6,75								4	3	1					8	973	10,13	1,82
7,25								3	3	1					7	980	10,21	1,85
7,75								1	3	1					5	985	10,50	1,56
8,25									3	1					4	989	10,75	1,44
8,75									1	1					2	991	11,00	0,83
9,25									1	1					2	993	11,00	0,93
9,75															0	993		0,00
10,25										1					1	994	11,50	0,60
10,75																		
sum:	0	0	22	134	230	234	185	109	53	21	6	0	0	0	994			42,11

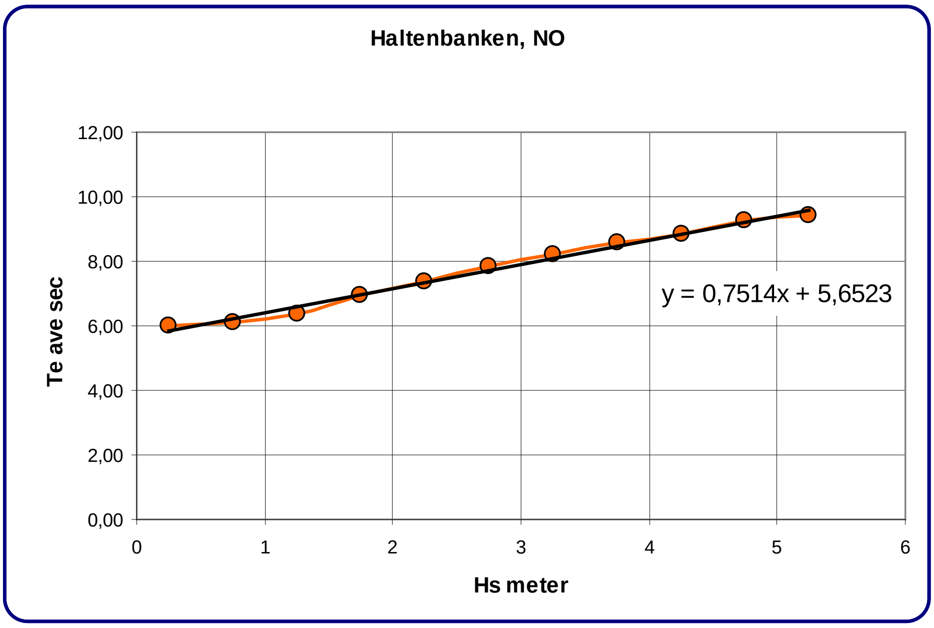


Figure 7 - Plot of the Average Energy Period $T_{e\ Ave}$ as a Function of the Significant Wave Height H_s, including the Linear Trend Line (In Black) fitted to the Data for Haltenbanken, Norway.

4.3 Data from AUK in the North Sea

Bivariate Frequency Table of (Hs,Te)

LOCATION: ATL.32 AUK (56,23° N ; 2,03° E)
DATA: Directional spectra from buoy measurements (1984 - 1994)
SEASON: Annual

Hs \ Te	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	Sum	Acc	Te ave	dP
0,25		4	14	7	4	2									31	31	5,05	0,00
0,75		9	64	56	23	10	6	2	1						171	202	5,45	0,26
1,25			38	93	41	15	7	2	1						197	399	5,84	0,89
1,75			2	75	64	21	9	4	1						176	575	6,36	1,69
2,25				23	76	25	8	4	1	0					137	712	6,75	2,31
2,75				2	49	32	10	4	1	1					99	811	7,22	2,67
3,25					19	38	9	3	1	0	0				70	881	7,49	2,73
3,75					3	27	12	2	1	0	0				45	926	7,86	2,45
4,25						13	12	2	0	0					27	953	8,09	1,95
4,75						3	11	2	1	0	0				17	970	8,56	1,62
5,25						1	8	3	0	0	0				12	982	8,67	1,41
5,75							3	3	1	0	0				7	989	9,21	1,05
6,25							1	2	1	0	0				4	993	9,50	0,73
6,75								1	1						2	995	10,00	0,45
7,25								1	0	0					1	996	9,50	0,25
7,75																		
	0	13	118	256	279	187	96	35	11	1	0	0	0	0	996			20,47

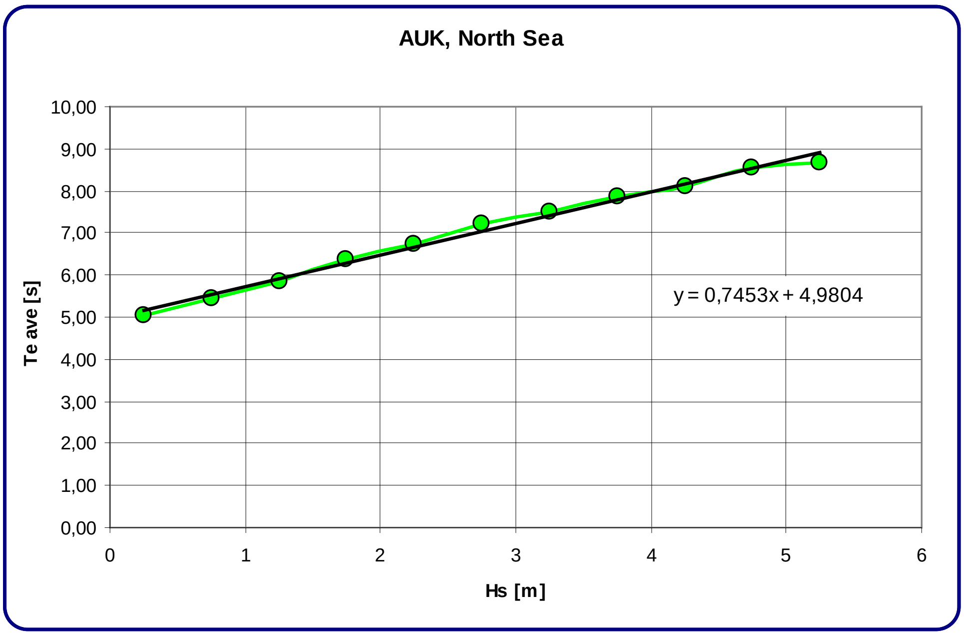


*Figure **8** Plot of the average energy period $T_{e\ ave}$ as a function of the significant wave height H_s, including the linear trend line (in black) fitted to the data for AUK, North Sea.*

4.4 Danish Part of North Sea Wave Power Levels

Typical wind generated waves within a sea area of limited fetch are found in the North Sea, the Baltic Sea and in the Mediterranean. In these areas the power levels vary between 5 and 20 kW/m.

The Danish part of the North Sea has been investigated in great detail, using numerical wind-wave models calibrated with wave measurements at the Gorm Oil production field and also using measurements at Fjaltring, th is closer to shore. Data have been extracted in six data points that are represented the map below enabling in this way to show how the wave power levels and design waves vary within the borders of the Danish part of the North Sea. The data are given in Table 7 below.

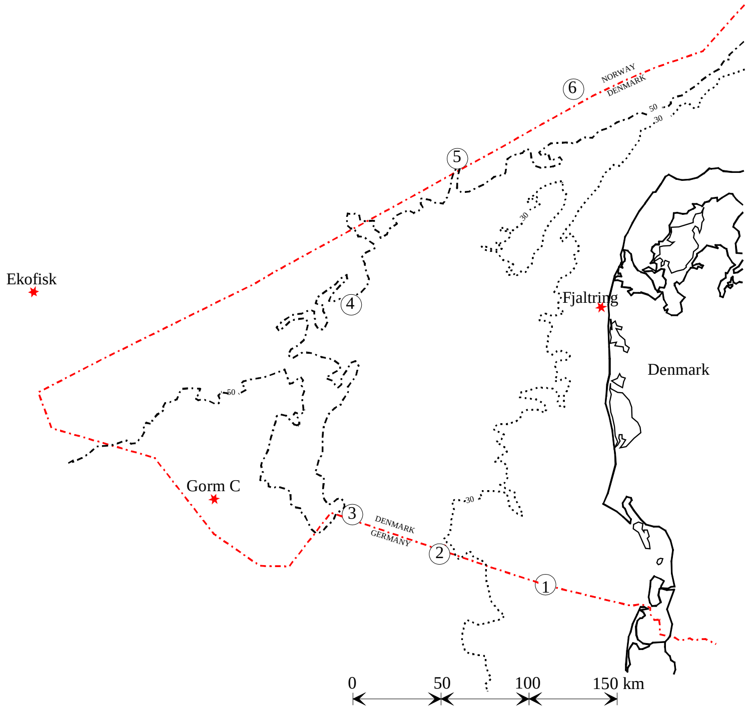


Figure 9 Map showing Six Selected Points in the Danish Part of the North Sea(5)

It is estimated that if a 200 km-long line of wave power converters were deployed along the north-south direction and 25% of the wave power could be converted this could cover about 20% of the Danish electricity consumption (5).

