The UK wave power resource

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SYNOPSIS

The characteristics of wave power around the UK are discussed in the light of recent studies carried out for the UK Department of Energy's reviews of both the shoreline and nearshore resources.

These studies used hindcast directional wave spectra from the UK Met Office for a network of sites around the British Isles, together with directional wave buoy measurements for two sites, in the SW Approaches and west of Shetland.

1 Introduction

The levels of wave power in deep water off Britain's Atlantic coasts have been studied extensively over recent years (1-3). Offshore sites with good exposure to principal (westerly) wave directions have annual averages of 60 to 80 kW/m (MW/km) gross, 40 to 50 kW/m net. [*Gross power* refers to the total of contributions from waves travelling in all directions. *Net power* refers to the amount crossing a line facing the best direction for that particular site; this is the maximum available for largescale exploitation by a line of devices.]

Recently the success of shoreline wave plant prototypes, particularly in Norway and on Islay, has led the UK Department of Energy to commission reviews of the nearshore and shoreline resources. Here *nearshore* is used to refer to depths where the wave climate is appreciably altered by the effects of the sea bottom (see §3.1).

This paper reports on statistical work carried out for these studies, particularly the evaluation of data sources (Section 2) and the selection of representative samples (Section 3).

2 Data Sources

2.1 Met Office model hindcasts

The basic data source used in the studies of the UK nearshore and shoreline wave energy resources was the UK Meteorological Office's wind-wave computer model, which calculates wave spectra from estimates of wind speed and direction over the entire ocean obtained through a 10-layer model of the atmosphere (4).

Directional spectra, using 14 frequency and 16 directional intervals, are available from the Met Office model for waters around the British Isles over a grid of approximately 50 km spacing from February 1983 to July 1986; since the latter date only summary statistics of the wave spectra have been stored. For the present resource studies data were obtained for 15 grid points, including three close to sites for which measured directional wave data were know to exist: west of Shetland, South Uist and SW Approaches.

The principal reason for preferring to use hindcast data was its unique availability, providing directional spectra at 12-hourly intervals (from October 1985 6-hourly) with only occasionally missing data, over the whole area of interest. Previous studies had shown it to be in good agreement with directional spectra synthesised from wave measurements at South Uist (5).

Also, it has the advantage of *calculating* the directional spectrum for a sea area; that is, it does not suffer from the sampling variability inherent in measurements at an individual site.

Figure 1 shows estimates from Met Office data of average gross and net power, and the directional distribution of power, for a selection of grid points covering the approaches to the UK's Atlantic coasts.

