Wave energy resource in the North Sea

C. Beels[1], J.C.C. Henriques[2], J. De Rouck[1], M.T. Pontes[2], G. De Backer[1] and H. Verhaeghe[1]

[1] Department of Civil Engineering, Ghent University
Technologiepark 904, B-9052 Zwijnaarde, Belgium
E-mail: charlotte.beels@UGent.be, julien.derouck@UGent.be, griet.debacker@UGent.be, hadewych.verhaeghe@UGent.be

[2] Department Renewable Energies, Instituto Nacional de Engenharia, Tecnologia e Inovação
Estrada do Paço do Lumiar, 1649-038 Lisboa, Portugal
E-mail: joao.campos@ineti.pt, teresa.pontes@ineti.pt

Abstract

Due to the high potential of wave energy and the goal to raise the share of renewable energy supply in the EU up till 20 % in 2020, the development of wave energy is accelerated. Until now the wave energy resource was highlighted in regions with a high wave energy density. As Wave Energy Converters (WECs) still contend with problems such as structural strength and mooring in a severe and energetic wave climate, the prospects of wave power conversion in a less aggressive wave climate should be investigated. This paper describes the wave power resource in a rather sheltered area i.e., the North Sea. The available wave power is studied on 34 locations. Characteristic sea states are defined for the Belgian, Dutch, German, Danish, Norwegian and UK Continental Shelf. An inverse-ray refraction model, implemented at INETI (Instituto Nacional de Engenharia, Tecnologia e Inovação), is presented to calculate the resource on more convenient locations for wave energy conversion. The wave power potential in the North Sea is compared with the resource of the West European coast. Near shore (< 30 km off the coast) up to a maximum of approximately 11 kW/m is available in the North Sea.

Keywords: North Sea, wave climate, wave energy.

Nomenclature

ρ	= sea water density
g	= acceleration due to gravity
f	= frequency
ω	= angular velocity
z	= water depth
θ	= wave direction
s,n	= tangential and normal direction
σ	= directional width
k	= wave number
C_g	= group velocity
C	= phase velocity
γ	= peak enhancement factor
α	= scaling parameter
s	= spreading parameter
$S(f)$	= frequency spectrum
$S(f,\theta)$	= directional spectrum
$D(f,\theta)$	= directional distribution function
m_n	= n[th] moment of spectral density
H_{m0}	= significant wave height
$T_{m0,2}$	= mean wave period
T_e	= energy period
P	= wave power

Subscripts

p	= peak value

Superscripts

$-$	= mean value

Introduction

Oceans are an enormous source of energy. Even for regions with rather limited average annual available wave power (e.g. 10-20 kW/m) the global technical resource is estimated to range from 200 till 1000 TWh/year [1]. The large density [2-3] and the favourable seasonal variation of ocean energy, make technologies for wave energy conversion worthwhile to be investigated and developed.

The amount of the wave power resource is often considered one of the most important features to determine interesting locations for wave energy conversion, whereas the survivability of the wave energy converter (WEC) is actually as important and should be taken into account. In general a severe wave climate has a larger potential, but a lot of difficulties related to the structural strength and the mooring of the device are still unsolved. Therefore the wave energy potential in calmer seas need to be considered, certainly in this stage of technology.

This paper describes the wave energy resource in the North Sea, based on data from wave measurements and numerical calculations. Further initial calculations with a refraction program, developed at INETI [4], to complete the two last mentioned data sources are described.

1 The North Sea

The North Sea (Figure 1) is an inland sea of the Atlantic Ocean in Northwestern Europe with an average water depth of 94 m. The North Sea is located between the European Continent (Denmark, Germany, The Netherlands, Belgium and France), the Scandinavian peninsula (Norway) and the UK, and is 575 000 km² large.

On Figure 1 different sites are indicated with numbers. On those sites wave measurement equipment is installed or wave data are available through numerical calculations. The data on those locations are used to identify the wave power resource in the North Sea.

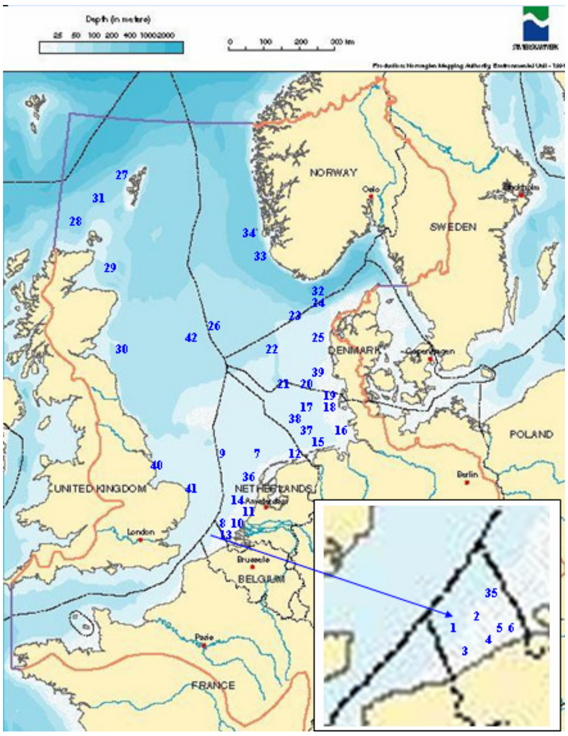

Figure 1: Locations with available wave data (wave measurements or numerical simulations) in the North Sea.