Table 8 - Wave Data at the six points shown in Figure 9

Location	Average Wave Power	Distance to shore	Water depth	50 years Design	
	(kW/m)	(km)	(m)	H_s (m)	T_p (s)
Point 1	7	64	20	5,7	10,0
Point 2	12	100	31	8,4	12,1
Point 3	16	150	39	9,6	12,9
Point 4	17	150	40	9,3	12,7
Point 5	14	100	58	11,4	14,1
Point 6	11	68	166	10,6	13,6
Fjaltring	7	4	20	6,4	10,5
Ekofisk	24	300	71	12,6	14,8

4.5 Atlas of UK Marine Renewable Energy Resources

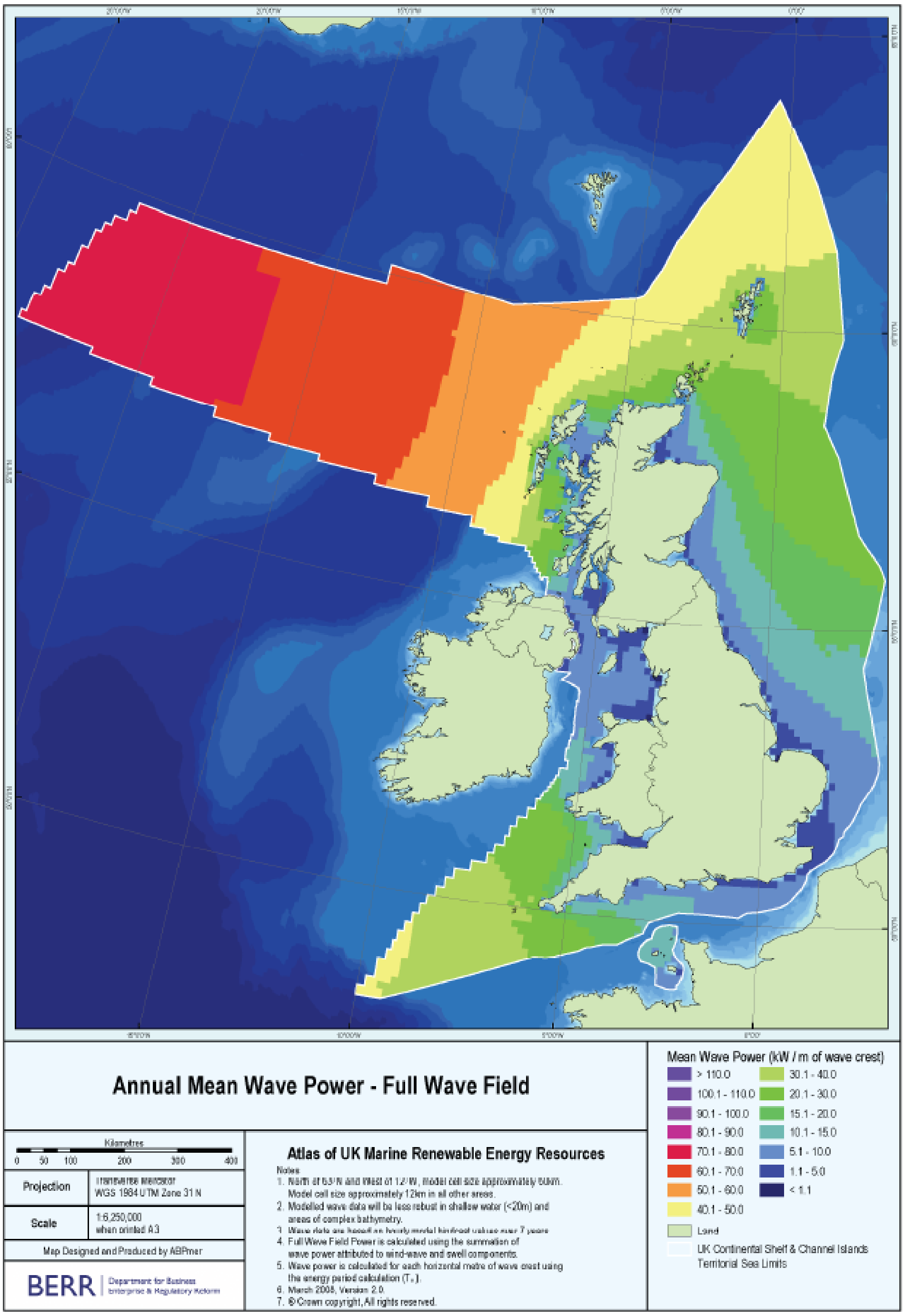


Figure 10 - Variation of Wave Power Levels (in kW/m) around UK

In Figure 10 one can observe that the power level varies from more than 70 kW/m at large distances from the Scottish west coast until 15 - 20 kW/m, as the coast is approached(6).

4.5.1 Design Wave Height Mapping in the United Kingdom

The power level is influenced by the location the same happens with the design wave height. A study has been carried out also to map the variation in design wave heights in UK waters such as found in (7), the 100-year H_s contour map being presented in Figure 11.

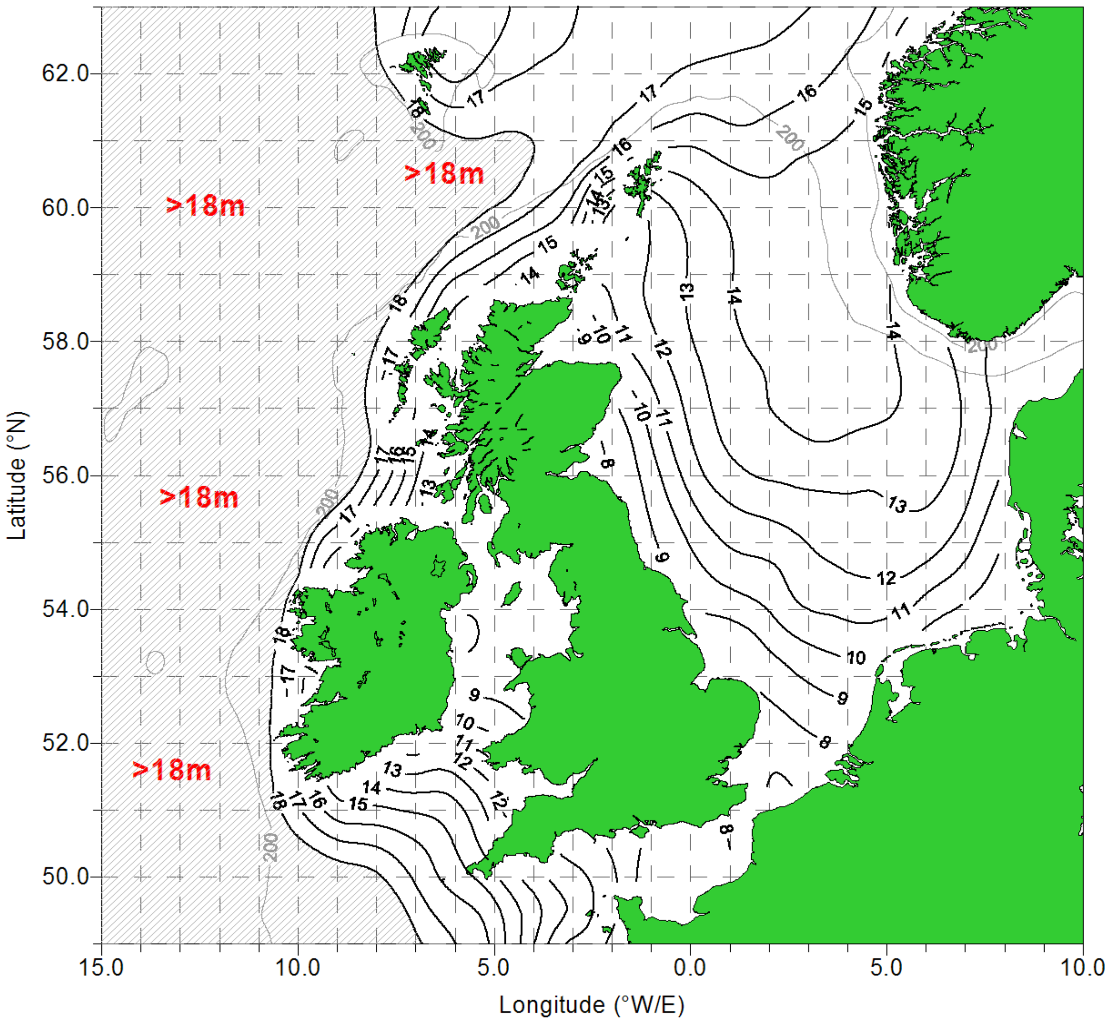


Figure 11 – 100-year H_s contour map (Reproduced under the terms of the Click-Use Licence). Important note: the information displayed on this map is intended as a guide and should not be treated as a substitute for site-specific study.(7)

4.6 Belmullet Ireland

Bivariate Frequency Table of (Hs,Te)

LOCATION: ATL.23 BELMULLET (54° N ; 12° W)
DATA: Directional spectra from WAM (1987 - 1994)
SEASON: Annual

Hs \ Te	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	Sum	Acc	Te ave	dP
0,25															0	0		0,00
0,75				1	5	6	1								13	13	7,04	0,03
1,25				8	28	44	23	7							110	123	7,44	0,63
1,75				8	38	48	45	24	5						168	291	7,82	1,98
2,25				1	28	37	30	33	14	3					146	437	8,32	3,03
2,75					7	34	30	25	18	6	1				121	558	8,79	3,96
3,25					1	16	28	20	18	9	1				93	651	9,24	4,47
3,75					0	4	21	17	15	12	5	1			75	726	9,89	5,14
4,25						1	14	19	14	10	5	2			65	791	10,13	5,86
4,75						0	4	15	14	10	5	3			51	842	10,62	6,02
5,25						0	1	9	13	9	4	2	1		39	881	10,91	5,78
5,75							0	3	11	9	5	2	1		31	912	11,34	5,72
6,25								2	7	6	5	2	1		23	935	11,54	5,11
6,75									4	5	4	2	1		16	951	11,94	4,29
7,25									2	4	3	2	1		12	963	12,17	3,78
7,75								0	1	3	4	2	1		11	974	12,41	4,04
8,25										2	2	2	1		7	981	12,79	3,00
8,75									0	1	2	2	1		6	987	13,00	2,94
9,25									0	0	1	1			2	989	13,00	1,10
9,75											1	1	1		3	992	13,50	1,90
10,25										0		2	1		3	995	13,83	2,15
10,75													1		1	996	14,50	0,83
12,75																		
Sum	0	0	0	18	107	190	197	174	136	89	48	26	11	0	996			71,74

Figure 12 - Plot of the average energy period Te ave as a function of the significant wave height Hs, including the linear trend line (in black) fitted to the data for Belmullet, Ireland

4.7 Lisboa Portugal

Bivariate Frequency Table of (Hs,Te)

LOCATION: ATL.13 LISBOA (39° N ; 12° W)
DATA: Directional spectra from WAM (1987 - 1994)
SEASON: Annual

