A Changing Climate for Wave Energy

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ABSTRACT

Wave energy is critical to the move to a low carbon economy. Unfortunately, like other renewables, it may be sensitive to changes in climate resulting from rising carbon emissions. Changes in wind patterns are forecast and these will alter wave regimes. Evidence indicates that wave heights have been changing over recent decades, although there is no proven link to global warming. Changes in wave climate will impact on wave energy conversion: resource restrictions may lower energy exports with consequent negative economic impacts. Alternatively, increased storm activity will increase survival risks for installations. Here, we outline evidence of recent wave climate change and projections of the future. Methodologies for inferring future change are compared and a simple case study is presented.

INTRODUCTION

Wave energy has a key role to play in meeting long-term renewable energy targets. This is particularly true of the Atlantic coast of Europe which possesses vast wave energy resources with some of the most favourable sites located off the Scottish west coast.

While wave energy is being developed in order to limit or avoid climate change, its reliance on the natural environment means that it may be vulnerable to changes in climate that result from rising carbon emissions. It shares this risk with other renewable sources like hydropower (Harrison and Whittington, 2002) and wind (Breslow and Sailor, 2002). Indeed, there is evidence that global wave heights have been changing over recent decades and while it has been suggested that this may be caused by global warming (Grevemeyer), there is no conclusive proof as yet.

Given the prospects for wave energy, there is a need to quantify the potential for climate change to alter wave energy resources and the ability of wave energy devices to extract energy on a commercial basis.

EVIDENCE OF CHANGE

Trends of increasing wave height in the Northeast Atlantic were identified in the late 1980s and early 1990s (Carter and Draper, 1988; Bacon and Carter, 1991). These suggested increases in mean wave height of some 2% per year and are in line with other sources that indicate changes of 30-50% over 30 years. Early studies were unable to link trends in local wind speed that with the larger waves (Bacon and Carter, 1991). However, additional work found a link between broader climate conditions in the form of a North-South North Atlantic atmospheric pressure gradient and the wave hight increases (Bacon and Carter, 1993).

More recent work (Woolf *et al*, 2002) based on satellite altimeter measurements is overcoming the problems associated with earlier in-situ data from buoys and weather ships (e.g., poor spatial coverage and changes in observational practice). The study suggests wave heights in the northeast Atlantic have increased by 0.6 m (15%) over the period between 1967 and 1991.

Evidence from wave measurement is backed up those indicating changes in storm activity. More locally, storm frequency in the far Northeast Atlantic has increased since 1958, although the frequency appears to be lower since the early 1990s (Weisse et al, in press). The changes in storm activity are mirrored by growth in extreme wave heights between 1958 and 1997: e.g., northwest of Ireland, winter extreme wave heights have grown by 0.5–1% per year (Wang and Swail, 2002).

To date, there has been no investigation into the impacts of changes in wave climate on wave energy conversion.

IMPLICATIONS

Changes in wind patterns are a widely anticipated consequence of climate change. Offshore winds will also change, particularly given historical long term trends in European wind speeds, with, e.g. UK winter speeds have increased by 15-20% over the past 40 years (Watson *et al*., 2001). With wave energy proportional to the fifth-power of wind speed (Jeffrey *et al*., 1974), a 5% change in wind speed would produce a 25% change in wave power. As such, even relatively small changes in wind patterns will have potentially significant consequences for wave energy availability.

Wave energy converters (WECs) are designed to capture energy within specific bands of wave height, period and direction. Although much research has focussed on developing 'tuneable' devices, changes in the resource will inevitably alter energy capture. Where the climate alters in such a way as to restrict the resource there may be reductions in energy production and consequent economic impacts, particularly where this coincides with high price periods. In cases where the wave resource increases it may bring revenue benefits although there is a likelihood that increased storm activity will pose an enhanced risk to the survivability of installations; installations will need to be designed with this in mind. The potential for climate to change in such a way as to enhance seasonal differences in wave activity may be of particular concern.

