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ASSESSING THE GLOBAL WAVE ENERGY POTENTIAL

Gunnar Mørk
Fugro OCEANOR AS
Trondheim, Norway
g.mork@oceanor.com

Stephen Barstow
Fugro OCEANOR AS
Trondheim, Norway
s.barstow@oceanor.com

Alina Kabuth
IST
Lisboa, Portugal
alina.kabuth@ist.utl.pt

M. Teresa Pontes
LNEG
Lisboa, Portugal
teresa.pontes@lneg.pt

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ABSTRACT

In this paper the evaluation of the global wave energy potential is presented based on data from a global wind-wave model (validated and calibrated against satellite altimeter data) and buoy data (the WorldWaves database).

The theoretical potential was computed first using all the available wave data and, in a second step, areas in which the power level is very low ($P \leq 5$kW/m) were excluded. Finally, in the third step, areas impacted by sea ice were removed. Annual and seasonal power distributions are presented both in tables and maps.

The technical resource was also assessed for the west coast of Iberian peninsula showing a significant power decrease from north to south within only 500 km.

ACRONYMS

CNES – Centre National d´Études Spatiales (France)
ECMWF - European Centre for Medium-Range Weather Forecasts
MEDS - Marine Environmental Data Services (Canada)
NOAA - National Oceanic and Atmospheric Administration
NDBC - National Data Buoy Centre
WERATLAS - European Wave Energy Atlas

INTRODUCTION

Since the mid 1970s, much R&D on Wave Energy has been carried out, and demonstration of the first wave energy converters started in the mid 1980s with various full- and part-scale prototypes being tested in the sea, increasing markedly over the last decade. We can now say that wave energy is in its pre-commercial phase, and much work is ongoing on the evaluation of the wave energy potential and the detailed characterization of this very important renewable energy resource.

The wave energy resources can be defined in different ways. First, the theoretical resource is actual hydrodynamic power contained in the ocean waves. An early assessment of this was made by Isaacs and Seymour (1973) who estimated the global wave power potential to be of the order of 1-10 TW, which was the same order of magnitude of the world consumption of electrical energy..

Over the last fifteen years several attempts have been made to map the offshore wave energy resource and to develop packages that enable the nearshore wave energy resource to be calculated. At the European level, WERATLAS or the European Wave Energy Atlas (Pontes, 1998) was developed by a team of seven institutions from six countries, describing the deep-water resources off the Atlantic and Mediterranean coasts of Europe. WorldWaves (Barstow et al., 2003) is a package including a global offshore wave database, bathymetric data, nearshore wave propagation models (SWAN and a backward ray-tracing model) as well as a statistical package for offshore and nearshore analysis, coupled together by means of a user-friendly geographic interface. In Portugal (Pontes et al, 2005), the UK (ABPMER et al, 2004) and Ireland (Marine Institute & Sustainable Energy Ireland, 2005) atlases of nearshore resources have also been produced. Maps of the global wave energy resources have earlier been published in the review book by Cruz (2008), based on the WorldWaves data.

In this paper the global offshore theoretical resource is assessed based on the WorldWaves wave database, and overall power estimates are given on a regional basis.

A wave power parameter more useful than the theoretical resource is the technical resource, which is the power that could be produced by wave energy converters (WECs). In addition, an even more useful parameter is the accessible resource or the power that can be produced in an area/region by a WEC; in order to produce a realistic evaluation, zones in which conditions do not allow the deployment of wave farms should be excluded. This was published for Ireland by MI - SEI (2005).

In addition to the global theoretical resource, the technical resource off the western Iberian Peninsula coasts (Portugal and Spain) is presented. The wave energy converter (WEC) selected to calculate the produced energy (i.e., the technical resource) is an offshore point absorber consisting of two concentric floaters, which convert wave energy from the relative motion of the two bodies (see, e.g. Candido and Justino, 2008).