Hs \ Te	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	Sum	Acc	Te ave	dP
0,25																0		
0,75				1	6	7	2	1							17	17	7,26	0,03
1,25				9	38	63	41	12	1						164	181	7,57	0,96
1,75				7	45	46	48	36	23	6	1				212	393	8,25	2,64
2,25				1	29	36	31	31	29	26	5	1			189	582	9,00	4,25
2,75					7	29	26	23	21	28	16	4			154	736	9,73	5,60
3,25					0	15	19	16	15	15	14	6	1		101	837	10,16	5,35
3,75					0	2	13	12	12	7	8	7	2		63	900	10,63	4,65
4,25							5	9	6	5	6	4	3	1	39	939	11,19	3,89
4,75						0	2	5	4	6	4	3	3	1	28	967	11,61	3,62
5,25						0		2	4	2	2	2	1	1	14	981	11,86	2,26
5,75							0	1	2	2	1	1	1		8	989	11,75	1,53
6,25									2	1	1				4	993	11,25	0,87
6,75										1	1				2	995	12,00	0,54
7,25											1				1	996	12,50	0,32
7,75																		
Sum	0	0	0	18	125	198	187	148	119	99	60	28	11	3	996			36,51

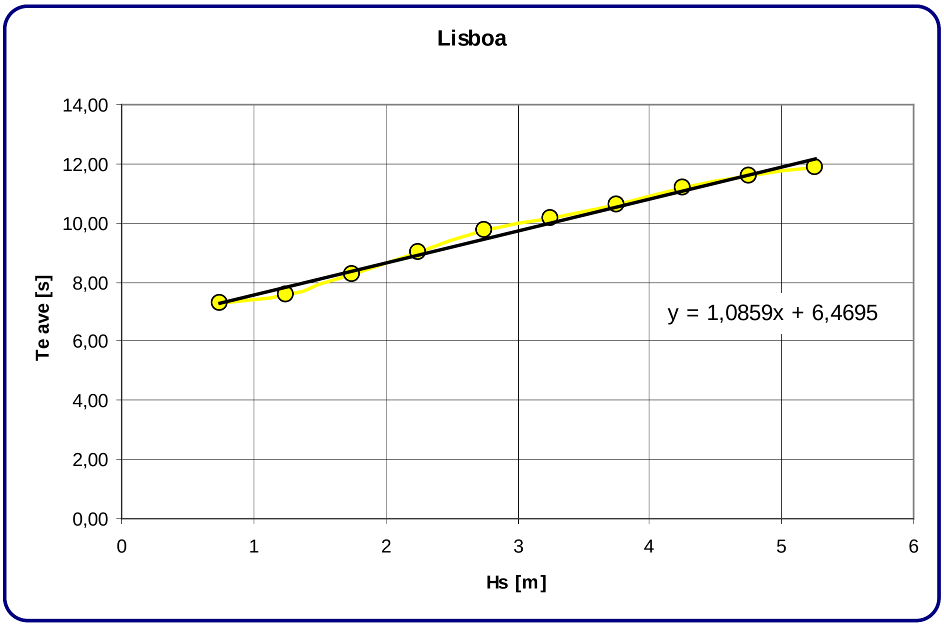


Figure 13 - Plot of the Average Energy Period $T_{e\ ave}$ as a Function of Significant wave height H_s, including the linear trend line (in black) fitted to the data for Lisboa, Portugal.

5 Data from Wave Test Sites

Since year 2005 the number of ocean test sites proposed and used for testing of wave energy systems has increased significantly. Figure 14 below shows some of the European sites.

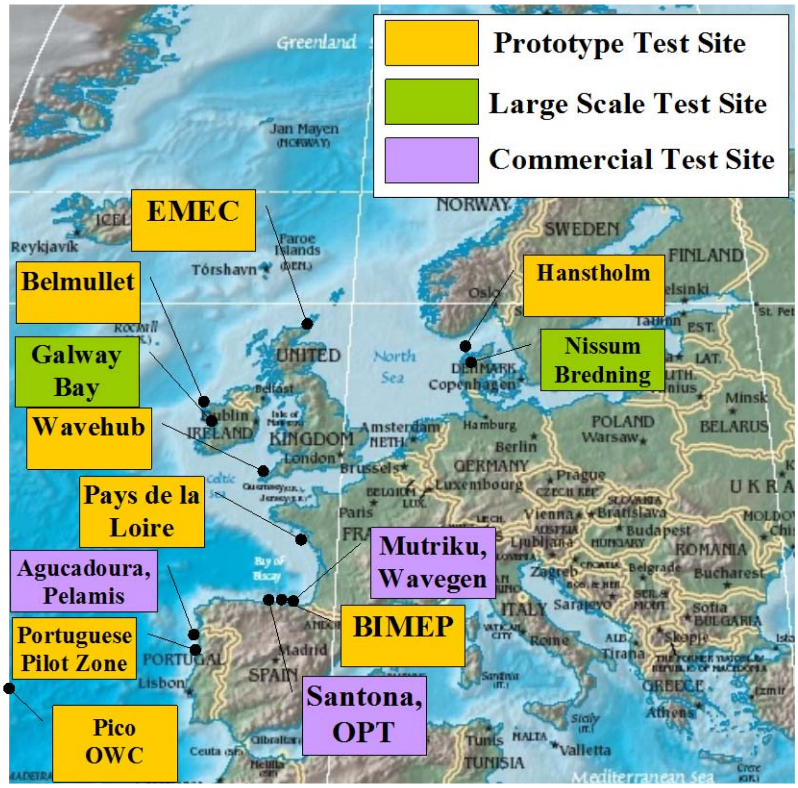


Figure 14 - Test Sites for Testing Ocean Energy Systems in Particular Wave Energy Systems [Map provided by HMRC, 2009]

In Portugal the first grid-connected OWC plant was build on the Azores island of Pico, being completed in 1999. The milder climate and, more recently, the favourable feed-in tariff have attracted several wave energy developers to Portugal, pioneered by AWS, followed by Wave Roller and Pelamis. Negotiations with other developers are underway having in view the deployment of their devices in this country. In 2008 a large dedicated area for deployment of prototypes, pre-commercial and commercial wave farms has been defined (the Wave Energy Pilot Zone).

One of the first well-established test sites within Europe is the European Marine Energy Centre (EMEC) on the Orkney Islands in Scotland. This site is exposed to the Atlantic waves with strong tidal streams between the Scottish isles. Both tidal and wave energy systems can be tested at EMEC. Marine energy converters like Pelamis (wave energy converter) and OpenHydro (tidal energy converter) have been tested there and the Aquamarine wave power system is currently deployed there.

In the UK the Wave Hub in southwestern England is being prepared for testing arrays of wave energy converters. It will be possible to test four different technologies with grid connections at the same time.

In contrast to these exposed sites the sheltered site Nissum Bredning in Denmark has become well known from the testing of the Wave Dragon scaled 1:4,5 prototype and the

Wave Star scaled 1:10 prototype. In addition an exposed location within Denmark DANWEC has been founded as a Danish wave energy test site in the North Sea off the coast of Hanstholm. A section of a half-scale prototype of the Wave Star is presently being carried out at this location.

Data from some of these wave energy test sites including information on power level, water depth and maximum significant wave height is shown on Table 8 below for a selected number of testing sites.

Table 9 - Summary Test Site Data

Site	Country	Power level [kW/m]	Water depth [meter]	Hs max (estimate) [meter]
EMEC	UK	21	50	15
Wave Hub	UK	17	50-65	14,4
Pilot Zone	PT	25	30-90	15,5 (d=30m)
bimep	Spain	21	50-90	11,4
Hanstholm	DK	6	20 - 30	6,5
Nissum Bredning	DK	0,2	5-8	1,2
Galway Bay	Ireland	2,4	20-25	5
Port Kembla	Australia	6,7	6	7

More detailed data collected from some of these sites are presented in the following sections of this chapter. The data has been collected initially from available data in literature and on the Internet and the available data types were found to vary from site to site.

As a consequence some guidelines have been drawn to indicate the typical information that is needed to make a preliminary design of a wave energy converter to a specific site or evaluate the results obtained at a specific site.

A questionnaire (8) including these guidelines has been circulated within the OES-IA to obtain information. Some of the information received has been included in this report as examples (Bimep, Galway Bay and Port Kembla).

In order to prepare preliminary planning and design of any ocean energy converter for testing at a specific site, the data described in the guidelines below are required. Further, these guidelines will encourage test sites to make such data available, e.g., on their web pages.

The summary data presented for various sites are in any case indicative and thus cannot be used in a detailed design study; this will require further information provided by the site, where the tests it is planned to be carried out.

5.1 Guideline for Test Site Information

In order to obtain comparable information from different wave energy test sites, the guidelines below show what type of information would be helpful to be made publicly available for preliminary planning purposes.

5.1.1 Site Host Address and Contact Details

Name and Address:
e-mail:
Web page:

5.1.2 Site Location & Infrastructure

A short description of the site, offices, and permits, including a map indicating the site, the size of the area and the co-ordinates of the location must be given. Ongoing projects and previous project/systems tested should be mentioned.

Distance to large town
Distance to nearest airport
Distance from nearest service port to site
Distance from nearest access harbour to site
Restrictions, availability & conditions if any

5.1.3 Grid Connection

- On land
- Off/shore (at what depth)

Connection voltage and power level

5.1.4 Water Depth and Seabed Conditions

Water depth at the site and the seabed material – mud, sand, gravel or rock - is useful for mooring and installation.

5.1.5 Distance to Shore

The shortest distance to shore should be indicated as well as the distance to the nearest harbour for maintenance.

5.1.6 Design Wave Data

The design wave conditions can be determined based on statistical information. The method used should be indicated as well as the chosen return period (10, 50 or 100 years). In this report the direction from where the (design) wave is coming should be indicated (nautical convention). In more detailed studies directionality is recommended.

5.1.7 Design Wind Data

Depending on the freeboard of the wave energy converter, the wind forces can have an impact on the design loads, the maximum wind speed (and most likely direction) with the same return period as the waves should be indicated.

5.1.8 Design Current Data

Depending on the submerged part of the wave energy converter, the current forces can have an impact on the design loads; the maximum current speed with the same return period as the waves and wind should be indicated as well as the expected direction.

5.1.9 Design Water Level Variation

High and low water conditions can have an impact on the mooring design of the converter; such extreme levels can be indicated relative to the MWL.

5.1.10 Joint Probability Diagram (Scatter Diagram)

The annual average power level of a given site (all year and all directions) is calculated from a scatter diagram that includes the frequency of occurrence of different combinations of sea states, described by intervals of T_e and H_s.