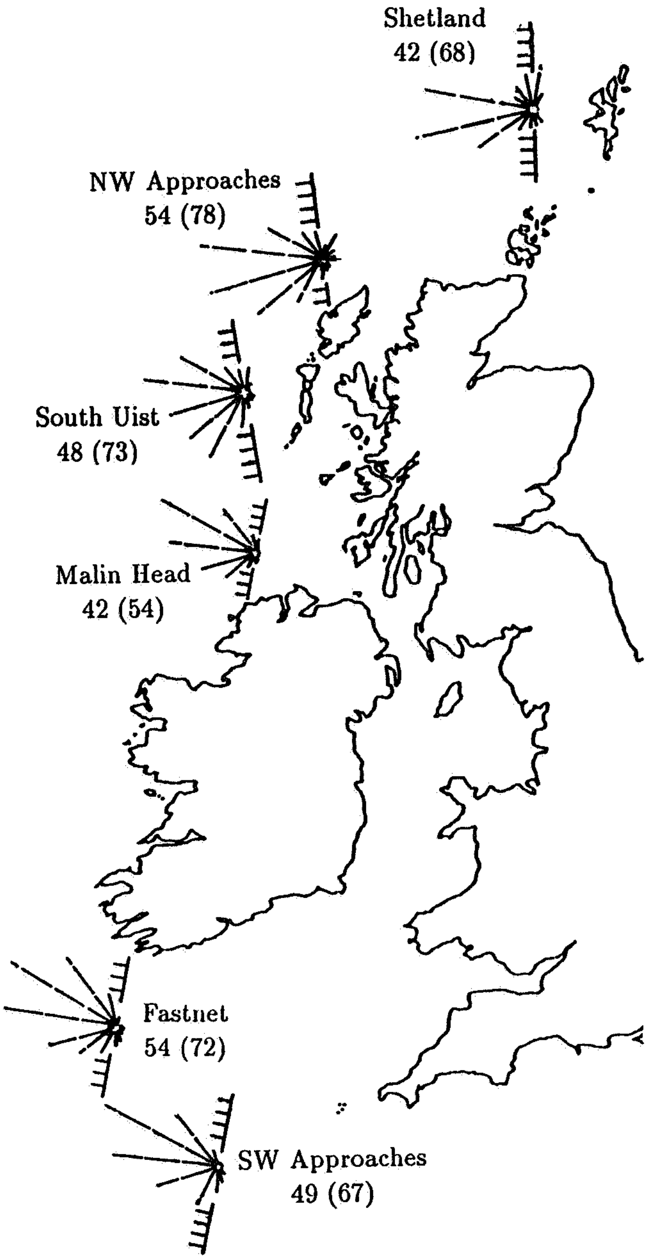

Fig 1 Wave power estimates for UK offshore sites, based on the UK Met. Office's wind–wave hindcast model. Wave roses mean power from each 22.5° sector, with marks at 5 kW/m intervals. Mean net (gross) power levels are shown in kW/m; the net figure is for power P_θ crossing the line (⊥⊥⊥⊥⊥) whose direction θ maximises P_θ for the particular site

2.2 Measured (DB) wave data

Directional wave spectra calculated from direct measurements of buoy accelerations were obtained from the British Oceanographic Data Centre (BODC) in their standard MIAS format. These data originate from two ODAS surface-following directional buoys deployed by Thorn EMI Electronics on behalf of the United Kingdom Offshore Operators Association (UKOOA), to whom they remain confidential for five years from the date of collection.

DB2 was deployed in the SW Approaches (approx 49° N, 9° W) from June 1984 to August 1986, and DB3 west of the Shetland Islands (approx 60° 30′ N, 3° W) from July 1984 to July 1988. DB2 was also deployed at a third site of wave power interest, in the NW Approaches (approx 59° N, 7° W), from August 1986 to July 1988; these data have not been used in the present study because they do not overlap in time with the Met hindcasts used.

Details of instrumentation, which included a variety of other meteorological variables, and site histories of the buoys' deployment and major problems involving missing or suspect data, are given in the documentation report (6) prepared by BODC who reformatted and checked the data.

Records were taken 3-hourly: normally for each Met hindcast there is a DB measured spectrum from a 2000-second sampling period beginning 40 minutes before the hindcast, sufficiently close in time to be reasonably described as simultaneous. The basic data set for the present study then consisted of wave spectra statistics for all such 'simultaneous' data pairs. In a few cases of missing data, DB measurements for 2-3 hours after the Met hindcast were taken instead.

These direct measurements have their own problems, including poorer data return, especially for Shetland, calibration difficulties and sampling variability. Thus it is not easy to say whether measurements or hindcasts should be preferred where estimates differ.

2.3 Comparison of data sources

For the present data sets, good general agreement is found between the Met hindcasts and the directional buoy (DB) data, in respect of height and period (and therefore power), and of direction.

Figures 2 and 3 show monthly power averages and the distribution of power (as exceedence curves) for the two data sets for the SW Approaches. The overall power averages for the periods of simultaneous data are 63 kW/m for Met data, 54 kW/m for DB.