2 Wave data

Not all sites in the North Sea are suitable for wave energy exploitation. The average annual available wave power and the dominant mean wave direction need to be calculated to predict the suitability of a specific location. Also the current activities in the North Sea have to be taken into consideration.

The average annual available wave power on a certain location is calculated based on scatter diagrams. For the Belgian, Dutch, German, Danish, Norwegian and UK Continental Shelf characteristic sea states are defined. Furthermore when data were available the distribution of mean direction is studied on the defined characteristic locations.

A. Scatter diagrams

Scatter diagrams, based on wave measurements or numerical calculations on the Belgian, Dutch, German, Danish, Norwegian and UK Continental Shelf, are analysed.

A scatter diagram shows the average occurrence frequency (in %) of different sea states for one year (or one specific month) and a given wave direction. A sea state is defined by a combination of significant wave height H_{m0} (1) and mean wave period $T_{m0,2}$ (2), both derived from spectral analysis:

$$H_{m0} = 4\sqrt{m_0} \quad (1)$$

$$T_{m0,2} = \sqrt{\frac{m_0}{m_2}} \quad (2)$$

where m_n is the n^{th} moment of spectral density. As an example the average annual scatter diagram for all wave directions at Westhinder (Belgian Continental Shelf) is shown in Figure 2 ($GTZ = T_{m0,2}$ and $H_s = H_{m0}$). H_{m0}-values are divided in intervals of 0.5 m (except for the first two intervals) and $T_{m0,2}$-values in intervals of 1 s (except for the first interval).

H_S (m)	GTZ (sec) 0- <=2.5	2.5- 3.5	3.5- 4.5	4.5- 5.5	5.5- 6.5	6.5- 7.5	7.5- 8.5	8.5- 9.5	>9.5	TOTAAL
<= 0.25	.	0.06	0.64	0.21	0.02	.	0.00	.	.	0.93
0.25 - 0.50	0.05	4.46	11.69	3.86	0.53	0.06	0.01	.	.	20.65
0.50 - 1.00	0.01	6.12	20.51	8.38	1.91	0.30	0.02	.	.	37.25
1.00 - 1.50	.	0.29	10.63	8.98	1.83	0.27	0.02	.	.	22.02
1.50 - 2.00	.	.	1.89	6.46	2.02	0.27	0.01	.	.	10.65
2.00 - 2.50	.	.	0.04	2.67	2.00	0.42	0.01	.	.	5.14
2.50 - 3.00	.	.	.	0.57	1.17	0.50	0.02	.	.	2.27
3.00 - 3.50	.	.	.	0.04	0.46	0.26	0.04	0.00	.	0.79
3.50 - 4.00	.	.	.	.	0.09	0.07	0.05	0.00	.	0.21
4.00 - 4.50	.	.	.	.	0.02	0.03	0.02	0.00	.	0.07
4.50 - 5.00	.	.	.	.	0.00	0.01	0.00	0.00	.	0.02
5.00 - 5.50	.	.	.	.	.	0.00	.	.	.	0.00
5.50 - 6.00	.	.	.	.	.	.	.	.	.	.
6.00 - 6.50	.	.	.	.	.	.	.	.	.	.
> 6.50	.	.	.	.	.	.	.	.	.	.
TOTAAL	0.06	10.93	45.39	31.17	10.04	2.20	0.20	0.01	.	100.00

Figure 2: Average annual scatter diagram for all wave directions at Westhinder (Belgian Continental Shelf), based on measurements from 1-7-1990 until 30-6-2004 (Source: Flemish Ministry of Transport and Public Works – Agency for Maritime and Coastal Services – Coastal Division).

B. Average annual available wave power

For each sea state in a scatter diagram the corresponding wave power (kW/m) is calculated as:

$$P = \rho g \int_0^{\infty} C_g(f) S(f) df \quad (3)$$

where ρ represents the sea water density, g the acceleration due to gravity, C_g the group velocity and $S(f)$ the spectral density. The spectral distribution of the energy in the

North Sea can be described by a parametric Jonswap spectrum with peak enhancement factor γ = 3.3 and scaling parameter α = 0.2044 [5]:

$$S(f) = \alpha H_s^2 f_p^4 f^{-5} \exp\left(\frac{-5}{4}\left(\frac{f_p}{f}\right)^4\right)\gamma^{\exp\left(-\frac{(f-f_p)^2}{2\sigma^2 f_p^2}\right)} \qquad (4)$$

where f_p is the peak frequency. The parameter σ equals 0.07 for $f \leq f_p$ and 0.09 for $f \geq f_p$.

The available wave power in each sea state is multiplied with its occurrence frequency given in the scatter diagram. Summation leads to the average available wave power (per meter of wave crest).