H_s - Significant wave height [meter]
T_e – Energy Period [seconds] or T_z – Zero-crossing Period [seconds]

The width of the period intervals (bins) is normally 1 second and for wave height intervals is 0,5 metre or 1 metre, depending on the wave climate (benign test sites for smaller scale testing, such as Nissum Bredning, will be presented with smaller intervals). In each cell the frequency of occurrence can be given in hours per year, in parts per thousands (ppt) and sometimes in percent.

Diagrams can also be generated for each month to illustrate the power variation over the year or representing waves coming from different directions. Variation in power from year to year is normal and thus the under laying data must cover a period of more than ten years to provide a fair average estimate.

Table 10 Example of the layout of a Joint probability diagram showing the annual number of hours each combination of Hs and Te prevail.

		Energy Period Te or Zero-crossing Period Tz												
	Hs\T	**3,5**	**4,5**	**5,5**	**6,6**	**7,5**	**8,5**	**9,5**	**10,5**	**11,5**	**12,5**	**13,5**	**14,5**	sum
Significant Wave Height Hs	**0,25**													
	0,75													
	1,25													
	1,75													
	2,25													
	2,75													
	3,25													
	3,75													
	4,25													
	4,75													
	5,25													
	5,75													
	6,25													
	6,75													
	7,25													
sum														

5.1.11 Additional information

Facilities available: Vessels, Cranes, Engineering, Industry
Equipment available at site:
Wave measurements (yes/no)
Wind measurements (yes/no)
Water level measurements (yes/no)
Current measurements (yes/no)
Water/air temperature measurements (yes/no)
Can additional information be obtained such as, typical wave spectra, directional spectra, tidal current profiles and turbulence?

The guidelines are based on the questions included in the test site questionnaire(8)

6 Specific Wave Energy Test Site Data

Specific test sites chosen to be included in this report are shown on the map below except the site at Port Kembla, 100 km south of Sydney, Australia.

Figure 15 - Test Sites along the Atlantic Coast

6.1 Pilot Zone, S. Pedro Muel, Portugal

Portugal has been able to attract many wave energy companies from abroad due to its favorable wave resource, its mild climate, and attractive testing conditions such as providing permits and favorable feed-in tariffs for produced energy. As such many of the first large scale tests such as the 2 MW Archimedes Wave Swing, tested near Porto in the period 2000 – 2006 (9) and Pelamis prototype tests in 2008 of three 750 kW devices have taken place in Portugal (10), as well as the Finish Wave Roller 2006 – 2007(11). In 2007 it was decided to provide a dedicated area for testing wave energy systems known as the Pilot Zone.

Site Location

The Pilot Zone is located off the west coast of Portugal about 130 km north of Lisboa, near a village S. Pedro de Muel. The area is about 320 km^2. It is planned for demonstration, pre-commercial and commercial exploitation, with a planed maximum grid integration of 250 MW [OES-IA newsletter 12].

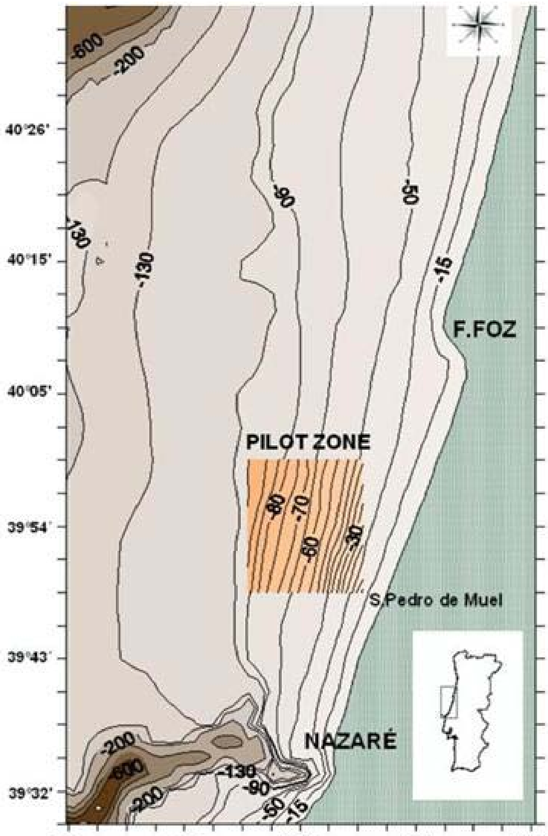


Figure 16 - Pilot Zone in Portugal

Water Depth and Seabed Conditions

The pilot zone was defined between 30 and 90 m water depth. In the area sand is abundant; a geological survey is planned. The distance from the 30 m bathymetric to shore is 4,5 km and the 50m bathymetric is 7 km off the coast. Some ***initial*** data related to the site are provided below.

Table 11 - Main characteristics of the Wave Energy Pilot Zone

Location: Pilot Zone Portugal	39º54' N 9º06' W	
Water depth	30 – 90	[m]
Design significant wave height Hs (at 30m depth)	11	[m]
Design energy period Te (at 30m depth)	19	[sec]
Max wind speed	25	[m/s]
Max Current speed	3,4	[m/s]
Max high water level	-	(m)
Min low water level	-	(m)
Maximum ice thickness	-	[m]
Wave power annual average (50 meter depth)	25	[kW/m]

The scatter diagram in Table 12 is obtained from buoy data 2004 – 2005 at 50 meter water depth. Using the full expression for group velocity taking the water depth into account the annual power calculated is 23,3 kW/m. Correcting this value to the 11-year period (1989 – 1999) the value becomes 25 kW/m as shown in summary Table 11.

Using the deepwater approximation for wave power calculation and the one year data shown in the scatter diagram Table 12 the annual wave power average is 21,1 kW/m.

Table 12 Joint probability diagram from the Pilot Zone in Portugal

Hs \ Te	≤5	5,5	6,5	7,5	8.5	9.5	10,5	11,5	12,5	13,5	14,5	15,5	≥17	Sum	Te ave	dP
0,25	1	3												4	5,25	0,00
0,75	10	26	42	43	14	8	1	1						145	6,90	0,29
1,25	3	21	41	54	47	41	17	5						229	7,97	1,45
1,75		8	36	48	47	34	35	17	6	4				235	8,73	3,19
2,25			15	30	37	36	30	18	7	2				175	9,23	4,15
2,75			3	18	17	19	19	16	6	1				99	9,61	3,65
3,25				6	9	8	9	14	6	2		1		55	10,09	2,97
3,75				1	1	3	6	6	7	3				27	11,28	2,17
4,25					1		6	3	4	2				16	11,44	1,68
4,75					1		1	3	1	1				7	11,36	0,91
5,25						1			1	1				3	11,83	0,50
5,75						1								1	9,50	0,16
6,25																
≥7																
Sum	14	58	137	200	174	151	124	83	38	16	0	1	0	996		21,11

References, (OES-IA Test site info provided by LNEG; Teresa Pontes)

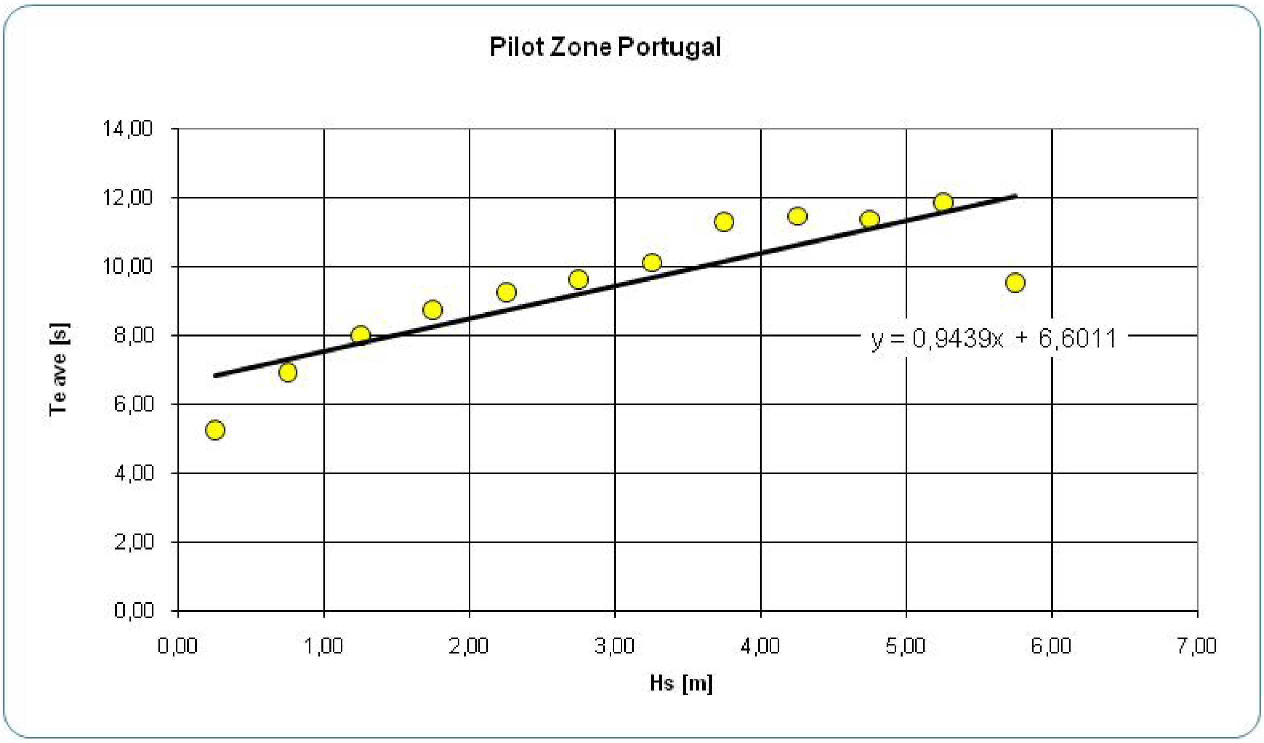


Figure 17 - Relationship between Significant Wave Height (H_s) and the average energy period (T_e)

6.2 Test Sites in Denmark

Figure 18 - Sheltered Test Site in Nissum Bredning and the Test Site in Hanstholm exposed to the North Sea.