Both monthly power averages and exceedence curves show generally good agreement between the two data sets, but with DB estimates usually below those of the Met model. Note though that these differences are considerably less than typical inter-year variation, as is illustrated in Figure 4, which shows exceedence curves for the Met data for each of the three years 1984/5, 1985/6 and 1986/7 (in each case for 1st May to 30th April).

Figure 5 shows the 'scatter diagram' of height ($H_{rms} = .25H_S$) against energy period (T_e) for the two data sets; note the rather wider range of the Met data, though their steepness limits (the upper left boundary of the scatter of points) are in good agreement.

Measured values of wave period show some large individual differences from the Met hindcasts, but no large systematic difference. There are small mean differences in direction between the two data sets, probably due to calibration errors for the buoy. The discrepancies in direction and period are sufficiently small that they can be expected to have negligible effect on the wave climate, except possibly for sites with very narrow directional exposure or subject to strong refraction effects.

Overall the DB data give rather lower mean power levels: 10% for the SW Approaches, 20-30% for Shetland (it is not possible to give a precise figure for Shetland because a substantial part of the year has no representation in the data set). However this difference is due mainly to discrepancies at high power levels. At very low power levels, the Met estimates are well below the DB data, while over the 10-100 kW/m range, which corresponds well to the range of most interest for wave power productivity, there is good agreement between the two data sets. Therefore the difference in productivity estimates for wavepower plant is likely to be considerably less, probably of the order of 5%.

3 Estimation of the nearshore and shoreline resources

3.1 Wave modifications and shoreline characteristics

When waves travel into water of depths small compared with their wavelength, they begin to lose energy through bottom friction and wave breaking, and to suffer changes of direction through refraction; the latter may either focus waves, giving concentrations of power ('hot spots'), or defocus them.

For the present resource assessments, refraction calculations were carried out at Kirk, McClure and Morton, using mathematical models developed by Hydraulics Research Ltd (7). For data on bathymetry a digitised grid was used, based on Admiralty Charts, with resolution down to a spacing of 150 metres in places.

To avoid excessive computing requirements, representative sets of spectra were chosen for four reference sites: Shetland, NW Approaches, South Uist and SW Approaches (see Figure 1): in a manner that will be described below (§3.2). From these the nearshore and shoreline wave climates were estimated for a range of sites around the UK.

For shoreline sites, a good wave climate is not on its own sufficient. We need also to consider the nature of the shoreline itself (which ranges from shallows with loose boulders to cliffs into deep water), the quality of rock for civil engineering purposes, and access, both physical and in terms of existing facilities, especially roads and the electricity grid.

3.2 Selection of representative subsets

We here describe the methodology developed to select a manageable subset of spectra for the refraction analysis from the basic data sets of over 2500 spectra. Broadly, the problem is as follows.

We are given a large set of sea states i with weights u_i; in the present case these come from Met Office data, with weights taking two values (one twice the other) to allow for the change of sampling interval from 12 to 6 hours during the data period. From these we select a much smaller 'representative subset' J, chosen so as to cover the range of values of direction, height and period.

The method of selection used here was motivated by the intended use of the representative set for estimating wave power productivity, while including seas of extreme power and/or steepness for survival analysis. The data were first divided into directional sectors, with the divisions corresponding to the 5, 20, 50, 80 and 95 percentiles of the distribution of power by principal direction d_i (thus 5% of the overall power is discarded from each end of the directional range.

For each of the four directional sectors seas were chosen with heights ($Hrms$) in four ranges: the first ($Hrms \approx .5$) representing low seas in which devices may be expected to operate at maximum efficiency, followed by two steps ($Hrms \approx .875, 1.25$) taking us up to seas in which devices may be expected to have reached their output limit, with the fourth representing the most extreme seas found in the data set (seas of extreme steepness but short period will also be included among those at the lower height steps).

