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**DEFINING THE LONG-TERM WAVE RESOURCE AT WAVE HUB:
THE ROLE OF MEASUREMENTS AND MODELS**

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ABSTRACT

Wave measurements made on the site of a potential wave energy project can be of high value to developers. Such data can be used to define both long-term and short-term wave energy resources available to devices as well as the optimal operations and maintenance strategy which should be employed for the project. All three of these applications are addressed in an ongoing study commissioned by the npower Juice Fund for the Wave Hub project which is planned off the South West coast of England. The aim of this work is to extract best value from the historical and future wave measurements from the project site. The programme of this project is outlined here with a technical description of activity in the three parallel strands of the study; wave resource assessment, short-term forecasting and O&M modelling.

The focus of this paper is on a key aspect of the ongoing work programme - that relates to the use of measured and modelled wave data to derive a prediction of the long-term wave climate at the Wave Hub site. In particular, various candidate methodologies for correlating short-term measured wave data and long-term modelled data are explored in the context of a Measure-Correlate-Predict (MCP) analysis. This work has also included consideration of the inter-annual variability of wave resource in order to examine the uncertainty associated with assuming that a finite historical reference period is representative of the long-term wave climate.

INTRODUCTION

Wave energy is reaching a pre-commercial stage with several full-scale prototypes being tested around the world. In these early days it is pivotal to ensure that proper test facilities are made available to the technology developers. The European Marine Energy Centre (EMEC) was a pioneer in the field, hosting a Pelamis Wave Energy Converter since 2004 [1]. Other full-scale test and demonstration centres are being planned (e.g. the 250MW pilot zone recently announced by the Portuguese government) in a clear sign that the industry is developing and that certain governments are keen on ensuring that their countries are leaders in the field. In the UK, the proposed Wave Hub project will offer device developers the opportunity to demonstrate multi-unit arrays within the context of shared grid infrastructure.

In these test centres, and also in the first pre-commercial wave farm sites, some sort of pre-construction wave measurement campaign should be implemented in order to accurately evaluate the wave climate for the purposes of design verification and energy output predictions. When selecting suitable sites, the main potential advantage of utilising an MCP-based approach is that a relatively short measurement campaign (1-2 years) can be used in conjunction with longer-term data sets (> 5 years) to better represent historical conditions at the site.

This paper describes a first attempt to transfer the MCP approach to the wave energy industry, by applying it to wave data gathered from the proposed Wave Hub site.

METHODOLOGY

MCP with Reconstruction

Measure-Correlate-Predict (MCP) is a method which is commonly used in the wind energy industry to determine the long-term wind resource available at a certain location where a short-term measurement campaign has been conducted [2, 3]. The process relies on a derived relationship between the short-term site measurements and a regional or local source of longer term reference data, for a concurrent period. This relationship is then applied to the long-term reference data such that it is made representative of conditions at the site, combining the benefits of the two data sets - the short-term measurements providing representation of conditions at the site and the long-term data setting these in a longer historical context. The aim of this process is to ensure that predictions of the future energy production of a project take account of the natural variability of the environmental resource over relatively long timescales.

A refinement to this process has been adopted for the current study which is outlined in broad terms in the diagram presented in Figure 1.

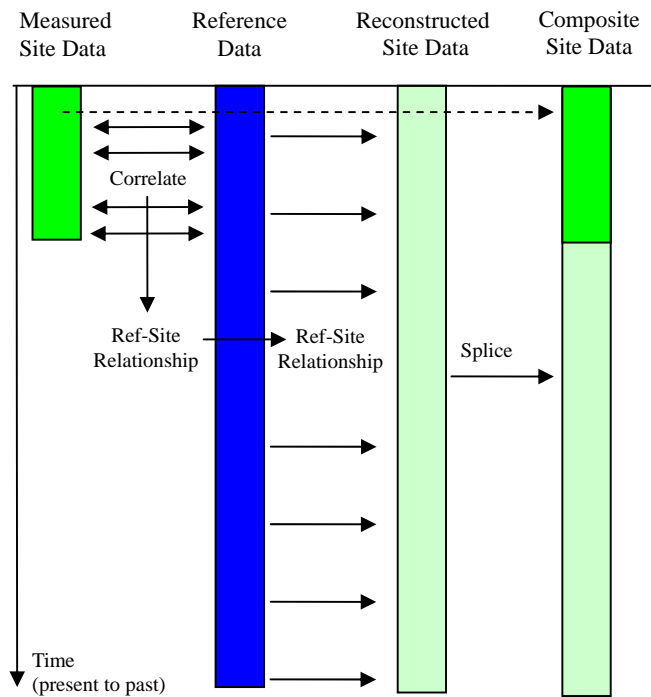


Figure 1: High-level illustration of MCP with Reconstruction

The principle of this form of MCP analysis is that the long-term reference time-series data is factored according to the results of the concurrent correlation, so as to be representative of the site.