Hanstholm is located in the NW part of Denmark at the North Sea with a fetch of about 600km to the west – sheltered by the UK. There is a large harbour, fishing industries and ferry traffic to Norway. During the period 1987–1996, Danish Wave Power Aps carried out experiments with point absorber system, initially with 6 metre diameter buoy - a 40 kW grid connected wave power converter, followed by a second test with a smaller 2,5 metre float, equipped with data collecting equipment, transmitting performance taken over 20 minutes, 6 times per day over a period of six months September 1996 – January 1997(12). One lesson learned from these tests was to start with the smaller scale tests at sea before the large scale.

Most recently in September 2009 WaveStar Energy *(13)* installed a platform including two floats of 5 meter diameter each installed with a generator power of 55 kW. This combined with other wave energy systems planning to install at Hanstholm, has led to the formation of the Danish Wave Energy Center (DanWEC) in Hanstholm*(14)*.

The sheltered test site in Nissum Bredning was established in 1999, during the Danish wave energy program(15), as a site for inventors to test their wave energy ideas in real sea waves. It is located in Nissum Bredning with a fetch of about 10 km in direction SW and water depth of about maximum 5-8 meter some 500 meter from shore.

6.2.1 Nissum Bredning

The facility includes a 200-meter long bridge, leading from the shore to a water depth of about 3 meter. Several small-scale devices have been tested from this platform, i.e., the Ecofys/Rossen Wave Rotor(16).

At some distance from the pier systems like the Point absorber system has been tested at a water depth of 5-6 meter in year 2000, for a period of 3 month(17).

The 20 kW WaveDragon prototype was installed in 2003 and connected to the grid. WaveDragon has been in operation on and off since then, also exploring another site approximately 13 km further to the south-east (18), as shown by the lower green arrow on the map (Figure 19).

Since 2006 the Wave Star Energy device was build and installed at the site connected to the pier. The results of the tests of a 5,5 kW device comprising 40 floats of 1-meter diameter are described in (19). The test site is hosted by the Folkecentre for Renewable Energy in Thy(20).

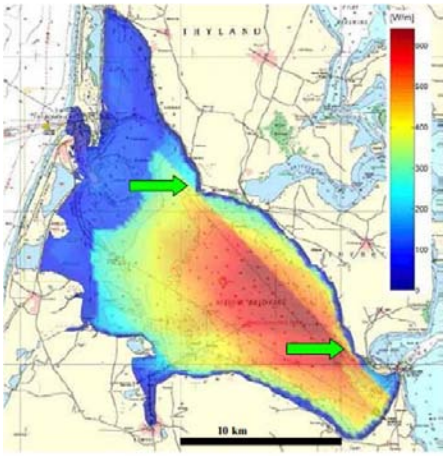


Figure 19 Nissum Breding power levels up to 500 W/m

Table 13 - Main Data from Nissum Bredning Site

Location: Nissum Bredning		
Water depth	3-5	[m]
Design significant wave height Hs, 1 year	1,3	[m]
Design zero-crossing period Tz, 1 year	4	[sec]
Max wind speed	30	[m/s]
Max Current speed	3,4	[m/s]
Max High Water level	1,6	(m)
Min Low Water level	-1,5	(m)
Maximum Ice thickness	0,15	[m]
Wave power annual average	0,2	[kW/m]

Table 14 - Joint Probability Diagram from Nissum Bredning(21)

Hs\ Tp	1,5	1,7	1,9	2,1	2,3	2,5	2,7	2,9	3,1	3,3	3,5	3,7	3,9	Sum	Tp ave	dP
0,05	3,3	11,1	6,6	3,6	2,4	3,3	0,8	0,7	0,7	0,3	0,1	0,1	0,1	33,1	2,00	0,00
0,15		1,6	2,2	1,4	0,6	0,8	1,4	1,7	1,5	0,8	0,4			12,4	2,47	0,00
0,25		0,1	1,3	1,1	1,6	1,3	0,4	0,9	0,5	1	0,7			8,9	2,57	0,01
0,35				0,8	1,3	3,7	1,6	1,2	0,7	1,6	1,6	0,2		12,7	2,80	0,02
0,45					0,7	2,6	1,9	1,9	0,8	0,4	0,7	0,1		9,1	2,79	0,02
0,55						1,7	2,5	1,3	1,2	0,5	0,1			7,3	2,81	0,03
0,65						0,2	1,1	1,5	1	1	0,3			5,1	2,99	0,03
0,75							0,1	0,2	1,3	0,7	1,8	0,5		4,6	3,33	0,04
0,85								0,2	0,4	0,3	0,8	1,4		3,1	3,48	0,03
0,95								0,1	0,1		0,2	0,6	0,9	1,9	3,70	0,03
1,05								0,1	0,1	0,1		0,4		0,7	3,44	0,01
1,15										0,1		0,2		0,3	3,57	0,01
1,25											0			0		0,00
1,35											0,2			0,2	3,50	0,01
1,45																
	3,3	12,8	10,1	6,9	6,6	13,6	9,8	9,8	8,3	6,8	6,9	3,5	1	99,4		0,22

6.2.2 Hanstholm

Water Depth and Seabed Conditions and Distance to Shore

In general the seabed at Hanstholm is covered with sand and silt. However, at some locations this cover is washed away and Chalk bedrock is exposed. Within 2 km of the coast water depth reaches 30 metres in a local area of about 500 m^2, further offshore the water depth decreases. The shortest distance to shore from the 30 m water depth location is about 2 km – the distance to the harbour for maintenance is about the same.

Table 15 - Main Wave Characteristics of Hanstholm Test Center

Location: Hanstholm		
Water depth	12 - 30	[m]
Design significant wave height Hs, 10 year	6,6	[m]
Design zero-crossing period Tz, 10 year	10	[sec]
Max wind speed	30	[m/s]
Max Current speed	3,4	[m/s]
Max High Water level	1,6	(m)
Min Low Water level	-1,5	(m)
Maximum Ice thickness	-	[m]
Wave power annual average	6	[kW/m]

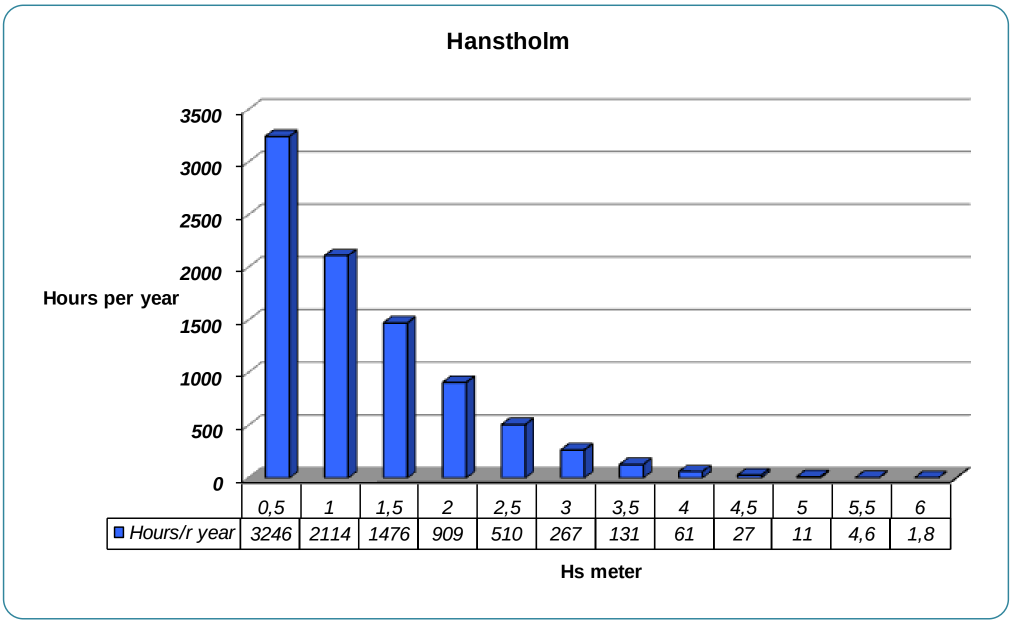
Statistical Wave Distribution

Based on the DWP *(12)* data there was no real scatter diagram available. However, the following distribution and relation between H_s and T_z was used.

$T_z = 3{,}55\ (H_s)^{0{,}5}$

The distribution of H_s was expected to follow a Weibull probability distribution as:

Hs ⊂ Wei(1,3; 1,4)



Hs meter	0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6
Hours/r year	3246	2114	1476	909	510	267	131	61	27	11	4,6	1,8

Figure 20 H_s distribution at Hanstholm

A recent study (22) completed at AAU has analysed measured wave data from Hanstholm (over the period 01/11/2005 – 25/02/2009) measured at a water depth of 20 metres. Based on the reported data the scatter diagram below has been prepared and it confirms that the average power at Hanstholm is about 6 kW/m. The distribution of H_s compares well to previous assumptions.