Table 1 shows the obtained average annual available wave power for the selected locations in the North Sea together with the data source, the mean water depth and the shortest distance to shore. The locations are indicated on Figure 1. From Table 1 the following can be concluded:

- On the Belgian Continental Shelf the resource increases from approximately 1.5 kW/m near the coast to 4.6 kW/m offshore.

- The average annual available wave power ranges from approximately 5.5 kW/m, 7.5 km offshore, to 10 kW/m, 30 km offshore on the Dutch Continental Shelf.

- The resource on the German Continental Shelf varies between approximately 5 and 12 kW/m (between 35 and 44 km offshore) and is comparable with the potential on the Dutch Continental Shelf.

- On the Danish Continental Shelf the resource is varying from 7 kW/m near the coast to 17 kW/m far from shore (150 km). The resource near the coast is slightly higher than the near shore resource on the Dutch Continental Shelf. Generally it can be concluded that the average annual available wave power is comparable with the resource on the Dutch and German Continental Shelf.

- The resource in front of the Norwegian coast is very high (as compared to other parts of the North Sea), since the Norwegian Continental Shelf is hardly shaded by the UK.

- For the UK Continental Shelf, it is clear that the northern part of the North Sea has a larger wave power resource (Shetland and Orkney). Only the resource at Marr Bank is comparable to the available wave power on the Dutch, German and Danish Continental Shelf.

C. Characteristic sea states in the North Sea

Characteristic sea states can be applied during the initial design of wave power devices and preliminary wave energy production calculations. Characteristic sea states are defined as a weighted average of the total number of sea states in a scatter diagram and are therefore a good approximation of the actual wave climate. The use of characteristic sea states results in a fast and accurate basis for preliminary design. For detailed design more site specific measurements and data are needed.

Omni directional characteristic sea states are defined for a location on the Belgian, Dutch, German, Danish, Norwegian and UK Continental Shelf, approximately 30 km offshore with a water depth of approximately 30 m (indicated in bold in Table 1). The derived characteristic sea states for the selected locations are given in Table 2 to Table 7.

The number of sea states depends on the number of H_{m0}-intervals in the obtained scatter diagrams. For each significant wave height (centre of H_{m0}-interval) with an average annual occurrence frequency higher than 1 % a weighted average period $T_{m0,2}$ is calculated. $T_{m0,2}$ is derived by using the second moment of spectral density (equation (2)) and as a result may be sensitive to high-frequency low energy variations in the wave spectrum. A more generally accepted parameter for wave power calculations is the energy period T_e which represents lower frequencies better.

$$T_e = \frac{m_{-1}}{m_0} \qquad (5)$$

A relation between T_e and $T_{m0,2}$ has been derived based on a Jonswap frequency spectrum with γ = 3.3. For peak periods between 3 and 15 s the ratio between T_e and $T_{m0,2}$ is approximately 1.162.

N°	Location	Research on which data are based	Average annual available wave power [kW/m]	Mean water depth [m]	Shortest distance to shore [km]
The Belgian Continental Shelf					
1	**Westhinder**	**Physical measurements (1990-2004) (1)**	**4.64**	**28.8**	**32**
2	ZW-Akkaert	Physical measurements (1984-2004) (1)	3.64	22.7	20
3	Trapegeer	Physical measurements (1994-2004) (1)	1.51	6.6	3.5
4	Oostende	Physical measurements (1997-2005) (1)	1.66	6.2	1
5	Wandelaar	Physical measurements (1995-2004) (1)	2.63	12.6	10
6	Bol van Heist	Physical measurements (1985-2004) (1)	2.54	11.7	6.5
The Dutch Continental Shelf					
7	**Eierlandse Gat**	**Physical measurements (1979-2002) (2)**	**9.86**	**26**	**31**
8	Euro platform	Physical measurements (1979-2002) (2)	7.04	32	36
9	K13a platform	Physical measurements (1979-2002) (2)	10.80	30	88
10	Lichteiland Goeroe	Physical measurements (1979-2002) (2)	6.13	21	15
11	Noordwijk Meetpost	Physical measurements (1979-2002) (2)	5.42	18	7.5
12	Schiermonnikoog N.	Physical measurements (1979-2002) (2)	7.44	19	16
13	Schouwenbank	Physical measurements (1979-2002) (2)	5.57	20	20
14	IJmuiden Munitie Stortplaats	Physical measurements (1979-2002) (2)	8.68	21	32
The German Continental Shelf					
15	**Fino-Borkumriff**	**Physical measurements (2003-2005) (3)**	**11.60**	**27**	**34.5**
16	Helgoland	Physical measurements (1990-2004) (3)	5.91	20	43
17	Nordseeboje NSB II	Physical measurements (1994-2004) (3)	17.55	42	118
18	Westerland	Physical measurements (2002-2005) (3)	4.47	18	43.5
The Danish Continental Shelf					
19	Point 1	MIKE 21 OSW (1979-1993) (4)	7	20	64
20	Point 2	MIKE 21 OSW (1979-1993) (4)	12	31	100
21	**Point 3**	**MIKE 21 OSW (1979-1993) (4)**	**16**	**39**	**150**
22	Point 4	MIKE 21 OSW (1979-1993) (4)	17	40	150
23	Point 5	MIKE 21 OSW (1979-1993) (4)	14	58	100
24	Point 6	MIKE 21 OSW (1979-1993) (4)	11	166	68
25	Fjaltring	Physical measurements (1979-1993) (4)	7	20	4
The Norwegian Continental Shelf					
32	Point 1160	WINCH model (1971-2000) (5)	23.60	200	57
33	Point 1261	WINCH model (1971-2000) (5)	32.52	270	43
34	**Utsira**	**Physical measurements (1974-1986) (6)**	**23.12**	**200**	**21**
26	Ekofisk	Physical measurements (1979-1993) (4)	24	71	300
The UK Continental Shelf					
27	Shetland (NW)	UK Waters Wave Model (2000-2004) (7)	42	200	30
28	Orkney (NW)	UK Waters Wave Model (2000-2004) (7)	33	90	27
29	Moray Firth	UK Waters Wave Model (2000-2004) (7)	19	112	55
30	**Marr Bank**	**UK Waters Wave Model (2000-2004) (7)**	**11**	**57**	**52**
31	Fair Isle	WAM (1987-1994)(6)	61.47	100	70