THE WAVE ENERGY RESOURCE

The wave energy resource is described starting with the usual seastate parameters: significant wave height $H_{m0} = 4\sqrt{m_0}$, energy (mean) period $T_{-10} = \frac{m_{-1}}{m_0}$, peak period $T_p = 1/f_p$, where f_p is the peak frequency (corresponding to the maximum spectral energy density), and mean wave direction θ_m ,the mean direction of the most energetic spectral frequency band. The spectral moments m_n are computed by $m_n = \iint f^n S(f,\theta) df d\theta$ where $S(f,\theta)$ is the directional spectrum. The wave power (or flux of energy per unit crest length) is defined by $P = \rho g \int_0^{\infty} \int_0^{2\pi} S(f,\theta) C_g(f,d) df d\theta$ where C_g is the group velocity given by $C_g = \frac{1}{2}\left[1 + \frac{2kd}{\sinh(2kd)}\right]C$ and C is the phase velocity $C = \left(\frac{g}{k}\tanh(kd)\right)^{(1/2)}$, d being the water depth, k the wave number $k = 2\pi/\lambda$ (λ is the wave length) and g the acceleration due to gravity. In deep water ($d \geq 0.5\lambda$) wave power is simply computed by $P = 0.49 H_{m0}^2 T_{-10}$ in units of kW/m if H_{m0} and T_{-10} are expressed in metres and seconds, respectively.

THE WORLDWAVES DATA

The global wave power dataset used is the default calibrated wave database contained in the standard WorldWaves package. These data consist of operational ECMWF WAM model data (Komen et al, 1994) for a 10-year period from 1997-2006 at 6-hourly intervals on a 0.5° lat/lon grid worldwide which have been validated and calibrated using global TOPEX and JASON (Table 1) altimeter significant wave height and wind speed data on a point-to-point basis. The correlation coefficient between significant wave height from the model and the satellites is displayed in the map in Figure 1 for all global calibration points, proving the high quality of these data. Buoy data from many measurement campaigns have also been used as a final verification of the final WorldWaves database.

Table 1 – Satellite altimeter missions used for the standard global WorldWaves data calibration

Availability	**Source**	**Satellite**
1992 – 2002	NASA /CNES	Topex/Poseidon
2002-2006	NASA/CNES	Jason-1 (Topex-Follow-on, old Topex orbit)

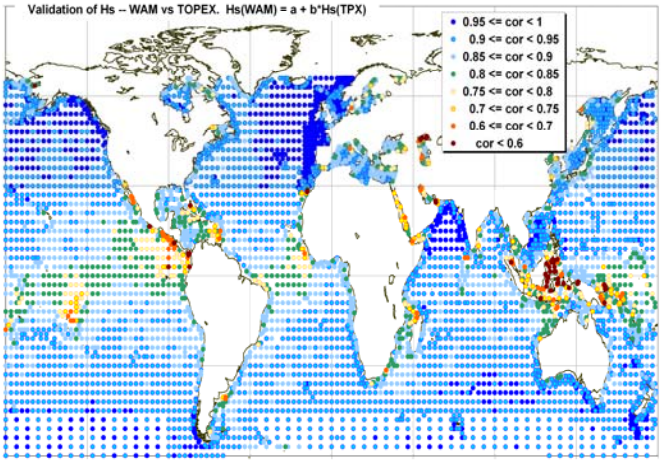


Figure 1 Global map showing the correlation coefficient between the ECMWF WAM operational model data and Topex/Jason data for all global validation points for 1997 to 2006. Correlation coefficients are naturally lower in areas with very low steady wave heights over most of the year.

In the calibration procedure, the WAM wave periods and directions over most of the world oceans were not changed. However, in most enclosed sea areas (such as the Mediterranean), dominated by wind sea (typically enclosed or semi-enclosed seas), the wave periods were adjusted (calibrated) along with wave height, conserving the wave steepness in the adjustment process.

In addition to the gross theoretical wave power computation, using the global WorldWaves dataset, it was decided also to compute the theoretical resource excluding (i) areas with very low (unusable) power levels ($P \leq 5$ kW/m) (although in restricted areas not resolved at the 0.5° level, higher power levels may still occur), and (ii) locations which at certain times of the year may experience ice coverage. In the second case, this was made possible using the WAM data themselves. In locations and times when the ice density is above 0.3, WAM assumes ice coverage, and all WAM wave parameters are then missing. Thus, where and when the percentage of non-missing values for the significant wave height is less than 100%, these are identified as potentially ice covered and excluded from the theoretical wave power computation.

THE THEORETICAL RESOURCE

The theoretical global wave power resource was computed using ArcGis software. The following sub-regions were considered for regional analysis, limited to deep water off the coastlines bounding each ocean basin.

- Europe (north and west coasts, the Baltic Sea, and Russia);
- Mediterranean Sea including the North Atlantic Archipelagos (Azores, Cape Verde and Canary Islands)
- North America – USA and Canada (east and west coasts)
- Central America (east and west coasts)
- South America (east and west coasts)
- Africa (Atlantic and Indian Sea coasts – north, west, middle; south and east coasts)
- Asia (east, southeast and Melanesia, south, west and Russia)
- Australia, New Zealand and Polynesia.