This long-term 'reconstructed' site time-series is then spliced together with the actual site measurements in order to minimise the reliance of the analysis on the strength of the correlation.

Available data sources

A measurement campaign spanning January 2005 to April 2006 has taken place at the Wave Hub site. During this time, five separate wave buoys have been deployed; three Seawatch Mini Buoys (SWM) and two Datawell Directional Wave Riders (DWR). Details of the site measurement campaign are shown in Table 1.

Buoy Type	Start	End
Seawatch Mini	30 Jan 2005	23 Feb 2005
Seawatch Mini	26 Feb 2005	02 June 2005
Seawatch Mini	08 June 2005	05 Oct 2005
Directional Wave Rider	11 Dec 2005	21 Jan 2006
Directional Wave Rider	25 Jan 2006	10 Apr 2006

Table 1: Measured data coverage

Also available for the study were two sets of modelled wave data from the UK Met Office. These consisted of twelve years of data from the Europeans Waters Model at point E04 from 1988 until 2000 (exclusively used in the independent inter-annual variation assessment, pp. 6) and six years of data from the UK Waters Model at point U04 from 2000 until 2006. The locations of these model data points are shown in Figure 2. The measured data sets were available as a time series of spectral parameters and the modelled data consisted of the wind, swell and resultant wave parameters. The measured data were available for an averaging period of 1 and 2 hours for the DWR and SWM buoys, respectively. The UKMO modelled data were available on a three hour averaging period. For the purposes of correlating measured and modelled data, the former were re-averaged to a three hourly interval.



Source: Google Earth™ mapping service

Figure 2: Data source locations

Candidate Correlation Methods

There are many different considerations when implementing correlations and trend-fitting procedures to wave data. In order to examine the most appropriate method for this assessment of the long-term wave resource at the Wave Hub site, a number of candidate methodologies were short-listed for evaluation. The selection of these candidates was designed to address potential variations in performance due to:

- Relational differences: Wave Height and Wave Period
- Trend-fitting methods
- Averaging period for correlations
- Single or multi-bin correlations

The correlation methods chosen for predicting wave height and wave period are presented in Tables 2 and 3.

Method	Measured Dataset	Modelled Dataset (U04)	Tertiary Binning Parameter	Force Through Origin
A	DWR	Resultant	Dir	Yes
B	DWR	Resultant	Dir	No
C	DWR	Resultant	Te	Yes
D	DWR	Resultant	Te	No
E	DWR	Wind	Dir	Yes
F	DWR	Wind	Dir	No
G	DWR	Wind	Te	Yes
H	DWR	Wind	Te	No
I	DWR	Swell	Dir	Yes
J	DWR	Swell	Dir	No
K	DWR	Swell	Te	Yes
L	DWR	Swell	Te	No
M	SWM	Resultant	Dir	Yes
N	SWM	Resultant	Dir	No
O	SWM	Resultant	Te	Yes
P	SWM	Resultant	Te	No
Q	SWM	Wind	Dir	Yes
R	SWM	Wind	Dir	No
S	SWM	Wind	Te	Yes
T	SWM	Wind	Te	No
U	SWM	Swell	Dir	Yes
V	SWM	Swell	Dir	No
W	SWM	Swell	Te	Yes
X	SWM	Swell	Te	No

Te = Energy Period $\left(m_{-1} / m_0, \text{ with } m_n = \int f^n S(f) df\right)$; $S(f)$ is the frequency spectrum; Dir = Mean Wave Direction

Table 2: Candidate correlation methods for significant wave height (Hs)

Method	Measured Dataset	Modelled Dataset (U04)	Force Through Origin
A	DWR	Resultant	Yes
B	DWR	Resultant	No
C	DWR	Swell	Yes
D	DWR	Swell	No
E	SWM	Resultant	Yes
F	SWM	Resultant	No
G	SWM	Swell	Yes
H	SWM	Swell	No

Table 3: Candidate correlation methods for wave energy period (Te)

The nomenclature for the modelled dataset follows directly from the UK MetOffice files. Following preliminary study it was found that correlating wave period by binning with respect to wave direction produced very poor correlations and so was disregarded. Also rejected were wave period correlations utilising the wind driven wave component from the modelled data as this also produced very poor correlations.