(1) Flemish Ministry of Transport and Public Works (Agency for Maritime and Coastal Services – Coastal Division)
(2) Rijkswaterstaat. Available:http://www.golfklimaat.nl
(3) The Federal Maritime and Hydrographic Agency (BSH)
(4) Dansk Hydraulisk Institut (DHI) – Based on wind data from the European Centre for Medium Range Weather Forecasting (ECMWF) from 1979 till 1993. Calibrated with wave measurements at Ekofisk and Fjaltring [6].
(5) Norwegian Meteorological Institute – Based on air pressure fields (digitized maps and ECMWF) from 1955-2005. Calibrated with buoy data from 1980.
(6) WERATLAS [2].
(7) Met Office [7-8].

Table 1: Average annual available wave power in the North Sea.

Location	Westhinder					
Mean water depth [m]	28.8					
Distance to shore [km]	32					
Average annual available wave power [kW/m]	4.64					
Sea State	1	2	3	4	5	6
H_s[m]	0.375	0.75	1.25	1.75	2.25	2.75
T_e[s]	4.68	4.87	5.35	5.89	6.45	6.93
Wave power [kW/m]	0.33	1.39	4.29	9.42	17.48	28.86
O.F.[%]	20.65	37.25	22.02	10.65	5.14	2.27

Table 2: Characteristic sea states on the Belgian Continental Shelf.

Location	Eierlandse Gat				
Mean water depth [m]	26				
Distance to shore [km]	31				
Average annual available wave power [kW/m]	9.86				
Sea State	1	2	3	4	5
H_s[m]	0.5	1.5	2.5	3.5	4.5
T_e[s]	4.72	5.58	6.44	7.29	8.13
Wave power [kW/m]	0.60	6.56	21.85	50.47	95.87
O.F.[%]	40.65	39.42	14.09	4.29	1.17

Table 3: Characteristic sea states on the Dutch Continental Shelf.

Location	Fino-Borkumriff			
Mean water depth [m]	27			
Distance to shore [km]	34.5			
Average annual available wave power [kW/m]	11.6			
Sea State	1	2	3	4
H_s[m]	0.25	0.75	1.25	1.75
T_e[s]	4.15	4.67	5.53	5.95
Wave power [kW/m]	0.13	1.35	4.50	9.57
O.F.[%]	9.14	27.31	22.62	18.55
Sea State	5	6	7	8
H_s[m]	2.25	2.75	3.25	3.75
T_e[s]	6.21	6.59	7.55	8.16
Wave power [kW/m]	16.77	27.73	45.39	66.54
O.F.[%]	10.25	5.08	3.35	1.63

Table 4: Characteristic sea states on the German Continental Shelf.

Location	Point 3				
Mean water depth [m]	39				
Distance to shore [km]	150				
Average annual available wave power [kW/m]	16				
Sea State	1	2	3	4	5
H_s[m]	1	2	3	4	5
T_e[s]	4.65	5.81	6.97	8.13	9.30
Wave power [kW/m]	2	12	32	66	115
O.F.[%]	46.8	22.6	10.8	5.1	2.4

Table 5: Characteristic sea states on the Danish Continental Shelf.

Location	Utsira				
Mean water depth [m]	200				
Distance to shore [km]	21				
Average annual available wave power [kW/m]	23.12				
Sea State	1	2	3	4	5
H_s[m]	0.5	1.25	1.75	2.25	2.75
T_e[s]	7.13	7.44	7.69	8.04	8.39
Wave power [kW/m]	0.88	5.76	11.69	20.20	31.49
O.F.[%]	19.70	21.80	17.10	12.90	9.40
Sea State	6	7	8	9	10
H_s[m]	3.25	3.75	4.25	4.75	5.25
T_e[s]	8.80	9.01	9.09	9.51	9.96
Wave power [kW/m]	46.17	62.78	81.31	106.17	137.56
O.F.[%]	6.40	4.20	2.70	1.60	1.20

Table 6: Characteristic sea states on the Norwegian Continental Shelf.