Table 2 presents the computed theoretical resource (in GW) for (i) the gross resource including all contributions (left column), (ii) excluding the areas where $P \leq 5$ kW/m (middle column) and (iii) the net resource, excluding areas where $P \leq 5$ kW/m and ice covered areas (right column).

The global gross theoretical resource is about 3.7 TW, 3.5 TW is the resource computed excluding areas with a benign wave climate (definition ii) and the net resource (option iii) is about 3 TW; the total reduction from gross to net resource is then about 20 %. Globally, the most important reduction is for areas where ice coverage is a problem. An inspection at the regional level, also shown in Table 2, shows that

- for Europe there is a decrease of 25% from gross to net resource, mostly a result of ice coverage, the gross and net values being 381 and 286 GW, respectively.

- In the Baltic and European Russia the net resource is a very small part of the gross resource; this considerable decrease is due to low wave power regimes ($P \leq 5$ kW/m) as well as ice coverage (it should be taken into account that a detailed assessment of the resource on the Baltic coasts would have shown zones where the resource is larger than 5 kW/m but it was not possible to examine the wave climate at such a detailed level in this assessment). In these two areas the net resource is 8% of the gross resource.

- for the Mediterranean as expected, a decrease of about 50% was found due to the rather low energy wave climates pertaining to this area, the total net resource being 37 GW. Again, a detailed assessment of the resource will show some areas not considered for the net resource computation where P is larger than 5 kW/m.

- North America – on the east coast, a decrease of 70% between gross and neat power potential is found mainly due to ice cover, the gross resource being 115 GW and the net resource only 35 GW. On the west coast the reduction is naturally smaller at 24% (271-207 GW) also mainly due to ice. The total gross resource is 388 GW against a net resource of 242 GW, about 7 times higher than on the east coast.

- Asia – due to ice coverage in Russian waters, the resource there decreases by almost 90% from gross (172 GW) to net (23 GW); in the other areas a moderate decrease of about 20% is found; the total net resource for Asia is estimated to be 547 GW.

- Finally, negligible decreases were found for Africa, Australia, New Zealand and Polynesia. In Africa, the resource amounts to 428 GW of which 178 GW originates from the south. In Australia and New Zealand an important contribution of 590 GW was found, as expected.

Figure 2 and Figure 3 show the global theoretical gross wave power and its seasonality (ratio of the minimum monthly mean power to annual average) for all the available WorldWaves grid points; Figure 4 and Figure 5 show the same information for the global net wave power, limited to the coastal grid points used in our global and regional calculations.

As it is well known, Figure 2 and Figure 4 show that the largest power levels occur off the western coasts of the continents due ultimately to the Coriolis force. In Europe the resource peaks at the latitude of Scotland and Ireland, and in North America peaks in Oregon (USA), British Columbia and Alaska. In the southern hemisphere, the largest values occur on the Pacific coasts of southern Chile, off South Africa and off the southwest and southern coasts of Australia and New Zealand.

In Figure 3 and Figure 5, the ratio of the minimum monthly to annual average power levels confirms that seasonality is much higher in the northern hemisphere. Wave resource stability is an important advantage for the southern hemisphere. Even with lower annual power levels, it is possible to produce energy over a longer period of time, thus making investment more profitable.