The chosen seas were then assigned weights W_J as follows. Each sea i in the larger sample is to contribute weights a_{iJ} to its nearest neighbours J among the representative set, where $\sum_J a_{iJ} = 1$. Thinking ahead to the use of our weighting for productivity estimation, this was done by interpolating between values of efficiency η rather than power, because efficiency will vary more slowly across the scatter diagram. Thus we think of estimating efficiency in sea i in terms of known efficiencies at representatives J by $\hat{\eta}_i = \sum_J a_{iJ}\eta_J$. Our overall estimate of productivity (mean output power) will then be $\hat{Q} = \sum_i u_i p_i \hat{\eta}_i$. This motivates the definition of the weights W_J for our representative seas as $W_J = \sum_i u_i p_i a_{iJ}$, since then $\hat{Q} = \sum_J W_J \eta_J$. Note that $\sum_J W_J = \sum_i u_i p_i$ = mean overall power. If we define $V_J = W_J / p_J$, we can think of the V_Js as frequencies of occurrence, in as much as $\hat{Q} = \sum_J V_J q_J$, where $q_J = p_J \eta_J$, output power in sea J; but note that the V_Js do **not** sum to 1.

The detailed sharing out of the weight for each sea i via the a_{iJ}s can be done in a number of ways. The method used here was that, for $Hrms < 1.25$, the a_{iJ}s were calculated by linear interpolation over period Te and energy $E = Hrms^2$ among the (at most) four nearest neighbours of i within its sector, i.e. the Js with period above and below Te_i at height steps above and below $Hrms_i$, with just one period/height step being used if the value for i is outwith the range of the representatives' values. For the more extreme seas, with $Hrms > 1.25$, interpolation over Te and $1/E$ was used. The justification for $1/E$ here rather than E is that in this range we expect output power to have reached more or less a constant (maximum) level, in which case efficiency would be proportional to $1/E$.

Figure 6 shows, as an example, the scatter diagram of $Hrms$ against Te for a typical directional sector. The representative seas J are marked with crosses, and surrounded by circles whose area is proportional to W_J in the upper figure, V_J in the lower.

4 Discussion

This paper has described the methodology behind the wave climate input used in current UK nearshore and shoreline resource studies, especially the verification of the hindcast data used against wave buoy data and the selection of representative subsets stratified by direction, height and period.

The conclusions of the verification study are that there is good broad agreement between the Met Office hindcasting model and the Data buoy measurements, although there are some discrepancies which warrant further investigation. Where the two data sources disagree it is unclear which provides the better estimates, and therefore no systematic correction to the Met Office model is proposed. The Met Office model possibly errs on the optimistic side by about 5% in regard to estimates of wave power plant productivity; but if so, it errs on the pessimistic side to a rather greater extent as regards estimates of strength, fatigue and survivability.

The wave climate estimates for the offshore resource are in good agreement with previous studies (1-3), not only as to the overall average power levels but also in the distributions of direction, height and period, and the variability on various time scales.

The resulting nearshore wave climates for selected sites have been calculated by refraction analysis, and the implications for the productivity and economics of wave power plant will be discussed by Tom Thorpe in the succeeding paper.

The refraction analysis has also been used, together with coastal engineering considerations, to estimate the UK's overall shoreline resource, and to identify a selection of especially promising sites. The conclusions of this shoreline resource study should appear shortly.

It is a pleasure to acknowledge the support of the Department of Energy, and the assistance of my collaborators in these studies, Trevor Whittaker of Queen's University, Belfast, and Adrian Bell and Alan Barr of Kirk, McClure and Morton).