A further issue is sea level rise, which is expected to be between 20-80 cm by 2050 (Hulme et al, 2002). While WECs moored in deeper water might experience limited impacts, shoreline based devices could be affected by raised water levels, albeit the effects may be tempered by the existing tidal range.

ASSESSMENT METHODOLOGIES

In assessing the impact of changes in climate on wave energy, there are several distinct stages:

- Projection of future greenhouse emissions,
- Resultant changes in climate variables,
- Translation into wave climate effect,
- Impact on energy production and economics.

General Circulation Models (GCMs) are complex atmosphere and oceans models, akin to weather forecasting models, that are driven with scenarios of greenhouse gas concentrations. A range of emissions scenarios are used to attempt to capture the uncertainty inherent in future energy use, economic activity and other socio-economic trends. The work of the IPCC has created a range of standardised scenarios to allow comparison between different models and consequent climate impacts.

The third aspect of the assessment process involves the translation of climate information into projections of wave climate. Approaches include:

- Climate proxy models
- Wind-wave models

The climate proxy approach involves finding relationships between important climate variables and the wave climate. Woolf *et al*. (2002) used satellite altimeter measurements to estimate the wave climate of the North Atlantic before identifying correlations between wave heights and the North Atlantic Oscillation (NAO), a measure of the pressure anomaly between Iceland and the Azores. Projections of the NAO from GCMs could then be used to infer future wave heights. To date this has been used to explore the vulnerability of Western Isles ferry services to a changing climate (Woolf *et al*., 2004). An alternative approach (Wang *et al*., 2004) correlated sea level pressure data with significant wave height data from a wave hindcast. Pressure data from several GCMs was then used to estimate trends in mean and extreme wave heights. The projections showed the trend in wave heights in the northeast Atlantic and North Sea to be sensitive to changes in greenhouse gas emissions. Under one scenario, mean winter wave heights would increase by up to 11%.

Third-generation wind-wave models (e.g. WAM) have also been used for projecting future wave climate. The approach has been to create a detailed historical wave climate based on measured and estimated wind speed datasets like those provided by NCEP/NOAA. The wind data is perturbed according to GCM data, the wind-wave model run again and the two climates compared. A notable example of this approach was the WASA Group study (WASA, 1998) which used GCM to infer future climate; unfortunately their results were inconclusive.

The two broad methods of translating climate data into wave information have advantages and disadvantages. While the regression approaches are fairly computationally intensive, they are much less so than hindcasting with wind-wave models (i.e. not parallel computing). However, their applicability has tended be on a seasonal basis with detailed wave height distributions generated by statistical models. The wind-wave models offer several advantages of which the main one is detailed time-series information that may be gained, as well as more ready availability of wave period information. Essentially, the choice between the approaches is a trade-off between speed (important given that several GCM scenarios may be required) and a more detailed temporal description of the wave climate.

While the methods described above offer the most scientific approaches to exploring climate impacts on wave energy a simpler approach was saught for initial investigations to quantify the extent of the potential changes. As such, was a sensitivity study was carried out.

SENSITIVITY STUDY

As a first attempt at indicating the degree to which wave energy conversion is influenced by climate change, its sensitivity to changes in mean wind speed was assessed. The work is described in detail by Harrison and Wallace (2005) and briefly here.

The assessment was carried out by combining the Rayleigh wind spectrum with the Pierson-Moskowitz wave spectrum to provide a link between wind climate and wave energy potential. The appraisal methodology, as adapted from the standard approach detailed by Thorpe (1999), is shown in Figure 1.