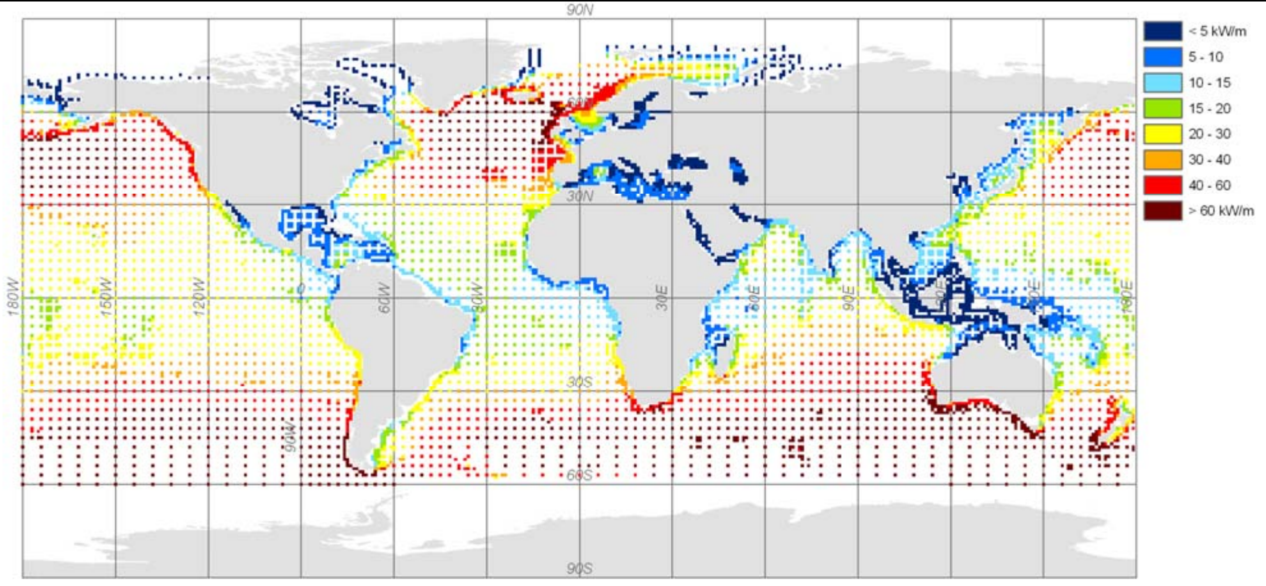


Figure 2 – Annual global gross theoretical wave power for all WorldWaves grid points worldwide.

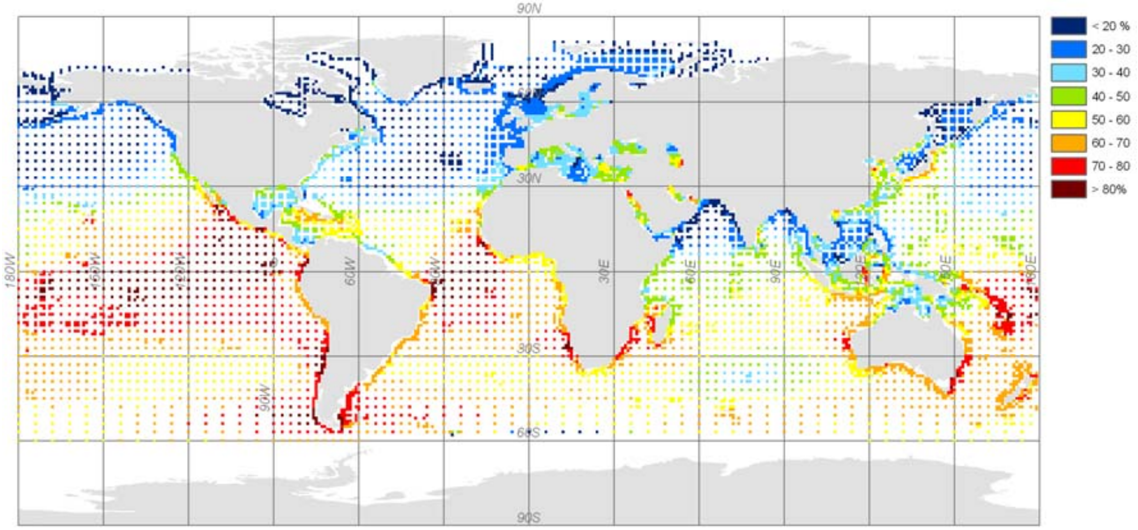


Figure 3– Seasonality of gross theoretical wave power distribution (ratio of minimum monthly wave power and annual wave power). A low percentage indicates a high degree of seasonality. Areas coloured brown, red and orange have relatively stable wave climate regimes.