In the study the period T_{mo1} is used and this period is shown to relate to the energy period T_e as

T_{mo1}=1,055 T_e

Table 16 Joint probability diagram from Hanstholm

Hs\Tmo1	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	>9,5	sum	Tmo1ave	Te ave	dPw	hours
0,125	0,0050	0,0081	0,0090	0,0048	0,0016	0,0004	0,0003	0,0002		0,0001			0,0001	0,0087	0,039	5,14	5,43	0,00	339
0,5	0,0240	0,0613	0,0677	0,0483	0,0316	0,0172	0,0081	0,0029	0,0016	0,0014	0,0008	0,0007	0,0002	0,0035	0,270	4,31	4,55	0,15	2361
1	0,0026	0,0161	0,0683	0,0815	0,0621	0,0429	0,0165	0,0056	0,0017	0,0004	0,0001			0,0006	0,298	4,72	4,98	0,73	2614
1,5	0,0001	0,0010	0,0099	0,0524	0,0608	0,0350	0,0156	0,0049	0,0031	0,0006	0,0002	0,0001		0,0002	0,184	5,06	5,34	1,08	1611
2		0,0003	0,0005	0,0031	0,0365	0,0420	0,0181	0,0046	0,0017	0,0007	0,0004	0,0003	0,0002	0,0001	0,108	5,48	5,78	1,23	950
2,5				0,0003	0,0013	0,0213	0,0220	0,0059	0,0012	0,0005	0,0003	0,0001			0,053	5,85	6,18	1,00	464
3				0,0003	0,0002	0,0008	0,0102	0,0127	0,0023	0,0007	0,0004	0,0002	0,0002	0,0003	0,028	6,39	6,74	0,84	247
3,5					0,0002	0,0003	0,0002	0,0043	0,0045	0,0010	0,0003	0,0002	0,0001	0,0001	0,011	6,78	7,15	0,48	99
4						0,0001	0,0001	0,0001	0,0020	0,0022	0,0002	0,0001			0,005	7,15	7,54	0,29	43
4,5							0,0001			0,0007	0,0010	0,0003	0,0001		0,002	7,53	7,94	0,18	20
5							0,0002	0,0001			0,0003	0,0003	0,0002	0,0001	0,001	7,89	8,32	0,11	9
5,5														0,0001	0,000				3
6															0,000				0
6,5															0,000				
7															0,000				
7,5															0,000				
sum	0,028	0,087	0,155	0,191	0,194	0,160	0,091	0,041	0,018	0,008	0,004	0,002	0,001	0,001	1,000			6,09	8760

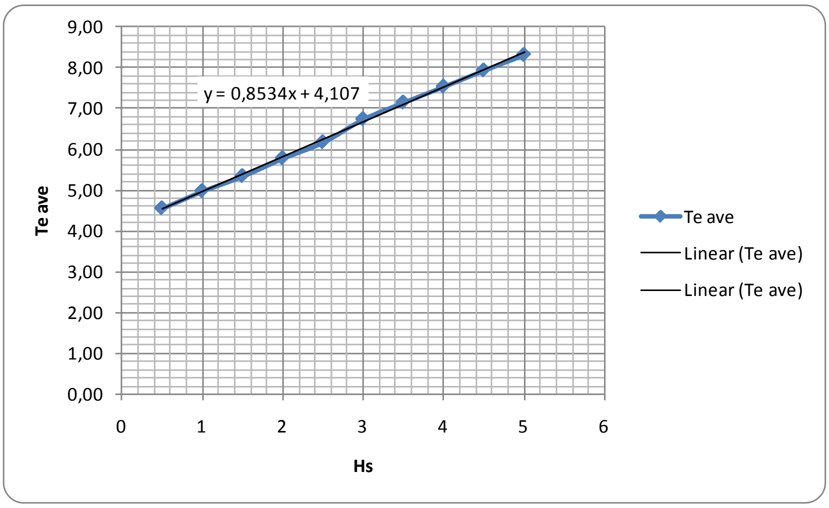


Figure 21 Linear Relationship between H_s and $T_{e\ ave}$ at Hanstholm

6.3 Test Sites in the United Kingdom

The UK being exposed to strong ocean waves it has been one of the first countries to realise the potential energy supply that could come from waves. Pioneers like Stephen Salter from the Edinburgh University(23) have inspired a new generation of engineers leading to the formation, i.e., of the team behind Pelamis.

Other teams such as the one team at Queen's University, Belfast (followed by WaveGen) developed in the beginning of 1990 the OWC, leading to the construction of the 500 kW LIMPET device on the shore at the Scottish island of Islay(24). More recently a 300 kW prototype of the nearshore Oyster device (also developed with contribution of Queen´s University) was installed at the EMEC test site on 20 November 2009 (25).

6.4 European Marine Energy Centre (EMEC)

The European Marine Energy Centre (EMEC) test facility was established in 2002 to create a North Atlantic test base for both tidal end wave energy devices. Much information is available on the website(26) from EMEC – related to guidelines and preliminary standards. EMEC has contributed the Task 3.3 report on design basis for wave energy converters.

The summary data below is extracted from the preliminary survey that was carried out in 2001(27). More detailed data can be obtained from EMEC at a moderate cost.

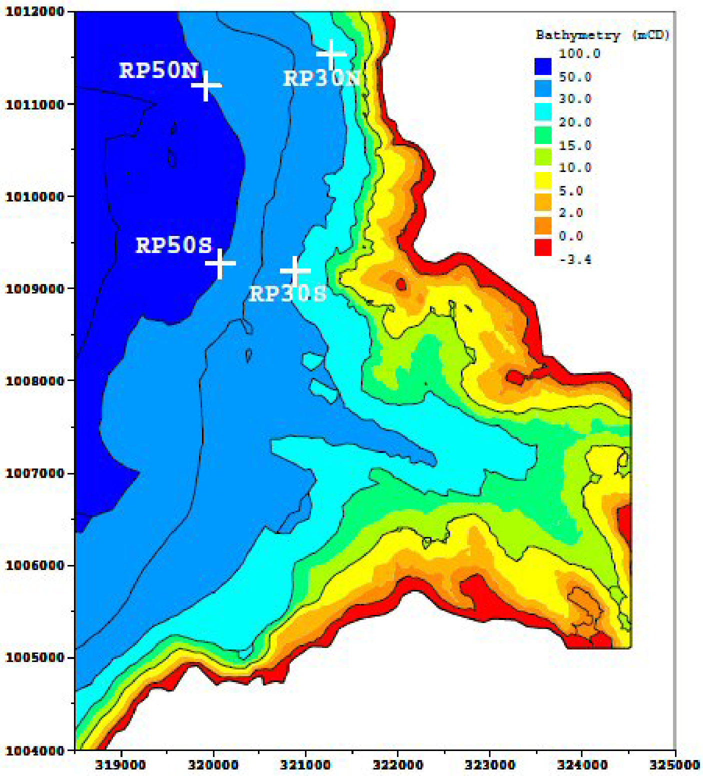


Figure 22 - Refraction Points used to calculate Nearshore Wave Conditions at 50 metre and 30 metre water depth

Table 17 - Main Characteristics of the Billia Croo Wave Site at EMEC Test Centre

Location: EMEC	59.00 N, 3.66W	
Water depth [m]	50	[m]
Design significant wave height H_s	14 -15	[m]
Design peak period T_z	14	[sec]
Max wind speed		[m/s]
Max Current speed		[m/s]
Max High Water level	2,5	(m)
Min Low Water level	-1,7	(m)
Maximum Ice thickness		[m]
Wave power annual average	21	[kW/m]

Table 18 - Joint probability diagram (H_s and T_z) for the EMEC location RP5OS 59,00°N;3,66°W (absolute numbers of occurrences, all directions, all year)

Hs \ Tz	<3	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	Sum	Tz ave	dP
0,25		2653	3618	1943	791	356	250	137	31	2				9781	4,89	0,02
0,75		2273	9363	5794	2063	734	182	85	40	2				20536	5,05	0,34
1,25		453	6484	6977	2946	1131	328	106	38		9	7	2	18481	5,48	0,93
1,75		130	2035	7652	2823	1029	352	139	21	0		5		14186	5,81	1,48
2,25			288	5405	3838	1081	319	184	66	9				11190	6,20	2,06
2,75			26	1135	5072	1135	234	137	52	17	2		2	7812	6,65	2,31
3,25			5	137	3278	2002	250	106	35	19	7			5839	7,01	2,54
3,75				14	713	2714	415	92	14	9	2			3973	7,49	2,46
4,25					57	1725	550	94	40	19	0	5	5	2495	7,88	2,09
4,75					7	430	861	118	26	14	5			1461	8,35	1,62
5,25						45	767	144	31	5				992	8,68	1,40
5,75						0	267	255	7	2	5			536	9,05	0,94
6,25					2	5	54	227	14	5				307	9,35	0,66
6,75						5	5	142	80	5				237	9,82	0,62
7,25								66	111		2			179	10,15	0,56
7,75								31	109	2	2			144	10,33	0,53
8,25								7	31	21				59	10,74	0,25
8,75									26	26				52	11,00	0,26
9,25									2	19	5			26	11,62	0,15
9,75										14	2			16	11,63	0,10
10,25										7	2			9	11,72	0,07
10,75											2			2	12,50	0,02
11,25											5			5	12,50	0,05
11,75														0		
Sum	0	5509	21819	29057	21590	12392	4834	2070	774	197	50	17	9	98318		21,46

6.5 Wave Hub

The Wave Hub test site is a project in the Southwest of England, located 16 km offshore near Cornwall St. Ives Bay (28)(29)(30). It will be the UK's first offshore facility for demonstration and proving of the operation of arrays of wave energy conversion devices. Up to four different technologies can be placed within a 1 km x 2 km sea area at any one time. This area will be leased to each developer for installation from 2010 onwards.

Leases will run for five years, or maybe longer, and will allow each developer to generate a maximum of 4-5 MW of power. Wave Hub will record the incoming waves and will enter into a power purchase agreement on behalf of all developers using the project.

Table 19 Summary data from the Wave Hub.

Location: Wave Hub	**50,36° N 5,67° W**	
Water depth [m]	50	[m]
Design significant wave height H_s	14,4	[m]
Design peak period T_z	14,1	[sec]
Max wind speed	33,2	[m/s]
Max Current speed	3,8	[m/s]
Max High Water level	4	(m)
Min Low Water level	-4	(m)
Maximum Ice thickness	-	[m]
Wave power annual average	17	[kW/m]

Table 20 Joint probability diagram for Wave Hub all directions all year (2005 – 2006)

Hs \ Tz	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	Sum	Tz ave	dp
0,25	3	9	5	2						19		
0,75	57	95	56	16	2					226	5,66	0,42
1,25	21	120	69	35	8	3	1			257	6,12	1,44
1,75		67	80	38	17	6	3		1	212	6,69	2,55
2,25		11	61	29	14	5	1			121	7,04	2,53
2,75			27	26	12	3	1	1		70	7,47	2,32
3,25			3	20	14	5	1			43	8,06	2,15
3,75				9	11	4	2			26	8,46	1,82
4,25				1	5	3	1	1		11	9,14	1,07
4,75					3	2	1			6	9,17	0,73
5,25					2	3	1			6	9,33	0,91
5,75						2	1			3	9,83	0,57
6,25						1				1	9,50	0,22
Sum	81	302	301	176	88	37	13	2	1	1001		16,73

6.6 Galway Bay, Ireland

The Irish test site at Galway Bay is an Intermediate Scale Test Site (quarter scale Atlantic seas) located at Spiddal, County Galway, Ireland. Two systems have been tested at the site so far:

1. WaveBob (April-May 2006, September-October 2007) (31)
2. OE Buoy (December 2006–August 2007, October 2007–August 2009) (32)

There are no onshore facilities at the site. Individual developers have made their own arrangements for data transmission, etc. Vessels and cranes are available in Galway Docks. A number of engineering companies exist in Galway, one heavy steel fabrication company is located on the Galway Docks site.