Performance Tests

To test the quality of the data produced from the candidate correlations in Table 2 and Table 3, a “reconstruction test” was undertaken for each candidate. This comprised of a comparison of measured and reconstructed time series for the period of concurrency, on the basis of two measures of error; average error and average absolute error. The former provides a measure of the overall level of agreement but is subject to error cancellation effects which may provide a misleading result. The latter provides a check of this result since errors are evaluated in an absolute sense and therefore no cancellation can take place.

The candidate correlations for each predictand (Hs and Te) were ranked on the basis of the two measures of the Performance Tests. Subjective cross-checks of the results were implemented in order to ensure that the highest ranked correlations from this process were indeed of the highest quality from an intuitive perspective. This was found to be the case.

Further Refinement

Once the strongest correlation method for each parameter was established through the Performance Tests described above, further refinement of the correlation methodology was investigated. Firstly, both measured and modelled data were re-averaged to longer averaging periods and then re-correlated on this basis. Secondly, potential improvements by not using a tertiary binning parameter were examined.

RESULTS

Correlation Method Assessment, Hs

The results of performance testing on each of the candidate correlation methodologies for Hs are presented in Table 4.

Method	Performance Indicators	
	Average Error (%)	Av Abs Error (%)
A	6.4	17.5
B	10.3	18.1
C	2.9	18.8
D	4.3	35.0
E	27.0	35.4
F	44.2	47.2
G	6.1	23.9
H	23.9	35.9
I	22.9	57.1
J	146.6	75.6
K	42.0	33.6
L	2.2	22.1
M	4.4	15.6
N	4.2	15.9
O	1.4	16.3
P	23.6	20.5
Q	36.4	35.0
R	22.9	40.8
S	1.6	31.6
T	26.6	112.4
U	22.9	71.7
V	47.1	173.2
W	34.2	35.5
X	3.4	32.7

Table 4: Correlation method Performance Test results, Hs

Using the ranking method described above, the most reliable of the correlation methodologies utilised was considered to be Method O entailing the use of the SWM buoy data correlated against resultant wave height from UKMO modelled data on the basis of tertiary binning by Energy Period, Te.

The assessment presented above is based on correlations implemented using a 3-hour averaging period. In order to refine the results, Method O correlations were repeated using longer averaging periods; 12, 24, 48 and 72 hours. Of these the optimum balance between minimising scatter in the correlation and retaining a sufficient number data points was found at 24 hours.

In addition to this refinement to Method O, the number and width of the tertiary data bins was varied. The optimum, according to the defined Performance Tests was found to be when three correlations were implemented for Te intervals of 1.5 seconds.

The final correlation, Method O with a 24 hour averaging period and the data split into three Te bins is presented in

Figure 3. As can be seen, this method captures the apparent slight non-linearity in the overall relationship by using a composite of three linear trends.

