Quantifying the Potential Global Market for Wave Power

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Abstract

Deployments of Wave Energy Converters (WECs) have been focused in European waters where the resource has been well-quantified. However, to justify large-scale deployment, detailed understanding of the distribution and size of the potential worldwide market is required.

Two figures are generally quoted: 1-10TW or 2TW. These numbers are demonstrated to be inadequate as the basis for a wave energy industry, given both their derivation and lack of geographic detail. Here, outputs from the WaveWatch III model were analysed to calculate the wave power across the globe. The power flowing to land was calculated and summed for countries, continents, hemispheres, and the entire globe. Using the Pelamis power matrix, an estimate of the power available to current-generation WECs was also derived. The global wave energy resource is estimated as 2.11TW, of which 4.6% can be extracted by WECs.

1 Introduction

Interest in the generation of electricity from waves has been sustained in the past decade by rising oil prices and the threat of climate change. From a sector driven mainly by experimentation, concerted efforts have recently begun to transform it into an industry, capable of delivering a significant proportion of the world's electricity needs. To achieve this, funding is required on a sustained and substantial basis from governments, venture capital funds and the energy industry. These bodies require estimates of the long-term potential market for the technology in order to determine the value of investing in wave energy.

Currently, wave energy is being sold to potential customers on the basis of wave resource estimates for the world, supplemented by more detailed studies for particular countries. In general, the world wave energy resource is quoted to be either "1-10TW" [22] (or its equivalent in TWh/year) or "2TW" [20]. An extensive literature survey has been required to trace these numbers to their original sources. Both these figures come from derivations pioneered by Kinsman [16], who comments openly on the lack of rigour in his methods, which are essentially inspired guesswork. More details are given in §4, along with comparisons and discussion of later work presenting global and regional wave power estimates.

The present authors re-establish the economic justification for wave power. A data-based methodology is described in §2 with clear discussions of assumptions enabling the calculation of both mean wave resource and an estimate of the error on that value. The new figure for global wave resource presented in §3 can therefore be assessed against future studies which calculate confidence using this methodology, in order to identify whether the estimates are consistent or in disagreement.

More detailed studies of specific countries often consider "theoretical" and "technical" resource. The intention of this additional calculation is to assess how much of the total resource is actually extractable, by applying restrictions based on the contemporary state of Wave Energy Converter (WEC) technology. This study applies the concept of an illustrative WEC array, built parallel with the coastlines of the world, to provide an initial estimate of the proportion of theoretical power which could be converted into useful electricity.

2 Method

Power estimates were made using outputs from the NOAA WaveWatch III (WW3) global model [23]. The outputs are provided in the form of spectral parameters at a spatial resolution of 30 arc-minutes and a temporal resolution of 3 hours. The outputs used were: peak period (T_p); significant wave height (H_s); and mean direction of the waves (Θ_m).

2.1 Power Density

In order to calculate power from these three spectral parameters it was necessary to assume a dominant spectral shape for the world's oceans. The Pierson - Moskowitz (PM) spectrum was chosen since locations with high wave power (which are of most interest) will be exposed to long fetch. The spectrum defined according to the Bretschneider formulation (rather than as a function of wind speed as for PM) was used for this study, thus the power density can be found by [24]:

$$p = 0.0134\frac{\rho g^2}{\pi}H_s^2 T_p \quad (1)$$

where the density of water was taken as $\rho = 1025\text{kgm}^{-3}$; and $g = 9.81\text{ms}^{-2}$ is the acceleration due to gravity.

The power density is converted into a vector taking its direction from Θ_m.

In addition to the power density, the power output (Ψ) from an illustrative WEC, the Pelamis P2, was calculated at each point on the WW3 grid by linearly interpolating the published Pelamis power matrix [3] to each T_p and H_s value.

Fig. 1 shows the global distribution of annual mean power density. The arrows on the plot show the mean best direction. This demonstrates that the locations of most interest for wave power are on the west coast of land masses, as waves flow primarily from west to east. This figure compares well to those produced by Cornett [8] and Barstow et al. [6]. Wave power is predominantly found between the 40^{th} and 60^{th} lines of latitude north and south, with a larger proportion in the southern hemisphere.

2.2 Power Quantification

The calculation of the total power flowing onto land masses is achieved by summing the power density over a "buffer" line offset from the land.

Due to the resolution of the WW3 model (30' of arc) the minimum distance offshore from which data can be used is 30 nautical miles (nm). Such a buffer was generated from the Natural Earth 1:50m coastline dataset [2].