Location	Marr Bank				
Mean water depth [m]	57				
Distance to shore [km]	52				
Average annual available wave power [kW/m]	11				
Sea State	1	2	3	4	5
H_s[m]	0.5	1.5	2.5	3.5	4.5
T_e[s]	5.30	6.01	7.05	8.23	9.12
Wave power [kW/m]	0.67	6.91	22.78	53.71	101.09
O.F.[%]	31.2	45.1	15.9	4.5	1.3

Table 7: Characteristic sea states on the UK Continental Shelf.

For each defined sea state the corresponding wave power and the occurrence frequency are given in Table 2 till Table 7. Comparison of the characteristic sea states on the selected locations in the North Sea leads to the following conclusions:

- Westhinder is chosen as characteristic location on the Belgian Continental Shelf. More than 50 % of the time the significant wave height is smaller than 1 m (Table 2).

- Characteristic sea states are defined for the location Eierlandse Gat on the Dutch Continental Shelf. Significant wave heights smaller than 1 m occur 40 % of the time (Table 3).

- Fino-Borkumriff meets the conditions for characteristic location on the German Continental Shelf (Table 4). The wave power resource and the occurrence frequencies of the characteristic sea states are comparable to those on the Dutch Continental Shelf.

- On the Danish Continental Shelf characteristic sea states (Table 5) are defined for a location 150 km offshore because this location is used as a standard in Denmark [6] and no data approximately 30 km offshore were available. The high distance to shore of this point should be taken into account when comparing the resource with other locations. Approximately 50 % of the time H_s is smaller than 1.5 m. The occurrence frequency of the smaller waves is still very high.

- At the Norwegian coast the water depth 30 km offshore is higher than approximately 30 m. Utsira is chosen as characteristic location (Table 6). Only 20 % of the time the significant wave height is smaller than 1 m.

- The wave power resource on the UK Continental Shelf is described by Table 7. Marr Bank satisfies the conditions for characteristic location. Significant wave heights smaller than 1 m occur approximately 30 % of the time.

In general there is a shift in occurrence frequency to higher significant waves when going more northwards in the North Sea. The wave period corresponding to a certain significant wave height is comparable on the Belgian, Dutch, German and Danish Continental Shelf, whereas the wave period on the UK and Norwegian Continental Shelf is slightly higher.

When available, the contribution of different wave sectors to the average annual available wave power for the selected locations is given through wave roses (Belgian, Dutch and Danish Continental Shelf: Figure 3 - 5). A segment of a wave rose shows the relative occurrence frequency of mean wave directions in that sector. Each segment is divided into power ranges to indicate the contribution of high and low energetic waves.

For the Belgian Continental Shelf (Figure 3), sixteen sectors (each 22.5°) are considered. It is assumed that wind and wave direction coincide.

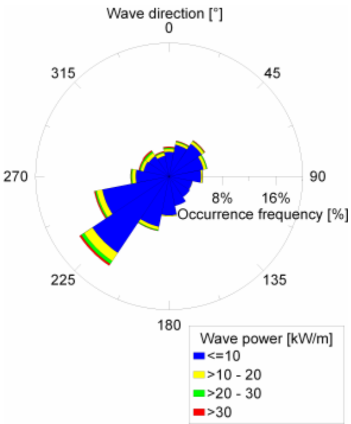

Figure 3: Wave rose at Westhinder, based on measurements from 1-7-1990 until 30-6-2004 – Belgian Continental Shelf (32 km offshore).

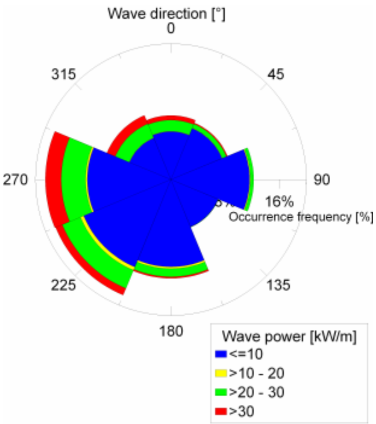

Figure 4: Wave rose at Eierlandse Gat, based on measurements from 1979 until 2002 – Dutch Continental Shelf (31 km offshore).

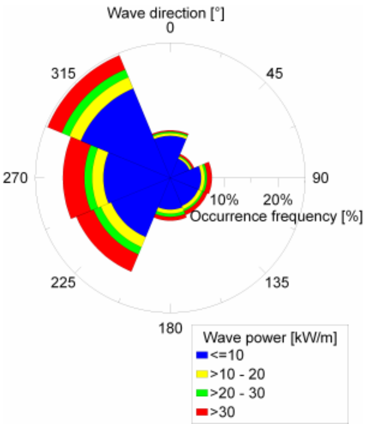

Figure 5: Wave rose at Point 3, based on calculations with the wave propagation model Mike 21 OSW (DHI) – Danish Continental Shelf (150 km offshore).

In all directions the contribution of low energetic (<= 10 kW/m) waves is dominant. From the sector east till south no high energetic (> 30 kW/m) waves occur. The prevailing wave direction is south-west. Also the neighbouring sectors have a large contribution.