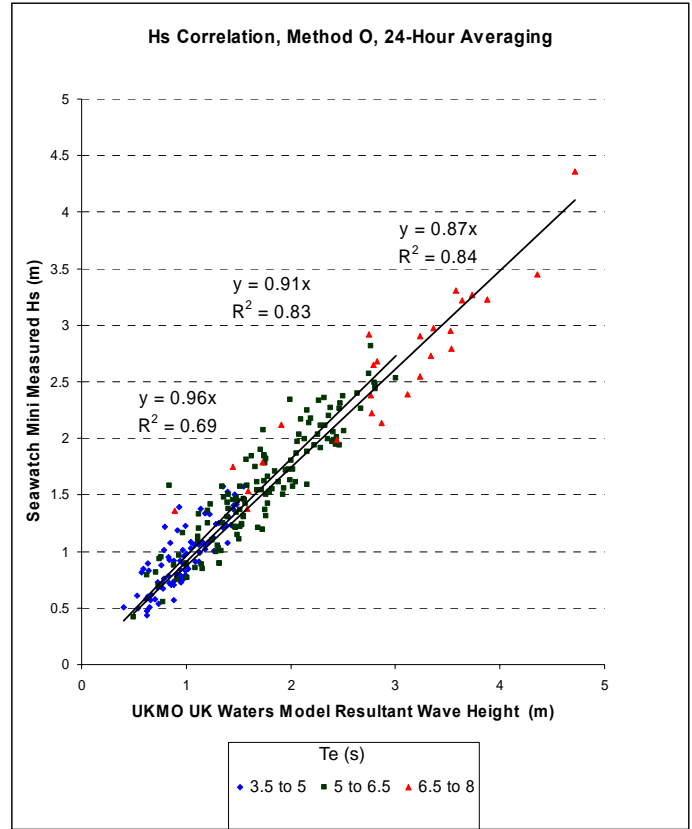


Figure 3: Correlation of Significant Wave Height, UKMO against Wave Hub, Method O.

Correlation Method Assessment, Te

The results of performance testing on each of the candidate correlation methodologies for Te are presented in Table 5.

Method	Performance Indicators	
	Average Error (%)	Av Abs Error (%)
A	0.6	27.7
B	0.8	26.9
C	10.7	31.7
D	0.6	27.3
E	0.1	11.5
F	0.4	11.3
G	13.3	23.5
H	0.1	13.7

Table 5: Correlation method Performance Test results, Te

Using the ranking method defined above, the most reliable of the correlation methodologies utilised was considered to be Method F. 24 hour averaging was also applied to this correlation however the optimum binning method was found to using a single correlation for all data. The corresponding correlation plot for this method is presented in Figure 4.

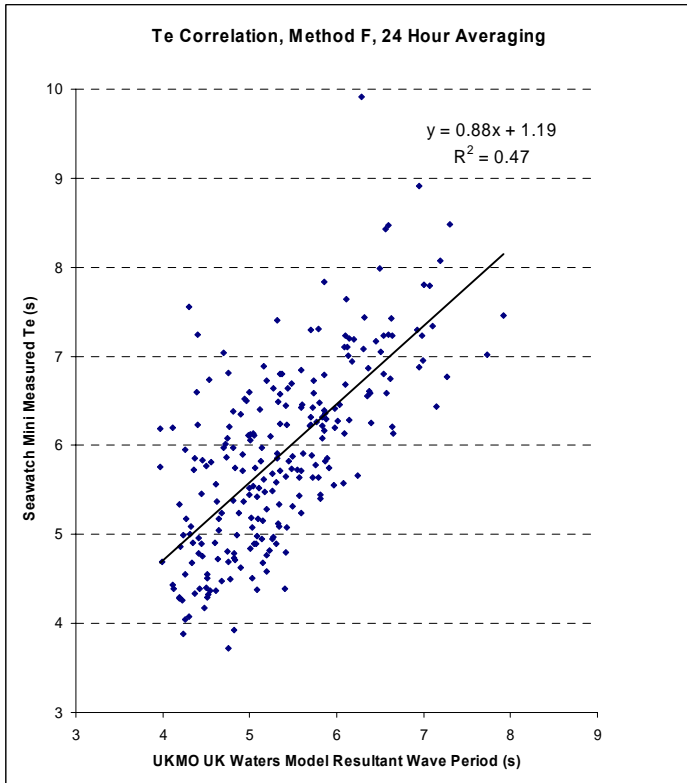


Figure 4: Correlation of Wave Energy Period, UKMO against Wave Hub, Method F.

It is evident that the overall quality of the correlation of Te appears to be substantially poorer than that associated with the optimal Hs correlations. It is speculated that this is primarily caused by the generally lower levels of accuracy associated with model predictions of wave period when compared with wave height.

Predicted long-term wave resource

Following the identification of preferred correlation methodologies, the resulting long-term time series of Hs and Te for the Wave Hub site were analysed jointly in order to provide a characterisation of the predicted long-term wave climate for the site. This analysis is presented below in the scatter-table and plot in Figure 5 and Table 6.