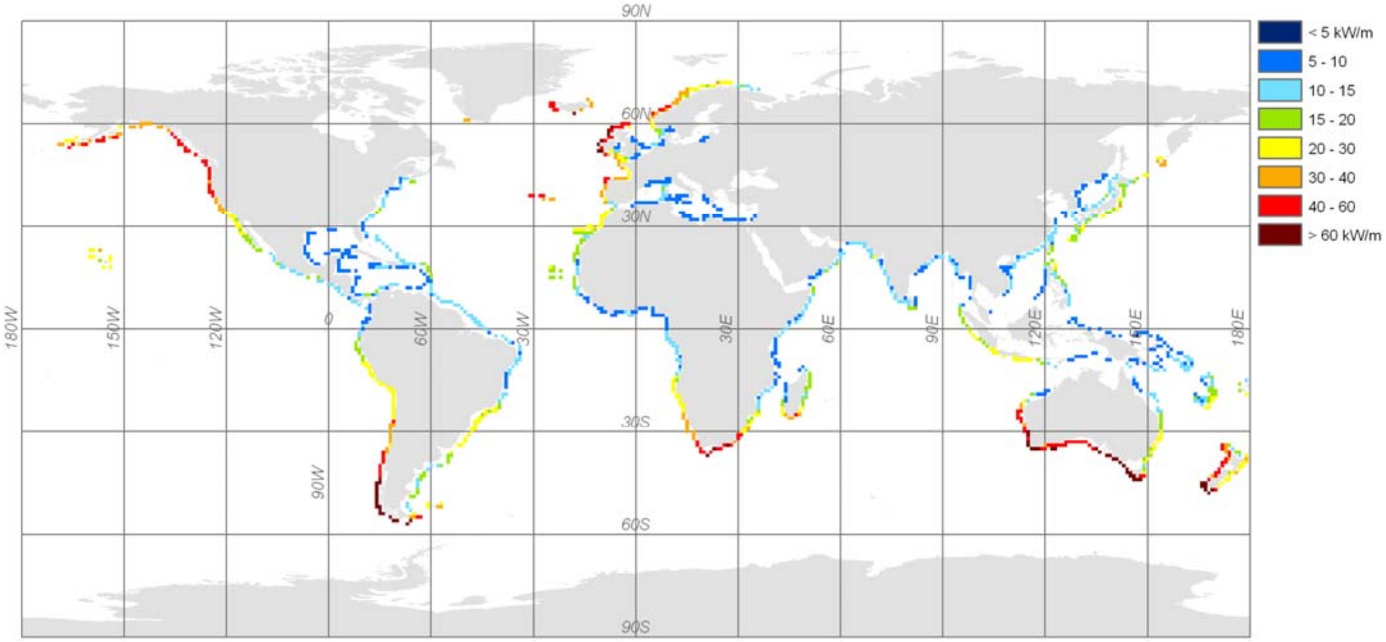


Figure 4 – Annual net theoretical coastal power worldwide (excluding contributions where P ≤5 kW/m and potentially ice covered areas).