On the Dutch Continental Shelf (Figure 4) eight sectors of 45° are taken into consideration. The waves are coming most frequently from the sectors west and south-west. The contribution of the sector west is higher and the share of the high energetic waves is increased, as compared to Westhinder.

Figure 5 shows the dominant wave directions at Point 3 based on the scatter diagrams in [6]. As on the Dutch Continental Shelf eight sectors are considered. Most of the waves are coming from the north-west. All sectors have a contribution of high energetic waves.

When comparing Figure 3, 4 and 5, an increasing share of high energetic waves (> 30 kW/m) and a shift in prevailing wave direction from south-west till north-west is observed.

On the German Continental Shelf no data on the wave direction were available. Data on the distribution of mean direction on the Norwegian and UK Continental Shelf are available at the Norwegian Meteorological Institute and in [8].

3 Refraction model

It is not obvious to compare the different parts of the North Sea; e.g. no wave data are available on a location approximately 30 km offshore on the Danish Continental Shelf. To improve the comparison between the different continental shelves in the North Sea, numerical calculations with an inverse-ray refraction program [4] are performed. Through these calculations the resource can be studied on selected locations.

Besides an improvement of the characteristic sea states, calculations of the resource on convenient sites for the installation of farms of WECs, are intended with the refraction model.

To select interesting locations for wave power conversion the current activities (e.g. ports, ship routes, military practice areas, extraction zones, pipelines, cables, offshore wind farm, …) in the North Sea have to be taken into account [9-11].

Sites near installed or planed offshore wind farms are chosen as possible locations for offshore wave farms, because on those locations the connection to the grid is already provided. In the scope of this work 12 locations are selected (Table 8).

The wave propagation model [4] used for this study is developed at INETI (Instituto Nacional de Engenharia, Tecnologia e Inovação) and translates offshore directional spectra in the North Sea to near shore directional spectra on specified locations. The model computes the wave conditions (directional spectra) on a near shore location, based on the Longuet-Higgins spectrum transformation along wave rays.

N°	Location	Mean water depth [m]	Shortest distance to shore [km]	Offshore location
1	Westhinder [(2)]	28.8	32	K13 [(1)]
2	ZW-Akkaert [(2)]	22.7	20	K13
35	Thorntonbank	20	46	K13
14	IJmuiden Munitie Stortplaats [(2)]	21	32	K13
36	Q7	20	27	K13
9	K13a Platform [(2)]	30	88	AUK [(1)]
37	Nordsee Windpower	35	115	AUK
38	Borkum West	30	60	AUK
21	Point 3 [(2)]	39	150	AUK
39	Horns Rev I	20	18	AUK
40	Scroby Sands	30	3.8	AUK
41	Inner Dowsing	15	5.7	AUK

[(1)] Rijkswaterstaat
[(2)] Locations to validate the numerical model

Table 8: Convenient locations for wave energy conversion in the North Sea.

These wave rays are calculated with an inverse formulation that solves [12]:

$$\frac{\partial \vartheta}{\partial s} = -\frac{1}{kC_g}\frac{\partial \omega}{\partial z}\frac{\partial z}{\partial n} \qquad (6)$$

with *(s,n)* the tangential and normal direction to the wave ray, θ the direction of the wave ray, z the water depth, ω the angular velocity, k the wave number and C_g the group velocity. Equation (6) is solved with a standard fourth order Runge Kutta method for each frequency and wave direction. The wave rays are calculated from the selected location towards deep water, resulting in a unique and fast solution. Figure 6 shows the calculated wave rays on the location ZW-Akkaert for a frequency of 0.24 Hz and an interval Δθ of 1°.

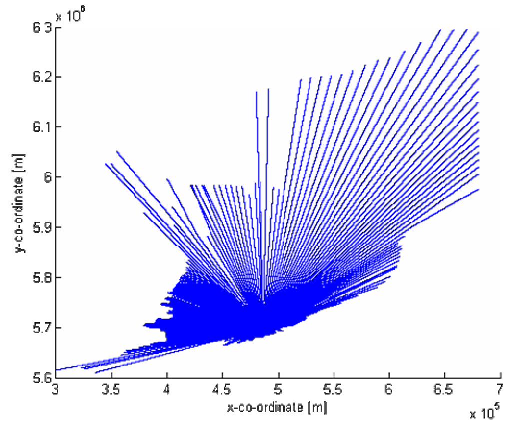

Figure 6: Wave rays ($\Delta\theta$ = 1°) at ZW-Akkaert (f = 0.24 Hz).

Longuet-Higgins [13] has proven that for linear waves the energy density $S(f,\theta)$, in absence of currents, wave breaking and diffraction, is conserved along wave rays:

$$\frac{CC_g}{4\pi^2 f} S(f,\theta) = \text{constant} \tag{7}$$

with C the phase velocity and f the frequency. Through a bilinear interpolation and a Delaunay triangulation the transformed spectrum is integrated. For each spectrum the wave power P, significant wave height H_{m0}, energy period T_e and mean direction are calculated. Several definitions exist for the mean direction. For wave energy studies it is most convenient to compute the mean direction from the directional power spectral density:

$$\bar{\vartheta} = \arctan \frac{\int_0^{2\pi}\int_0^{\infty} C_g(f) S(f,\theta) \sin\vartheta \, df d\theta}{\int_0^{2\pi}\int_0^{\infty} C_g(f) S(f,\theta) \cos\vartheta \, df d\theta} \tag{8}$$

Moreover the average available wave power and a scatter diagram, corresponding to the selected location are calculated.