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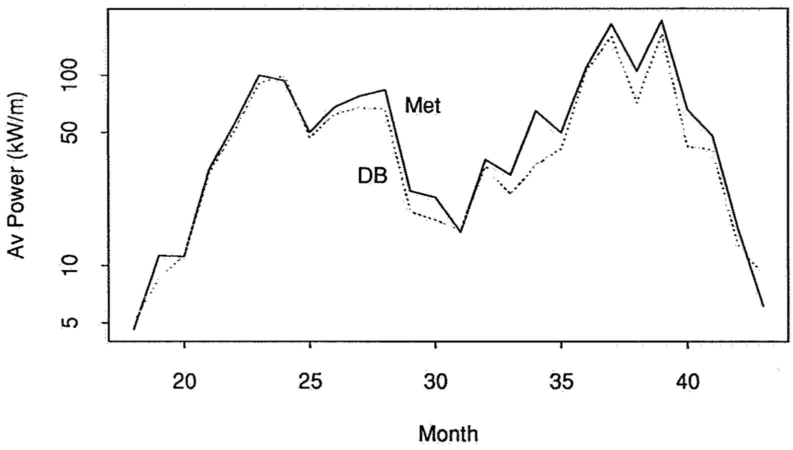

Fig 2 SW Approaches: monthly averages of gross power for Met. and DB data, June 1984 (month 18 on scale) to July 86 (month 43)

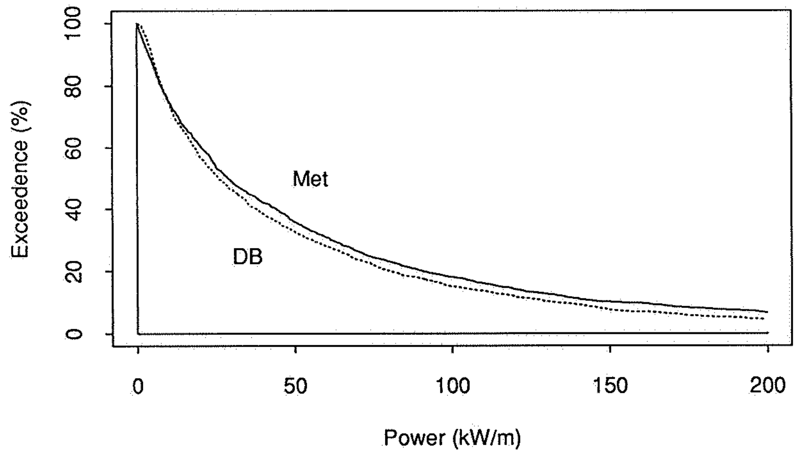

Fig 3 SW Approaches: distribution of power for Met. and DB data for 1984–86

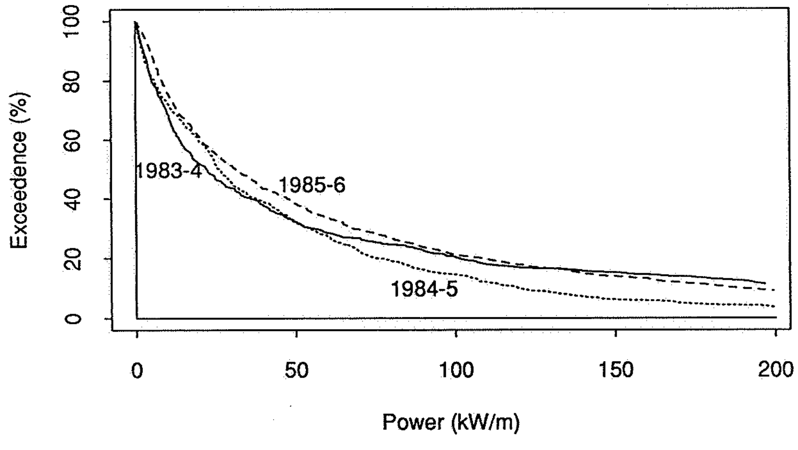

Fig 4 SW Approaches: year-to-year variability of power distribution (averages of gross power for the three years 1983–4, 1984–5, and 1985–6 were 78.8, 50.9, and 73.5 kW/m)