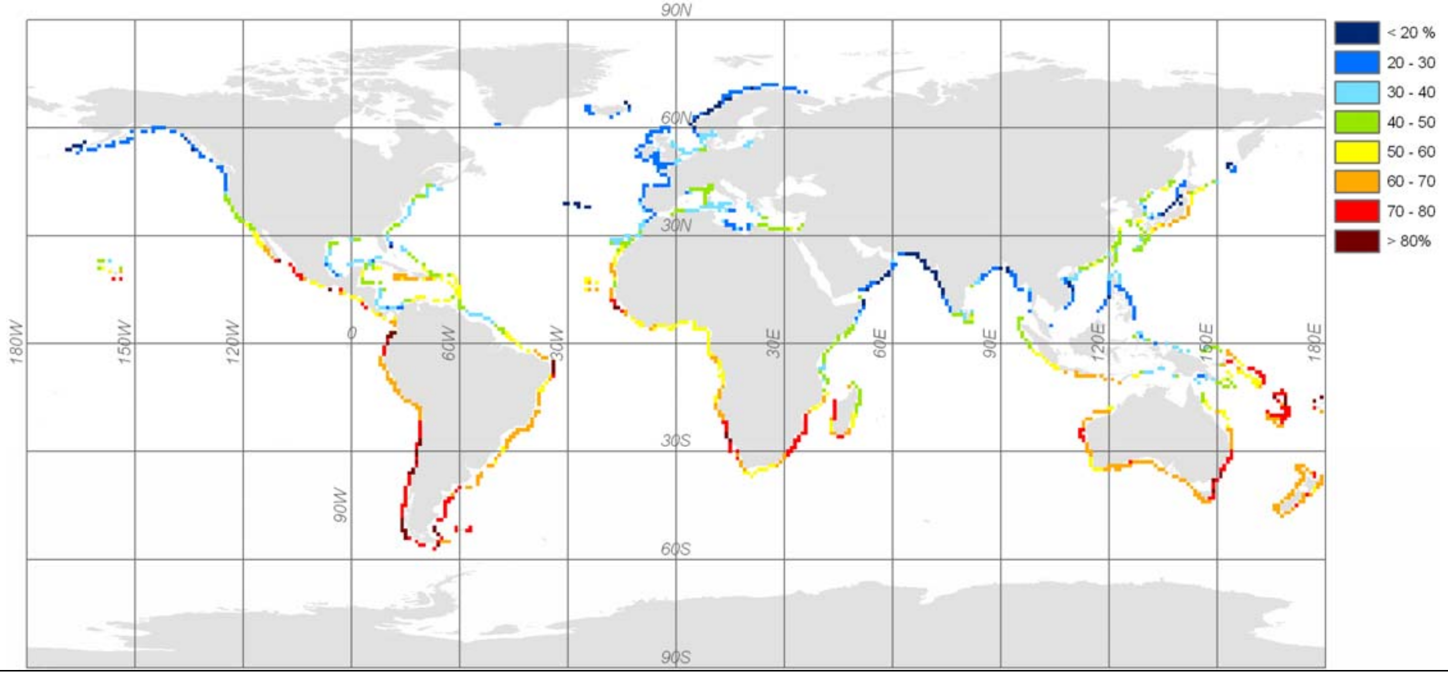


Figure 5 - Seasonality of the net coastal theoretical wave power worldwide (ratio of minimum monthly wave power and annual wave power)

Table 2 – Global and regional theoretical wave power resource (in GW). Left column presents the gross power, the middle one the power excluding the areas where $P<5$ kW/m and the right column the net power (excluding areas where $P<5$ kW/m and potentially ice covered ones).

REGION	P_{gross}	P	P_{net}
Europe (N and W)	381	371	286
Baltic Sea	15	4	1
European Russia	37	22	3
Mediterranean	75	37	37
North Atlantic Archipelagos	111	111	111
North America (E)	115	103	35
North America (W)	273	265	207
Greenland	103	99	3
Central America	180	171	171
South America (E)	206	203	202
South America (W)	325	324	324
North Africa	40	40	40
West and Middle Africa	77	77	77
Africa (S)	178	178	178
Africa(E)	133	133	127
Asia (E)	173	164	157
Asia (SE) and Melanesia	356	283	283
Asia (W and S)	100	90	84
Asiatic Russia	172	162	23
Australia and New Zealand	590	574	574
Polynesia	63	63	63
TOTAL	**3702**	**3475**	**2985**

THE IBERIAN TECHNICAL RESOURCE

The technical resource was also computed for three locations off the western coast of the Iberian Peninsula (Portugal and Spain) as shown in Figure 6, their coordinates and depth being presented in Table 3.

To compute the power extracted from the waves an offshore WEC composed of two concentric cylinders that extract the energy through the relative heave motion of the two bodies was considered (Candido and Justino, 2008), its geometry being presented in Figure 7. With a null spring coefficient, the optimal mechanical damping coefficient for each sea-state was computed. Figure 8 presents the variation of the optimum capture width with energy period of the WEC shown in Figure 7. Depending on the energy period, different optimal capture widths allow power extraction with varying efficiency. Figure 9 depicts the variation of the power extracted with energy period for sea-states with 1m significant wave height.

Based on the WorldWaves 10-year wave dataset statistics, the average annual technical power value for the three locations was computed, as shown in Table 3.

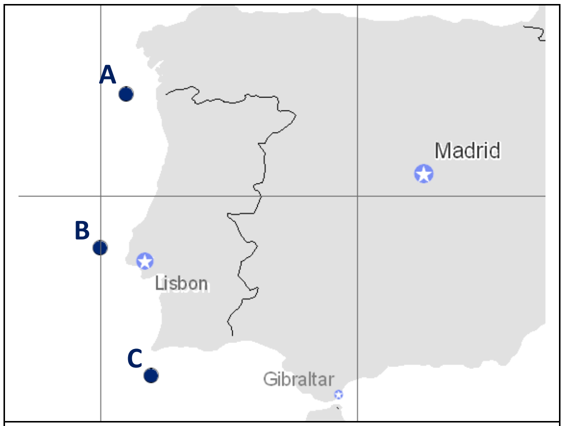


Figure 6 – Location of points where the technical resource was computed.

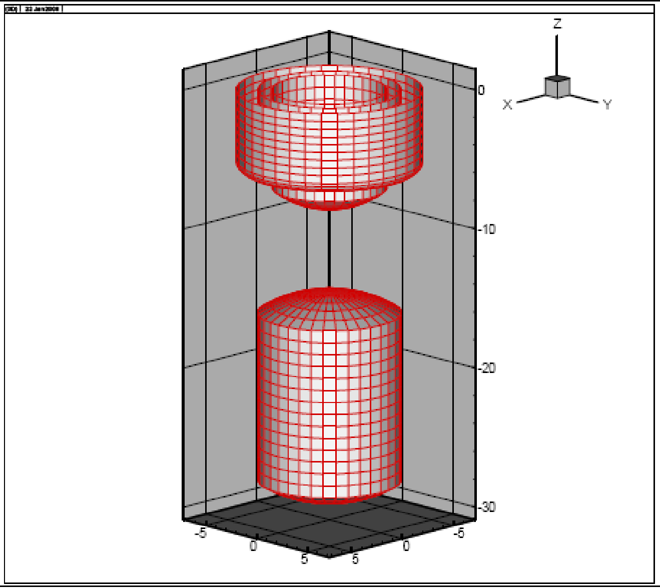


Figure 7 – Geometry of the WEC considered for the assessment of the technical resource. The radius of the wider cylinder is 6.5m and the radius of the inner cylinder is 4m.