The buffer was then split into segments by the Exclusive Economic Zones (EEZs) of each country, as defined by the VLIZ Maritime Boundaries Geodatabase [4]. Finally, some segments were removed from form the buffer for the following reasons:

- first, the use of the entire buffer would result in double counting of the energy flux in locations with groups of small islands (were energy would flow through the 30nm buffer of multiple islands);
- second, locations in the Arctic and Antarctic are of no interest for wave energy extraction, given that deployment in these locations is not feasible and there is little need for electricity.
- last, some sections of the buffer are counted twice due to multiple political claims registered in the VLIZ database such as between Chile and Peru.

Each line segment was additionally assigned to a continent and a hemisphere to allow power availability to be calculated for these geographical regions. Fig. 1 shows the land buffer used in this study, coloured by continent.

2.2.1 Calculating Total Power Crossing the Buffer

The global power density estimates generated from the WW3 data were used to calculate the energy flux over the buffer lines. A similar approach was used to estimate power extraction if WECs were to be installed along each buffer. These estimates were calculated for each month within the dataset separately.

These estimates were achieved by defining nodes at 1km intervals along the buffer. The energy flux across this buffer was then calculated from the component of the power flowing towards (normal to) land. Power flowing away from land, i.e. out of the buffer, was neglected. It can be shown that this corrects the common historical assumption of omni-directional power that overestimates power by up to 300% (see ref. [10] for details).

In order to calculate the power extracted by the illustrative WEC (Pelamis) at the line buffer, some further assumptions were required. First, it was assumed that the direction of the waves could be neglected, since the Pelamis is designed to align itself with the direction of highest power. A decision also needed to be taken on the array layout. Two lines of Pelames spaced at 400m intervals was chosen, giving a packing density (D) along the buffer of 5 Pelames per km. The final assumption, which is likely to be valid given the wide spacing in the array configuration chosen, was that neighbouring Pelames do not interact to affect each other's power absorption.

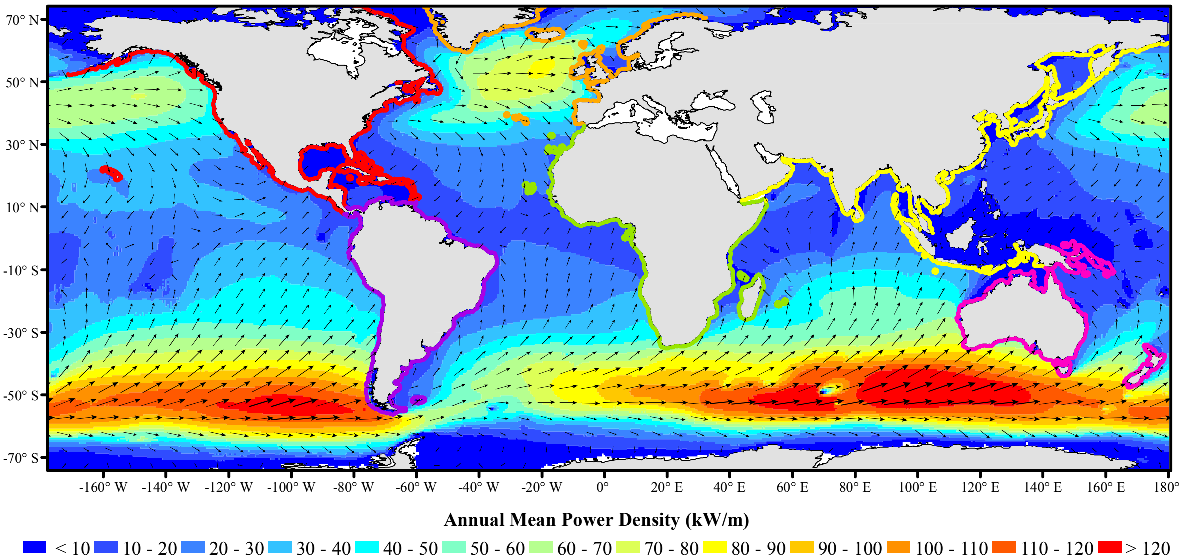

Figure 1: Annual mean wave power density (colour) and annual mean best direction (→). The land buffers used to quantify the resource are also shown, coloured by continent (see §2.2).