The bathymetry of the North Sea and offshore directional spectra are needed as an input for the refraction program. The bathymetry was obtained at different institutions[1]. All co-ordinates were transformed to UTM-co-ordinates (geodectic datum WGS84) and all water depths were determined against the vertical datum Mean Low Low Water (MLLW). The MLLW is the average of the lowest points the tide reaches on each day during a measurement period of several years. Different bathymetries were interpolated [14].

Two datasets (AUK and K13, n° 42 and 9 on Figure 1) with frequency spectra $S(f)$, mean direction $\bar{\theta}(f)$ and directional width $\sigma(f)$ per frequency band Δf, measured between 1993 and 2002 with an interval of 3 hours, were obtained as an input for the spectrum transformation. Directional spectra were computed based on $S(f)$, $\bar{\theta}(f)$ and $\sigma(f)$. A directional spectrum is composed of a frequency spectrum $S(f)$ and a directional distribution function $D(f,\theta)$:

$$S(f,\theta) = S(f) D(f,\theta) \tag{9}$$

In the current study $D(f,\theta)$ proposed by Longuet-Higgins et al. [15] is used:

$$D(f,\vartheta) = \frac{2^{2s-1}}{\pi} \frac{\Gamma^2(s+1)}{\Gamma(2s+1)} \cos^{2s}\left(\frac{\theta-\bar{\theta}}{2}\right) \tag{10}$$

The parameter s gives the degree of directional energy concentration. s can be written as a function of the directional width:

$$s = \frac{2}{\sigma^2} - 1 \tag{11}$$

When using equation (11) only unimodal (never two directional peaks at the same frequency) and symmetrical directional peaks can be modelled. As only the mean direction is considered important in the current study, equation (11) can be used. A calculated directional spectrum is shown in Figure 7.

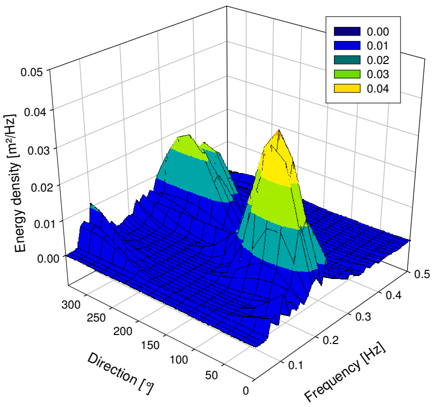

Figure 7: Calculated directional spectrum with the directional distribution function proposed by Longuet-Higgins et al. [15].

With the described inverse-ray refraction model wave data on the twelve selected locations will be obtained. A better comparison between the different continental shelves and data on more convenient locations for wave energy conversion will be available.

4 Comparison with the resource of the West European coast

Further two existing resources, WorldWaves [3] and WERATLAS [2], that show the average annual available wave power along the West European coast, are explored. Worldwaves is a global offshore wind and wave database. The data originate from the ECMWF (European Centre for Medium Range Weather Forecasting) WAM model archive and are calibrated and corrected (by Oceanor) against a global buoy and Topex Satellite altimeter database.

The resource in the North Sea varies from less than 10 kW/m to 60 kW/m in the north, mainly due to the

[1] VLIZ (Vlaams Instituut voor de Zee), Ministerie van de Vlaamse Gemeenschap (Afdeling Kust), Koninklijke Marine (Ministerie van Defensie – Dienst Hydrografie) and Oceanographic Department (Royal Danish Administration of Navigation and Hydrography).

sheltering effect of the UK. The results from the current study are comparable with the resource described in WorldWaves and WERATLAS.

In front of the French and Portuguese coast an average annual available wave power of approximately 30 to 50 kW/m is observed. In general the wave power resource in the North Sea is small compared with the (ocean-) resource in front of the French or Portuguese coast. Only the resource in the northern part of the North Sea is comparable with the one in front of the West European coast.

However the importance of a less aggressive wave climate for the development and installation of WECs in current stage of technology should be stressed:

- A WEC should be able to withstand storm conditions in large open oceans. So far this problem is still unsolved.
- Not all severe, energetic sea states are useful for energy conversion, depending on the type of WEC.
- When the technology of wave energy conversion improves, its efficiency in smaller waves may increase.

5 Conclusions

The potential of wave power conversion in the North Sea is studied. The average annual available wave power is calculated on 34 locations in the North Sea. Furthermore characteristic sea states for initial design are defined for the Belgian, Dutch, German, Danish, Norwegian and UK Continental Shelf. Moreover when data were available the distribution of mean wave direction is presented in wave roses. Further an inverse-ray refraction model, implemented at INETI (Instituto Nacional de Engenharia, Tecnologia e Inovação), to calculate wave data on more convenient sites for wave energy conversion, is proposed. Finally the wave power resource in the North Sea is compared with the resource of the West European coast.