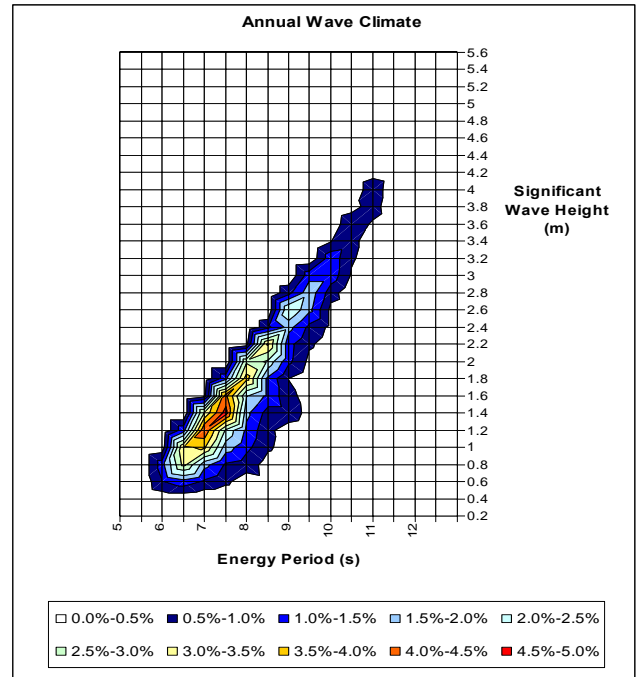


Figure 5: Predicted long-term annual wave climate at the Wave Hub site

Hs (m)	Energy Period, Te (s)								Total
	5	6	7	8	9	10	11	12	
6.0	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.18	0.48
5.5	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.22	0.40
5.0	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.00	0.35
4.5	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.00	0.48
4.0	0.00	0.00	0.00	0.00	0.00	0.75	1.98	0.00	2.7
3.5	0.00	0.00	0.00	0.00	0.13	3.64	0.44	0.00	4.2
3.0	0.00	0.00	0.00	0.00	5.44	2.99	0.13	0.00	8.6
2.5	0.00	0.00	0.00	4.70	6.89	0.88	0.18	0.00	12.6
2.0	0.00	0.00	2.85	12.07	2.63	0.61	0.00	0.04	18.2
1.5	0.00	1.27	17.52	6.01	1.93	0.48	0.09	0.00	27.3
1.0	0.00	9.70	8.74	3.03	0.97	0.22	0.09	0.00	22.7
0.5	0.04	0.75	0.79	0.31	0.00	0.00	0.00	0.00	1.9
Total	0.04	11.7	29.9	26.1	18.0	9.6	4.2	0.44	100

Bin labels refer to top end of bin (e.g. '6m' is 5m to 6m)
Data entries are frequency in percentage.

Table 6: Scatter-table (Hs-Te) representing average long-term predicted wave climate for the Wave Hub site.

The method utilised results in a mean long-term predicted wave power density of 16.8 kW/m. This figure is comparable to the 17.7 kW/m predicted by Pitt [4] for the Wave Hub site. A breakdown of the annual average Hs, Te and Power Density can be seen in Table 7.

Year	Hs (m)	Te (s)	Power Density (kW/m)
Apr-Dec 2000	1.89	7.62	21.89
2001	1.62	7.49	13.78
2002	1.86	7.68	21.66
2003	1.57	7.26	13.07
2004	1.75	7.65	17.58
2005	1.70	7.48	15.94
Jan-Aug 2006	1.60	7.40	14.08
Average	1.71	7.51	16.81

Table 7: Annual averages of key parameters at the Wave Hub site

Inter-annual variation assessment

In addition to the correlation method assessment activity described above, an independent but related study examining the inter-annual variation of wave resource for the Wave Hub site was undertaken utilising 11 years of modelled data from the European waters model, point E04. The standard deviation of Significant Wave Height (Hs), Energy Period (Te) and Wave Power Density (P) has been calculated on an inter-seasonal and inter-annual basis from these data as presented below in Table 8.