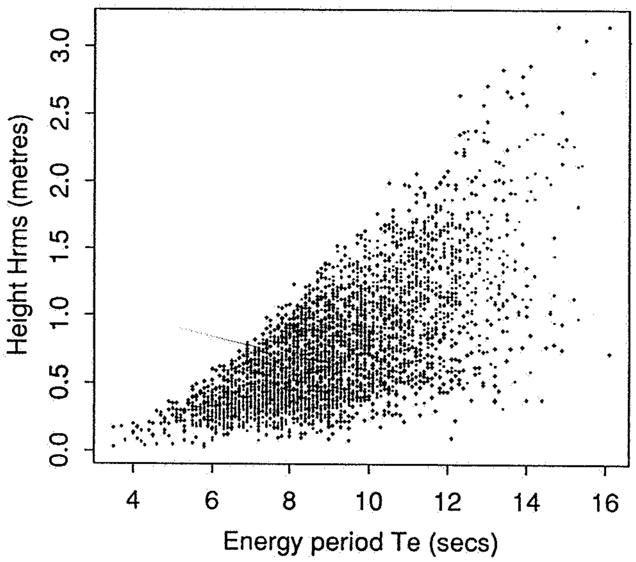

Fig 5 SW Approaches: scatter diagram of height and period for Met. (+) and DB (•) data for 1984–86. (Note: the commonly used 'significant wave height', $H_S = 4\ Hrms$)

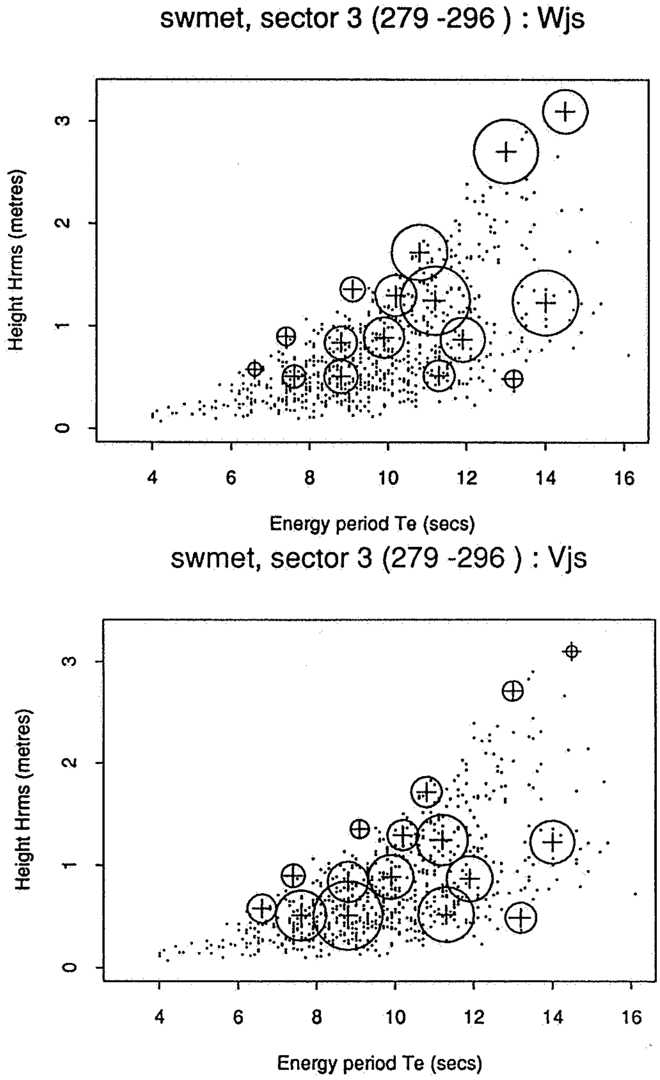

Fig 6 SW Approaches: scatter diagram for one directional sector (the 50–80th percentiles, 279–296°, of the power distribution), showing selected representatives (+), with circles whose area is proportional to their weights: in the upper figure W_J, in the lower V_J (see text for definitions of W_J and V_J)