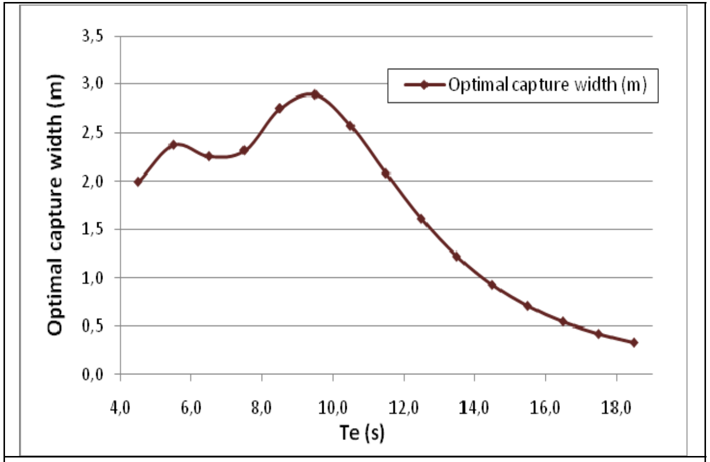


Figure 8 – Variation of the optimal capture width against energy period for the WEC presented in Figure 7.

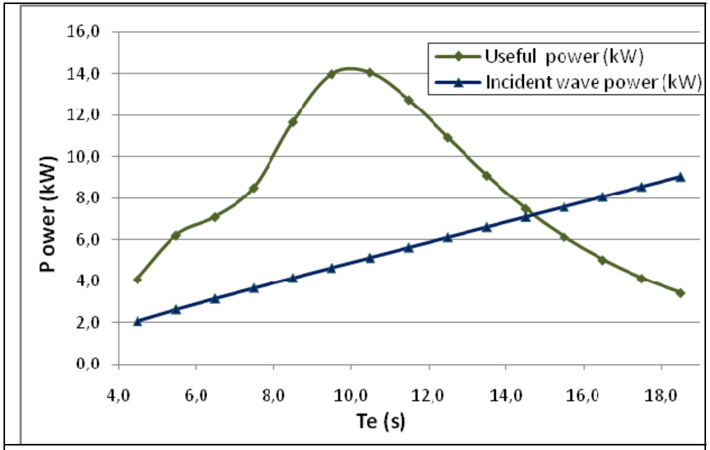


Figure 9 – Variation of the incident wave power (blue) and of extracted power (green) with energy period, for sea-states with 1m significant wave height.

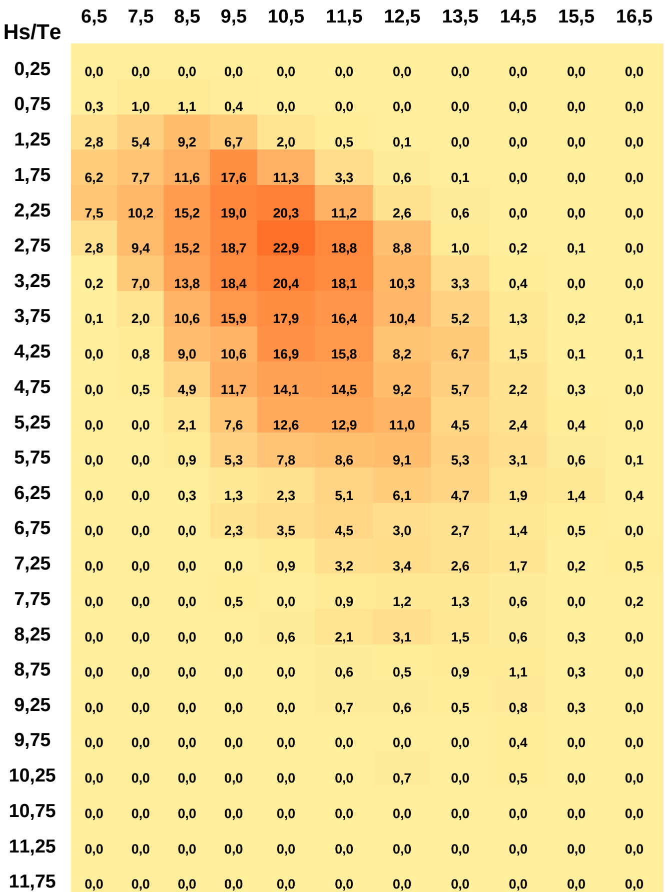
Table 3 – Location, depth, wave power and extracted power by the point absorber offshore WEC shown in Figure 7.