2.2.2 Calculating Long-Term Statistics

The next stage of resource assessment is to generate long-term statistics from the time series of data. The robust methodology used here can be applied equally easily to data from numerical models or measurements [10], enabling resource assessment figures to be directly comparable.

It is proposed that mean monthly power estimates ($\bar{P}_m$) should be fundamental to resource calculations. This avoids data loss due to the use of data records which do not exactly span full calendar years, or which contain corrupted or missing data. Either of these instances could lead to collateral data loss in avoiding generating a biased resource estimate.

All other statistics for longer time periods are derived from these monthly values by a weighted mean:

$$\bar{P}_n = \frac{1}{\sum_{m=1}^{n} d_m} \sum_{m=1}^{n} d_m \bar{P}_m \qquad (2)$$

where d_m is the number of days in each month (here assigning to February 28.25). Thus, the initial stage is to use the individual monthly data for each year ($P_{(y,m)}$) to calculate the mean for all instances of that month ($\bar{P}_m$).

In order to perform calculations for continents, hemispheres etc., the $P_{L(y,m)}$ values were summed first. Mean values and associated standard deviations for each calendar month were then calculated. This order of calculation is important since, for instance, adjacent lines forming a single continent's coastline buffer are likely to have correlated power values.

2.3 Estimating Errors

Although some numerical oceanographic models are available covering multiple decades [25, 21], it is often necessary, as in this instance, to use data which cover a shorter period. It is therefore important to assess the likelihood that an estimate of the mean power (taken from a finite sample) is within a certain distance from the true mean power. This can be achieved by use of the "confidence interval" [14].

The confidence interval implicitly combines both natural variability between independent measurements of the power in a particular recurring time period and the uncertainty associated with a limited sample size. Having calculated the confidence interval on a mean measurement, for example the power in a calendar month (i.e. $\bar{P}_m = x \pm \delta x$, where δx is the confidence interval on x), confidence intervals can be combined in the same way as independent errors. Some statistical assumptions need be made for the approach in this section to be valid; these are shown to hold by Gunn and Stock-Williams [10].

3 Results

Selected results are included in this section: either for comparison with earlier studies; or to be of use to the wave energy industry for the reasons outlined in the introduction. The statistics available - which can be presented monthly, quarterly and annually - include:

- mean wave power density;
- total mean wave power;

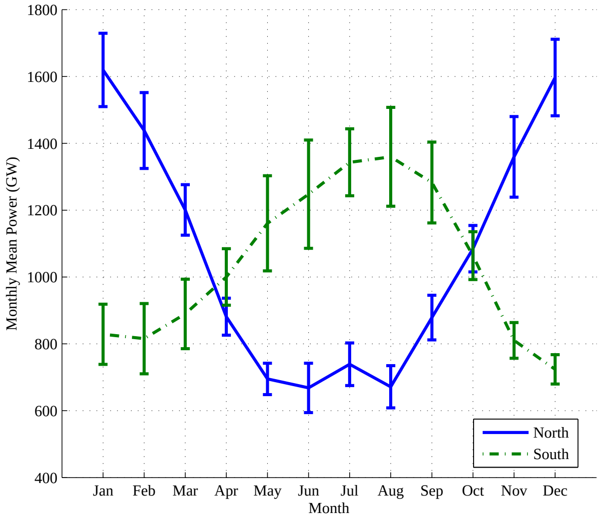

Figure 2: Hemisphere power fluctuation. The error bars show the 95% confidence intervals.

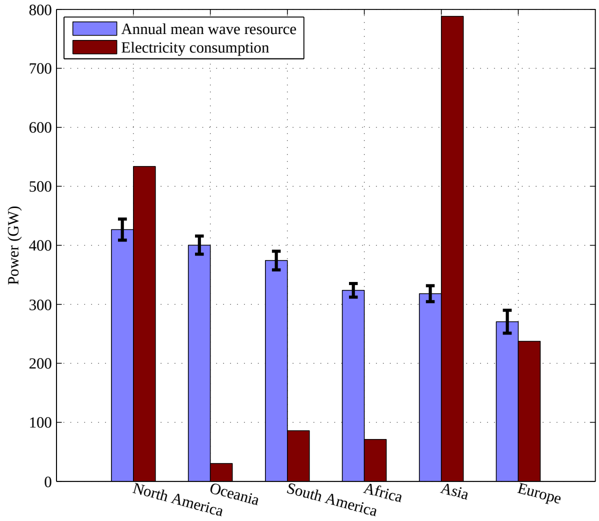

Figure 3: Wave power available compared to electricity consumption for continents. The error bars show the 95% confidence intervals.