Season	Standard Deviation / Mean [%]		
	Hs	Te	P
Spring	13 %	5 %	30 %
Summer	16 %	7 %	32 %
Autumn	13 %	3 %	30 %
Winter	23 %	8 %	47 %
Annual	8 %	2 %	18 %

Table 8: Inter-annual variation of key parameters for the Wave Hub site

As one would expect, this assessment shows that winter-to-winter variation of wave resource is considerably greater than summer-to-summer variation. It is also clear that should Power Density be an important summary statistic for device and project developers, that certainly in this region there is considerable inter-annual variation, implying that a long-term reference period of substantial duration will be required to reduce uncertainties associated with historical climate representation to within an acceptable range.

The assessment of the inter-annual variation has been used to calculate the uncertainty associated with assuming that a finite historical reference period is representative of long-term mean conditions. For this assessment, it has been assumed that the mean wave resource for each successive year is independent - that is, no long-term trends have been considered. Therefore, a Gaussian distribution may be assumed for long-term populations of annual means Hs, Te and P leading to results presented in Figure 6. As can be seen, this shows that to reach a

reasonably low uncertainty level of 5% on Power Density, a relatively long reference period of 12 years is required.

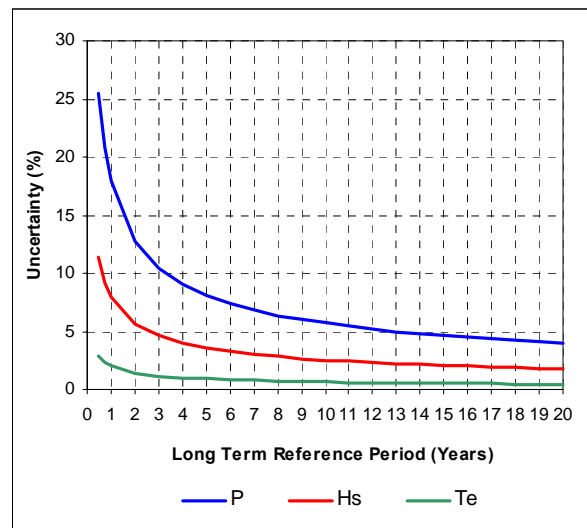


Figure 6: Uncertainty variation with the length of reference data

Other uncertainties and reservations

The predicted wave climate for the Wave Hub site presented in this paper is subject to a number of further sources of uncertainty. The most important of these are listed below:

- Inherent measurement uncertainty
- Data processing uncertainty
- Correlation uncertainty
- Spatial variation of resource
- Future inter-annual resource variability

Each of these issues requires careful consideration and methodologies for their quantification should be developed to enable a formal uncertainty assessment to be undertaken for the predictions presented in this paper.

Resource assessment is inherently conditioned by the quality and consistency of the data sets (both the local and reference). To minimise the error associated with predictions it is essential that there is absolute control on the derived spectral parameters when these have been obtained from field measurements. Such issues have been stressed in Cruz et al. [5], where a novel methodology was applied to wave data from EMEC.

In order for a data set to be used as a long-term reference source it is critical that the reference data is consistent throughout the long-term period considered. This is because the method is reliant on the assumption that a relationship derived over a short concurrent period may be applied to a longer

historical period. Should the reference data be subject to changes that affect its consistency, then this assumption is immediately invalidated and application of MCP in these circumstances can result in a substantial bias in predictions. Inconsistencies in the reference data can be introduced through changes to numerical modelling methods or introductions of new model initiation data. This issue is a particular issue in this study where reference data was sourced from the UK waters model (which is refined periodically to improve short-term forecast accuracy). Therefore, caution should be exercised when utilising the results provided here pending a more detailed investigation of this issue.

Another issue affecting the confidence that can be placed in the results presented here is that some of the data sources utilised did not contain the energy period, T_e . Instead the zero up-crossing period, T_z , was present. In these cases T_z was transformed to T_e using the relationship given in the Atlas of UK Marine Renewable Energy Resources [6]: $T_e = 1.1625T_z + 0.3285$. This is an approximation and as such should be considered as another significant source of uncertainty.

FUTURE WORK

Wave Resource Assessment

Clearly, further R&D work is necessary in order to develop wave resource assessment techniques with the aim of improving confidence in the climatic predictions and achieving consensus amongst the emerging wave energy industry with regard to the most suitable methods for measuring, modelling and analysing wave resource. In particular, it is considered that there needs to be a greater focus on how best to characterise the resource in light of substantial conceptual differences between the leading devices. The requirements of measurements and analysis is likely to be somewhat different depending on the technology to be deployed.