Site	**A**	**B**	**C**
Longitude W (deg)	9.5	10.0	9.0
Latitude N (deg)	42.0	39.0	36.5
Depth (m)	1390	245	1658
Annual Incident Power (kW/m)	38	36	27
Annual Extracted Energy (MWh)	751	666	525

Table 3 shows that although sites A, B and C cover only about 500 km, the annual wave power decreases significantly from north to south. The power level decreases 11 kW/m or about 30%, resulting in a theoretical decrease of 226 MWh, which is again about 30% of the energy production at the northernmost site (site A).

Table 4 presents the scatter table of the extracted power at site A. It shows that the majority of the energy is extracted in sea-states with H_{m0} in the range from 1.5m to 5.5m and with T_{-10} between 7 and 14s.

Table 4 – Annual scatter table for extracted energy at site A (in MWh). Wave height is expressed in meter and period in second.



Hs/Te	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	16,5
0,25	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,75	0,3	1,0	1,1	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0
1,25	2,8	5,4	9,2	6,7	2,0	0,5	0,1	0,0	0,0	0,0	0,0
1,75	6,2	7,7	11,6	17,6	11,3	3,3	0,6	0,1	0,0	0,0	0,0
2,25	7,5	10,2	15,2	19,0	20,3	11,2	2,6	0,6	0,0	0,0	0,0
2,75	2,8	9,4	15,2	18,7	22,9	18,8	8,8	1,0	0,2	0,1	0,0
3,25	0,2	7,0	13,8	18,4	20,4	18,1	10,3	3,3	0,4	0,0	0,0
3,75	0,1	2,0	10,6	15,9	17,9	16,4	10,4	5,2	1,3	0,2	0,1
4,25	0,0	0,8	9,0	10,6	16,9	15,8	8,2	6,7	1,5	0,1	0,1
4,75	0,0	0,5	4,9	11,7	14,1	14,5	9,2	5,7	2,2	0,3	0,0
5,25	0,0	0,0	2,1	7,6	12,6	12,9	11,0	4,5	2,4	0,4	0,0
5,75	0,0	0,0	0,9	5,3	7,8	8,6	9,1	5,3	3,1	0,6	0,1
6,25	0,0	0,0	0,3	1,3	2,3	5,1	6,1	4,7	1,9	1,4	0,4
6,75	0,0	0,0	0,0	2,3	3,5	4,5	3,0	2,7	1,4	0,5	0,0
7,25	0,0	0,0	0,0	0,0	0,9	3,2	3,4	2,6	1,7	0,2	0,5
7,75	0,0	0,0	0,0	0,5	0,0	0,9	1,2	1,3	0,6	0,0	0,2
8,25	0,0	0,0	0,0	0,0	0,6	2,1	3,1	1,5	0,6	0,3	0,0
8,75	0,0	0,0	0,0	0,0	0,0	0,6	0,5	0,9	1,1	0,3	0,0
9,25	0,0	0,0	0,0	0,0	0,0	0,7	0,6	0,5	0,8	0,3	0,0
9,75	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,4	0,0	0,0
10,25	0,0	0,0	0,0	0,0	0,0	0,0	0,7	0,0	0,5	0,0	0,0
10,75	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
11,25	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
11,75	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

CONCLUSIONS AND FURTHER WORK

The work presented in this paper constitutes a first step towards the assessment of more detailed global and regional wave energy resources.

Based on possibly the highest quality global database available at present, we have estimated that the global gross resource is about 3.7 TW, which lies in the range of earlier evaluations (1-10 TW). However the exclusion of areas with very low energy ($P \leq 5$kW/m) and in particular areas impacted by sea ice decreases this resource by about 20%. The study confirms that the seasonality is much greater in the northern hemisphere, one of the main disadvantages for wave power in the north.

The evaluation of the technical resource off the western coast of Portugal and Spain (Iberian peninsula) shows a significant north-south power gradient of around 30% over

500 km, with a consequent similar decrease in the extracted energy.

With the existing global database of known accuracy, the results of this study can potentially lead to more detailed comparative assessments of the theoretical and technical resources for any area worldwide, particularly useful for companies looking for most suitable areas for technology introduction.

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