The site access is pre-permitted with conditions set down by the Marine Institute (33)
The most relevant information for this test site follows:

Distance to large town – 15km,
Distance to nearest airport – 20km,
Distance from nearest service port to site – 20km,
Distance from nearest access harbour to site – 1,5km,
Distance from site to shore – 1km,
Restrictions, availability & conditions if any – Access Harbour Tidal – 2 hours either side of high water

Water depth at site is about 22m.
Tidal range up to 5m (Spring tidal)
The seabed material is mud, sand, gravel or rock – sand / mud

Wave measurements have taken place since 2005 – directional buoy deployed since end of 2008. During this period the highest sea state was measured on 31 December 2006 with 4,3 meter H_s.

Table 21 – Summary Data for Galway Bay

Location: Galway Bay	**43° 28´ 22.6´´ N; 2° 51´ 15.9´´ W**	
Water depth	22	[m]
Design significant wave height H_s (estimate)	5	[m]
Design peak period T_p (estimate)	10	[sec]
Max wind speed	NA	[m/s]
Max Current speed	NA	[m/s]
Max High Water level	2,5	(m,MSL)
Min Low Water level	-2,5	(m,MSL)
Maximum Ice thickness	-	[m]
Wave power annual average	2,4	[kW/m]

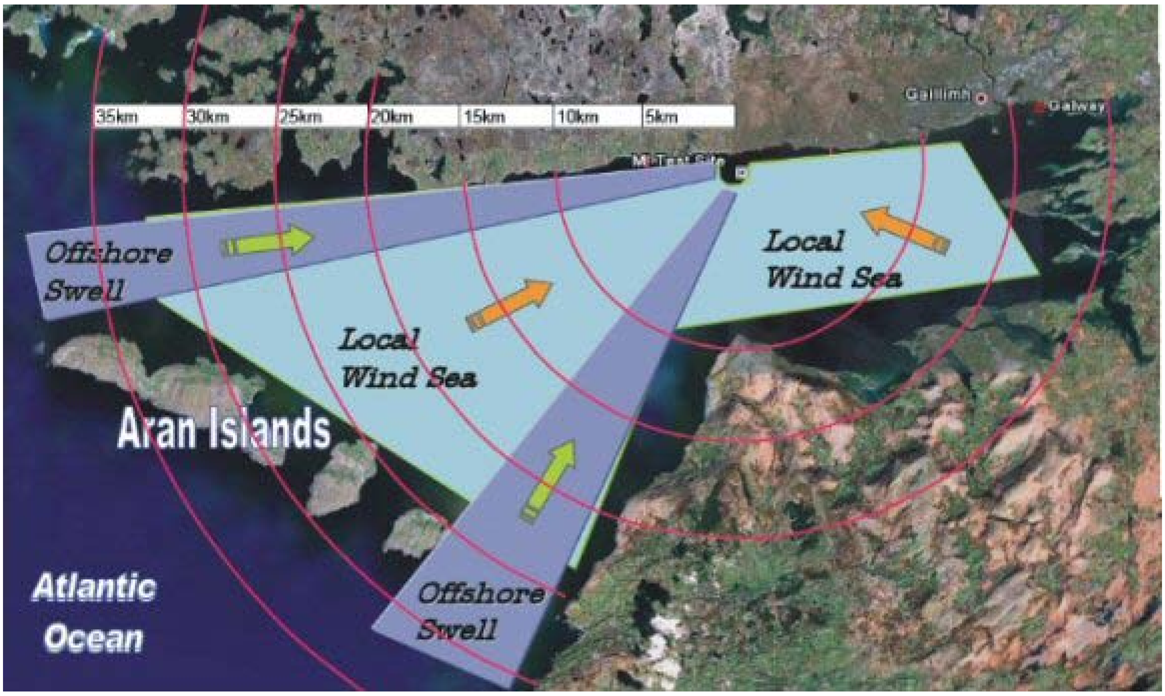


Figure 23 Sea Conditions in Galway Bay

Table 22 Joint Probability Diagram from Galway Bay

Galway Bay test site: pos 53,228°N; 9,266°W															
Hs\Tz	2,25	2,75	3,25	3,75	4,25	4,75	5,25	5,75	6,25	6,75	7,25	7,75	Sum	Tz ave	dP
0,25	4,21	9,04	6,66	5,65	5,14	4,38	3,6	2,45	1,3	0,73	0,1	0,02	43,28	3,85	0,06
0,75		2,48	9,21	8,15	4,41	3,05	2,11	1,2	0,77	0,12	0,05		31,55	3,95	0,41
1,25			0,36	4,21	6	2,86	0,83	0,45	0,15	0,01			14,87	4,30	0,59
1,75				0,12	1,72	3,15	0,85	0,17	0,03	0,03			6,07	4,70	0,51
2,25					0,02	0,85	1,72	0,08	0,01	0,02			2,7	5,11	0,41
2,75							0,61	0,41	0,01				1,03	5,46	0,25
3,25								0,28	0,07				0,35	5,85	0,13
3,75								0,01	0,14				0,15	6,22	0,08
4,25													0		
Sum	4,21	11,52	16,23	18,13	17,29	14,29	9,72	5,05	2,48	0,91	0,15	0,02	100		2,44

6.7 Biscay Marine Energy Platform (bimep), Spain

The Biscay Marine Energy Platform (**bimep)** test site is located in the sea off the coast of the village of Armintza, in the municipal area of Lemoiz, some 30 kilometres north of Bilbao in the Basque Country, Spain.

Reserved offshore area of 4 x 2 km, marked with navigation buoys. These dimensions include a 500 m guard area between the outer limits of the converter sites and the edge of the reserved area. *bimep* is expected to start operation in 2011.

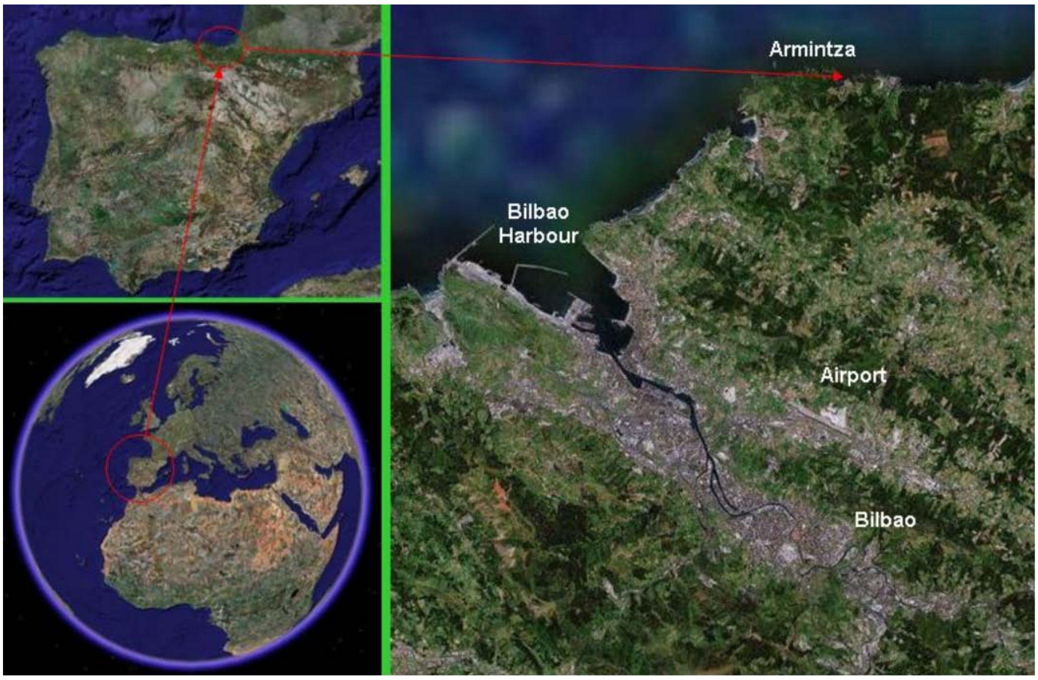


Figure 24

bimep will be associated to a marine energy research centre located in the town of Lemoiz. Applications for permits have been handed in according to Spanish legislation. Applications have been submitted for "*Consultation for the necessity of Environmental Impact Assessment, Electric installations under special regime, and Occupation of public maritime domain*", so the licensing is now in process.

Distance to large town: 30 km
Distance to nearest airport: 24 km
Distance from nearest service port to site: 10 Nautical Miles [NM] (1NM = 1,852 Km)
Distance from nearest access harbour to site: small harbour at 1 NM, bigger ones at 6NM and 10NM.

Distance from site to shore: nearest point at 0.54 Nautical mile (NM), distance from closest test berth to shore: 1 NM
Restrictions, availability & conditions if any: interference with singular geological formation and shadow to nearby beaches have been avoided.

Water depth and seabed conditions
Water depths at site: 50-90 m
The seabed material: sedimentary material filling old river bed, composed by gravelly sand to sandy gravel grain size sediment, in between rocky outcrops

The WECs can be connected to the grid at 4 offshore power connection points, one for each of the 4 export power cables. Each connection point basically consists of a 13,2 kV and a 5 MW submarine junction box designed for easy connection /disconnection of WECs and allowing several WECs to be connected to a single power cable.