The focus of many studies examining wave resource to date has been on assessing the potential impact of a device or devices on the surrounding environment with particular attention paid to impacts on baseline coastal processes. For this purpose it is normal for environmental analysts to rely on nested numerical modelling techniques. These same model-based techniques have sometimes also been applied when assessing the impact of the *environment on the devices* in the field of wave resource assessment. It is argued here, that for this type of analysis that measurements should be central to the prediction methodology rather than models. In order to support this assertion, further analysis of existing measurements is required as well as validation of leading industry models against these measurements. In addition, new measurements will be

necessary and these campaigns need to properly address the practical difficulties of gathering reliable data in the marine environment for extended periods.

Short-term Wave Forecasting

The second 'strand' of the Juice funded project (of which the wave resource assessment work presented here is the first) is to investigate the applicability of site specific wind energy forecasting techniques to the field of wave energy forecasting and extend this work to develop improved methods focused specifically at wave energy forecasting.

This work will utilise forecasting techniques developed within Garrad Hassan for the purposes of wind energy forecasting. Input data for the forecasting models will be from the npower juice Wave Buoy and the UK Met Office European Wave Model.

The forecasting models will refine the UK Met Office surface parameter inputs. The refinement of the UK Met Office input will be implemented by feeding back the observed conditions at the npower juice Wave Buoy and utilising adaptive "learning" algorithms to continuously adjust the predictions based on the calculated error in previous time steps. Forecasts will be generated of the total hourly energy in the waves and the theoretical energy output from an appropriate device. The accuracy of the predictions shall be assessed at various forecast horizons through comparison with actual measurements at the Wave Hub site.

O&M Simulation and Optimisation

The third and final strand of the npower Juice funded project is designed to improve understanding of Operation and Maintenance (O&M) issues surrounding the Wave Hub project in light of the predicted long-term wave climatology predicted in this paper.

In 2005 GH launched an O&M simulation tool primarily intended for the offshore wind industry, known as O2M ("Optimisation of Operations and Maintenance") [7]. This service has now been implemented for more than 20 offshore wind projects throughout Europe. The strong industry take-up is attributable to the uncertainty surrounding project performance in light of plant reliability and weather related access problems. Similar issues face the Wave Hub project and the proposed analysis is aimed at evaluating O&M risks through cost and availability prediction. The O2M model is now suitable for wave energy technology without further development.

Simulations of the operation of the Wave Hub project shall be implemented based on the analysis of climatic conditions (as discussed in this paper) and nominal project assumptions (based on current plans) for a range of O&M strategies. Repeated simulations shall be implemented whilst varying the level of resourcing (staff and vessels) as well as plant reliability. The latter is particularly critical to the outcomes of the modelling and so a wide range of reliability profiles shall be implemented to allow device and project developers to select results most relevant to their technology. A causal breakdown of lost production and direct O&M costs shall be provided and recommendations made on the project OPEX assumptions that should be taken forward into the detailed design phase.

CONCLUSIONS

Several conclusions can be drawn from the work presented in this paper, in relation to wave resource assessment and in particular to the resources available at the Wave Hub site.

- The application of a Measure-Correlate-Predict (MCP) approach to the assessment of the key oceanographic parameters on the basis of short-term measurements from a potential site is a promising method for the prediction of long-term wave resource.
- MCP has the benefit of making site measurements central to the prediction. The uncertainties associated with the use of modelled data are reduced as these data are used only in a relative rather than an absolute sense, so as to make the short-term site measurements representative of a longer historical period.
- The strongest method for the prediction of H_s at the Wave Hub site was found to be MCP-reconstruction using 24-hourly linear regression, forced through the origin for three T_e bins (bin width = 1.5 seconds). By this method, the long-term mean significant wave height at the Wave Hub site is predicted to be 1.7m.
- The strongest method for the prediction of T_e at the Wave Hub site was found to be MCP-reconstruction using 24-hourly linear regression, not forced through the origin with all data in a single bin. By this method, the long-term mean energy period at the Wave Hub site was predicted to be 7.5 seconds.
- Through combination of reconstructed time series of H_s and T_e for a long-term period of 6 years, the predicted annual average wave power density is evaluated as 16.8 kW/m.

ACKNOWLEDGEMENTS

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