- power extracted by the chosen array of Pelamis WECs; and
- 95% confidence intervals on the above.

Each buffer line has been used to calculate these values for countries, continents, hemispheres, and the whole world.

3.1 Global Resource Estimate

The total wave power incident on the ocean-facing coastlines of the world (neglecting certain islands and the poles) is:

$$2.11 \pm 0.05\text{TW}$$

to 95% confidence.

Using the array of illustrative WECs array it is calculated that:

$$\eta_\Psi = 4.6\%$$

of this energy can be extracted with the current generation Pelamis.

3.2 Hemisphere Power Estimate

Fig. 2 illustrates the monthly variation in power between north and south hemispheres. The expected seasonal variation can be seen for both hemispheres. The annual means are given in Table 1a.

3.3 Continental Resource Estimate

The incident wave power on each continent is shown in Fig. 3. For comparison, electricity consumption figures from the CIA World Factbook [1] are also presented. Table 1b also presents the power extracted by the illustrative Pelamis array and the extraction efficiency.

3.4 Country Resource Estimate

Annual mean statistics for selected countries are given in Table 1c. These give an indication of the mean wave power resource for each country, along with the degree to which the wave climate is matched to the Pelamis power matrix.

4 Analysis

Observations are now extracted from the resource figures presented in §3. It is also essential that these results are compared with those from earlier studies, so this is subsequently performed on a global and country-by-country basis, where possible, to assess the methods and data used in this study.

4.1 Distribution of Wave Resource

It appears surprising that, given the strength of the southern hemisphere's resource as shown in Fig. 1, the quantities of wave power reaching coastlines in the northern and southern hemispheres are equal, to 95% confidence. This highlights the fact that high wave power results from long fetch, which requires no coastline to interrupt the flow of power: thus the power cannot be extracted at coasts.

At first glance, the values for extractable power from the illustrative WEC are even more surprising, since the southern hemisphere is calculated to have approximately 40% *less* power than the northern hemisphere. From an examination of the 3-hourly record, however, it appears that this is because the power matrix made publicly available by PWP is designed for a site in the UK. A large proportion of the

Hemisphere	P (TW)	η_Ψ (%)
North	1.07 ± 0.03	5.7
South	1.05 ± 0.02	3.4

(a) Hemispheres

Continent	P (GW)	η_Ψ (%)
North America	427 ± 18	4.8
Oceania	400 ± 15	3.7
South America	374 ± 16	3.6
Africa	324 ± 12	4.0
Asia	318 ± 14	6.4
Europe	270 ± 20	5.4

(b) Continents

Country	P (GW)	η_Ψ (%)
Australia	280 ± 13	3.0
United States	223 ± 12	1.6
Chile	194 ± 11	2.4
New Zealand	89 ± 6	4.0
Canada	83 ± 7	6.2
South Africa	69 ± 4	3.1
United Kingdom	43 ± 4	5.7
Ireland	29 ± 4	3.8
Norway	29 ± 4	5.7
Spain	20 ± 3	3.3
Portugal	15 ± 2	3.2
France	14 ± 3	3.9

(c) Selected countries

Table 1: Resource with ±95% confidence intervals and yield estimates.

most energetic wave conditions experienced in the southern hemisphere exceed the maximum values in the power matrix and so zero power is extracted. The P2 would instead be designed for, and tuned to, each installation site.

While it has been a useful exercise to apply this power matrix across the world's oceans, it is recommended that this set of results is used with extreme caution. Any hypothesis about the potential contribution of wave energy to a region's electricity generation should require a far more detailed study of local conditions, including consideration of physical barriers to consent and construction. In the judgement of the authors, however, this method represents an improvement on the simple assumption of a capacity factor or capture width.

4.2 Global Wave Power

It is now necessary to consider whether these figures alter or confirm the marine energy sector's general view of the potential wave power market. Tracking down the derivation of the various figures generally quoted has not been a trivial task, due to a paucity of references to the original sources of each resource estimate.

Methods for calculating global wave resource have historically used one of three methods, which shall here be named M1, M2 and M3. The first two were pioneered by Kinsman [16], who points out the assumptions in his derivation at each step and prepends the section with the following discussion of its likely accuracy:

> "In this footnote we are again going to misapply an oversimplified relation to get an estimate that will be dressed up to look as though it said something about the real ocean."