Connection voltage and power level: 13,2kV, 5 MW

Table 23 - Summary data from the bimep Test Center

Location: bimep, Spain	**43° 28´ 22.6´´ N; 2° 51´ 15.9´´ W**	
Water depth	50 – 90	[m]
Design significant wave height H_s	11,45	[m]
Design peak period T_p	15,4	[sec]
Max wind speed	47	[m/s]
Max Current speed	1,4	[m/s]
Max High Water level	5,37	(m)
Min Low Water level	-0,49	(m)
Maximum Ice thickness	-	[m]
Wave power annual average	21	[kW/m]

Table 24 - Joint Probability Diagram (all year, all directions) for the Bimep Site.

Hs \ Tz	5	7	9	11	13	15	17	19	Sum	Tz ave	dP
0.75	0,017	0,025	0,009	0,002	0,000	0,000	0,000		0,052	6,79	0,12
1.5	0,098	0,327	0,165	0,058	0,009	0,001	0,000	0,000	0,657	7,56	6,57
2.5	0,000	0,085	0,064	0,037	0,018	0,004	0,000	0,000	0,208	8,83	6,75
3.5		0,010	0,030	0,007	0,006	0,004	0,001		0,058	9,66	4,01
4.5		0,000	0,012	0,004	0,001	0,001	0,001		0,020	10,20	2,43
5.5			0,001	0,003	0,000	0,000	0,000		0,005	10,45	0,85
6.5				0,000	0,000	0,000			0,000	12,85	0,12
7.5					0,000	0,000			0,000	14,33	0,01
Sum	0,115	0,447	0,279	0,111	0,035	0,010	0,002	0,000	1,000		20,87

A directional wave buoy (WaveScan from FUGRO:Oceanor) has been deployed at the site, it can transmit real time data and store spectral data

6.8 Port Kembla, Australia

Port Kembla in Australia is the site where the Oceanlinx OWC (34) system has been tested on the east side of the country. The Port Kembla Wave Energy Barge is located about 80m offshore from Rockwall Road, Port Kembla in a licenced area bounded by the Rockwall Road to the West, the Groyne to the North, a line of longitude 15º 054’ 10,4” E and a line of latitude 34º 27’11,8” S

Adjacent shore facilities include a security hut, trial generator and load bank plus switchboard enclosure for LV grid connection. Oceanlinx maintains a small office near number 6 berth within the Port Kembla harbour for the administration of maintenance crew.

The main characteristics are:
Distance to large town: 3 km
Distance to nearest airport: 75 km
Distance from nearest service port to site: 1 km
Distance from nearest access harbour to site: 1 km
Distance from site to shore: 100 m.
Water depths at site: 6 m.
The seabed material: mainly sand, with occasional rock.

Table 25- Summary Data for Port Kembla Test Centre

Location: Port Kelemba, Australia	34°27’11,8”E 15°54’10,4”S	
Water depth	6	[m]
Design significant wave height H_s, 10 year	6,6	[m]
Design zero-crossing period T_z, 10 year	10	[sec]
Max wind speed	50	[m/s]
Max Current speed	1	[m/s]
Max High Water level	1,25	(m)
Min Low Water level	-1,25	(m)
Maximum Ice thickness	-	[m]
Wave power annual average	6,7	[kW/m]

Table 26 - Joint Probability Diagram from Port Kembla (all year all directions)

Hs \ Te	1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	16,5	17,5	18,5	19,5	20,5	Sum	Te ave	dp
0,125	16	68	38	10	2	2	72	18	29	49	39	32	13	4	2	0	0	0	0	0	394	7,59	0,00
0,375	0	177	68	48	188	393	316	834	1762	2226	1323	1619	748	131	79	25	1	0	0	1	9939	10,38	0,03
0,625	0	32	531	724	1896	3019	3695	5495	6414	7045	3842	4214	1841	699	481	130	28	3	0	0	40089	9,64	0,35
0,875	0	0	119	1332	2904	5221	7107	10412	10404	10206	3964	3761	1471	534	343	78	13	0	1	0	57870	9,18	0,95
1,125	0	0	1	656	1816	3961	5683	8114	8682	8980	3461	3230	1156	325	269	82	13	7	0	0	46436	9,33	1,28
1,375	0	0	0	62	601	1820	3254	4526	5285	5768	2171	1856	774	236	159	79	3	4	0	0	26598	9,59	1,12
1,625	0	0	0	0	59	598	1470	2157	2607	3118	1233	1072	526	155	129	53	5	0	0	0	13182	9,94	0,80
1,875	0	0	0	0	1	154	591	956	1224	1871	772	675	326	130	54	27	1	0	0	0	6782	10,28	0,57
2,125	0	0	0	0	0	25	168	417	774	1162	476	377	130	63	37	12	1	0	0	0	3642	10,48	0,40
2,375	0	0	0	0	0	4	63	251	480	726	368	293	62	39	35	9	0	0	0	0	2330	10,65	0,33
2,625	0	0	0	0	0	0	25	120	142	305	186	259	26	11	37	16	0	0	0	0	1127	11,08	0,20
2,875	0	0	0	0	0	0	6	56	40	147	108	210	25	8	21	12	0	0	0	0	633	11,51	0,14
3,125	0	0	0	0	0	0	3	19	31	112	112	148	28	4	7	7	0	0	0	0	471	11,58	0,12
3,375	0	0	0	0	0	0	0	9	11	53	83	126	26	4	6	9	0	0	0	0	327	11,98	0,10
3,625	0	0	0	0	0	0	0	6	11	18	51	87	16	1	6	9	0	0	0	0	205	12,15	0,08
3,875	0	0	0	0	0	0	0	5	15	13	36	44	21	1	2	4	0	0	0	0	141	11,92	0,06
4,125	0	0	0	0	0	0	0	0	8	11	39	30	9	2	2	2	0	0	0	0	103	11,94	0,05
4,375	0	0	0	0	0	0	0	0	4	13	23	22	17	0	0	1	0	0	0	0	80	12,00	0,04
4,625	0	0	0	0	0	0	0	0	2	11	25	21	9	1	0	0	0	0	0	0	69	11,89	0,04
4,875	0	0	0	0	0	0	0	0	1	5	10	24	7	1	0	0	0	0	0	0	48	12,21	0,03
5,125	0	0	0	0	0	0	0	0	0	4	2	5	6	4	0	0	0	0	0	0	21	12,69	0,02
5,375	0	0	0	0	0	0	0	0	0	0	1	6	2	3	0	0	0	0	0	0	12	13,08	0,01
5,625	0	0	0	0	0	0	0	0	0	0	0	3	0	2	0	0	0	0	0	0	5	13,30	0,00
5,875	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	14,50	0,00
6,125	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	12,50	0,00
Sum	16	277	757	2832	7467	15197	22453	33395	37926	41843	18325	18116	7239	2360	1669	555	65	14	1	1	210508		6,74

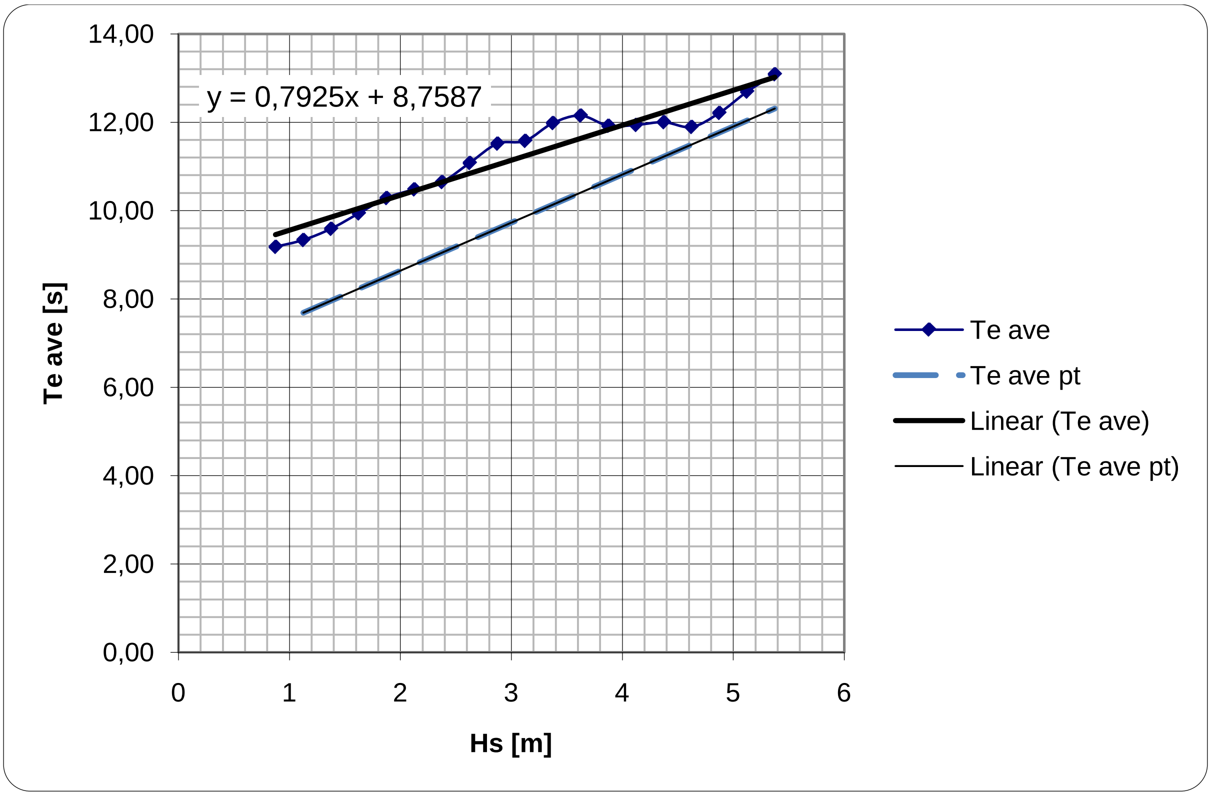


Figure 25 Fitted linear relationship between the average wave energy period ($T_{e\ ave}$) and the significant wave height (H_s) at Port Kembla. For comparison the linear relationship found at Portugal Figure 13 is shown with a dashed line. The waves at Port Kembla seems to be even more swell-dominated the than the waves in Portugal.

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