In general the wave power resource in the North Sea is rather small compared with the resource in front of the West European coast (40 – 50 kW/m). Near shore (< than 30 km), less than 11 kW/m is available, not only on the Belgian Continental Shelf, but also on the Dutch, German, Danish and UK Continental Shelf. Only the resource in the northern part of the North Sea is comparable with the one of the West European coast.

On the other hand the wave climate is less aggressive and this feature makes the North Sea attractive for wave energy conversion.

When planning wave power extraction in the North Sea, a detailed study on the planned location is needed. The characteristic sea states, presented in this paper, should only be used for preliminary design.

Acknowledgements

The authors whish to acknowledge J. Cândido and Jean-Baptiste M. G. Saulnier (INETI – Instituto Nacional de Engenharia, Tecnologia e Inovação) for advice on the directional spectra, B. Colbrandt, G. Dumon, T. Mertens, M. Roesbeke and J. Vercruysse (Flemish Ministry of Transport and Public Works (Agency for Maritime and Coastal Services – Coastal Division)), R. Maddens and T. Versluys (Ghent University), Pieter Deckers (VLIZ – Vlaams Instituut voor de Zee), A. Visser (Koninklijke Marine – Ministerie van Defensie, Dienst Hydrografie), National Institute for Coastal and Marine Management (Rijkswaterstaat), R. Berger and M. Zeiler (BSH – Bundesambt für Seeshiffahrt und Hydrographie), J. Oakley (DHI Water & Environment), J.J. Woodward (Oceanographic Department, Royal Danish Administration of Navigation and Hydrography), P. Frigaard, J.P. Kofoed and M. Kramer (Aalborg University), K.A. Iden (Meteorological Institute in Norway), R. Jorge (IST – Instituto Superior Técnico) and B. Sellar (University of Edinburgh) for providing necessary data on the Belgian respectively Dutch, German, Danish, Norwegian and UK Continental Shelf.

Research funded by Ph.D. grant of the Institute for the Promotion and Innovation through Science and Technology in Flanders (IWT-Vlaanderen), Belgium.

Part of the research was funded by the EU project Coordinated Action on Ocean Energy (CA-OE – contract n°: SES6-CT2004-502701) within the 6th Framework Programme. The additional support of the European Community is gratefully acknowledged.

The research fits into the project ‘feasibility of wave energy exploitation along the Belgian and neighbouring coastlines’ funded by Electrabel. Electrabel is gratefully acknowledged.

References

[1] H. Bernhoff, E. Sjöstedt and M. Leijon. Wave energy resources in sheltered sea areas: A case study of the Baltic Sea. In *Proc. 5th European Wave and Tidal Energy Conference*, Cork, 2003.

[2] INETI. WERATLAS, European Wave Energy Atlas. Instituto Nacional de Engenharia, Tecnologia e Inovação, Lisbon, Portugal, 1997. Available : www.ineti.pt/proj/weratlas

[3] WORLDWAVES. Available :www.geos.com/services/consultancy/worldwaves.asp

[4] M. T. Pontes, J. Cândido, J.C.C. Henriques and P. Justino. Optimizing OWC sitting in the nearshore. In *Proc. 6th European Wave and Tidal Energy Conference*, Glasgow, 2005.

[5] Z. Liu and P. Frigaard. Random Seas. Hydraulics and Coastal Engineering Laboratory, Aalborg University, 1997.

[6] Dansk Hydraulisk Institut. Raport50105_dhi. Technical report, DHI, 1999.

[7] ABP Marine Environmental Research Ltd. Atlas of UK marine renewable energy resources: Technical report. Technical report, Department of Trade and Industry, 2004.

[8] T. Boehme. Matching Renewable Electricity Generation with Demand in Scotland. Ph.D. thesis, University of Edinburgh, 2006.

[9] Rijkswaterstaat, Nederland. Available: http://www.hydro.nl

[10] Bundesambt für Seeschiffahrt und Hydrographie, Duitsland. Available: http://www.bsh.de/en/Marine%20uses/Industry/CONTIS%20maps/index.jsp

[11] Offshore Center, Denmark. Available: http://www.offshorecenter.dk

[12] O.M. Phillips. The dynamics of the upper ocean. Cambridge University, Press, Cambridge, 1997.

[13] M.S. Longuet-Higgins. On the transformation of a continuous spectrum by refraction. In Proc. Of the Cambridge Philosophical Society, volume 53, pages 226-229, 1957.

[14] W.H. Press, B.P. Flannery, S.A. Teukolsky and W.T. Vetterling. Numerical recipes in C: The art of Sientific Computing. Cambridge University, Press, Cambridge, 1992.

[15] M.S. Longuet-Higgins, D.E. Cartwright and N.D. Smith. Observations of the directional spectrum of sea waves using the motions of a floating buoy. In Ocean Wave Spectra, pages 111-132. Prentice Hall, Englewood Cliffs, N.J., 1961.