The three methods are:

M1 Guesses are made for the mean global wave height and period. These are used, assuming monochromatic Airy waves, to calculate the power density. This is then multiplied by the length of the global coastline.

M2 A mean wave height value is guessed for the entire surface of the ocean. This is used (again assuming monochromatic Airy waves) along with the total surface area of the oceans to estimate the total instantaneous wave energy across the planet. Finally, by assuming a value for the number of times this energy runs ashore per year, an estimate for power is obtained.

M3 Boud and Thorpe [7] take a different approach, by quantifying the deep-water global wave resource using various sources of power density data. This is close to the approach used here. However, it is unclear which areas have been excluded for having too low a wave power; or what length of coastline was used and from what distance to shore the power is taken.

Table 2 presents original estimates from the literature (i.e. those which are not cited to earlier work). The fact that Kinsman's two estimates are close, bounding the value calculated here, does not really tell us anything. As Kinsman [16] says of his two methods:

> "The above is an example of the "razzle-dazzle" or "guessing-from-both-ends" ploy. If done rapidly, it can be pretty impressive, but it doesn't prove anything except your ability to make two guesses come out in the same place. If you use it, be careful not to have the two estimates exactly equal. Equal estimates make the listener suspect that he is being one-upped."

To prove his point, the mean of all the values in the table (if one excludes 1-10TW and 0.8TW, which

P (TW)	Method	Reference
2.11 ± 0.05	New M3	Present authors, 2012 [10]
1.87	M1	Kinsman, 1965 [16]
2.22	M2	
2.5	M1	Inman and Brush, 1973 [12]
2.5	Not stated	Isaacs and Seymour, 1973 [13]
2.6	M1[1]	Panicker, 1977 [17, 18]
1-10	M1[2]	
2	M2	Pond and Pickard, 1978 [19][3]
1.3	M3	Boud and Thorpe, 2003 [7]
≥ 2	Not stated	Strange et al., 1993 [20]
3	Not stated	Hermann, 2006 [11]
0.8	See note[4]	Thorpe, 2011 [22]

[1] Panicker [17] gave a value of 5.3TW, however Jonsson [15] responded to correct this by a factor of two to 2.5TW, which Panicker [18] accepted.

[2] Panicker [17] states 1-10TW as the rate of renewal of wave energy by wind (not the power available at the coast), a range chosen to contain the (incorrect) 5.3TW value presented in the paper and 2.2TW by Kinsman [16]. It is presented here due to a later reference to it as a global resource estimate [9].

[3] Pond and Pickard [19] attribute this to Arthur [5]

[4] Thorpe [22] provides this estimate, referencing it to Cornett [8]. However, this paper contains no quantification of the global resource.

Table 2: Comparison with previous global resource studies.

are not true resource estimates) happens to be equal to Kinsman's M2 value (2.22TW). Such numerology, however, does not improve understanding of whether the final global wave resource estimate presented in this paper is accurate. The previous estimate which differs most from the value presented here is the one which uses the closest method, and it is obviously impossible to assess the reason for differences in those values which have been stated without being derived. The accuracy of the global values presented here can therefore only be tested by comparison with regional studies.

5 Conclusions

Data for 2005-2011 from the WaveWatch III global model run by NOAA have been used to quantify the wave power experienced by the world's oceanic coastlines. The power is calculated at a buffer line running 30 nautical miles offshore. Power from a WEC array using the published Pelamis P2 power matrix is also applied to give an indication of extractable power.

The world's theoretical wave power resource is estimated to be 2.11 ± 0.05TW to 95% confidence, with equal amounts in the northern and southern hemispheres. As a worldwide average, 4.6% of this is estimated to be extractable by the illustrative WEC array chosen. However, this number is to be treated with caution since the array is sparse and the device is not tuned to each wave climate.

Comparison to previous global estimates indicates that the estimate in wide currency today of 2TW, which is generally referenced to Strange et al. [20] is not completely inaccurate. However, that report does not cite any further authority or present any derivation for the resource estimate stated, which is understandable given that it is an industry summary paper.

The robust assessment methodology presented here results in resource values which have quantified confidence and which can be queried to various levels of spatial and temporal detail. It is therefore recommended that the wave energy sector begins to use these estimates, which will increase the status of wave energy in the eyes of those bodies able to provide financial and political support. It is also recommended that this methodology guides future studies, which should use longer periods of data at finer spatial resolution.

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