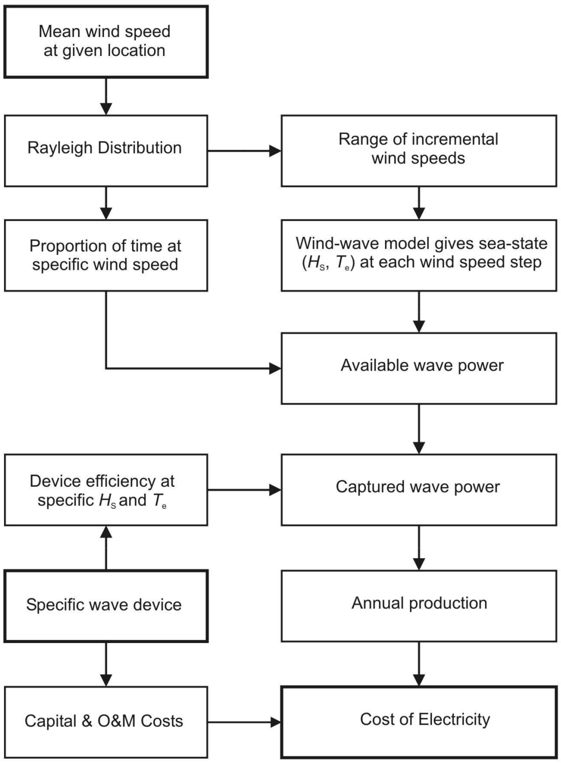

Figure 1 Wave energy appraisal methodology using wind speed (after Harrison and Wallace, 2005)

The main premise is that according to the Pierson-Moskowitz spectrum a particular wind speed defines a particular sea state in terms of wave height and period. The Rayleigh wind speed distribution provides the probability of a particular wind speed occurring given a specified mean wind speed. Each incremental wind speed therefore relates to a specific sea state and the probability of its occurrence given by the Rayleigh distribution. As such this provides a probability distribution for a range of sea states, albeit with these falling along a curve in the wave height/period domain rather than a true scatter diagram (Figure 2). By changing the mean wind speed, the proportion of time for which a given sea state occurs also changes. This approach is not dissimilar from that used by Ertekin and Yu (1994). By combining the sea state distribution with device specific power output and efficiency data, estimates of energy production and financial performance may be gained.

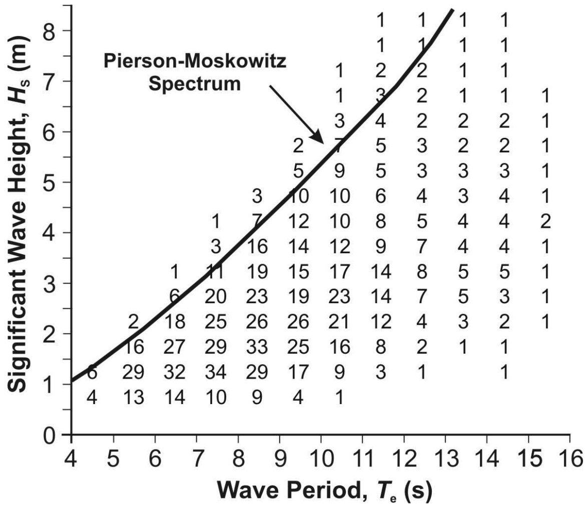

Figure 2 Scatter diagram and Pierson-Moskowitz spectrum (after Harrison and Wallace, 2005)

Using this approach, a hypothetical WEC installation was modelled assuming a mean wind speed of 10 m/s which is approximately that of the northeast Atlantic. The Pelamis power matrix provided a convenient means of converting the sea state distribution into estimates of power output. Together with some fairly simple cost and revenue estimates for the device, this allowed financial performance to be assessed. By varying mean wind speed by ±20% of the initial amount, the effect on a range of resource, production and financial indicators could be explored. The results for wind speed changes of ±10% are shown in Table 1.

Table 1
Indicators with changes in mean wind speed (after Harrison and Wallace, 2005)

INDICATOR	**CHANGE IN WIND SPEED (%)**		
	-10	**0**	**+10**
Mean RMS wave height (m)	2.19	2.70	3.27
Mean wave period (s)	5.63	6.25	6.88
Mean wave power (kW/m)	49.5	83.73	134.4
Production (GWh/yr)	1.61	2.04	2.45
Load factor (%)	24.5	31.0	37.3
Internal Rate of Return (%)	6.18	9.36	12.16

The results indicate that changes in wind speed have a significant impact on the available wave resource

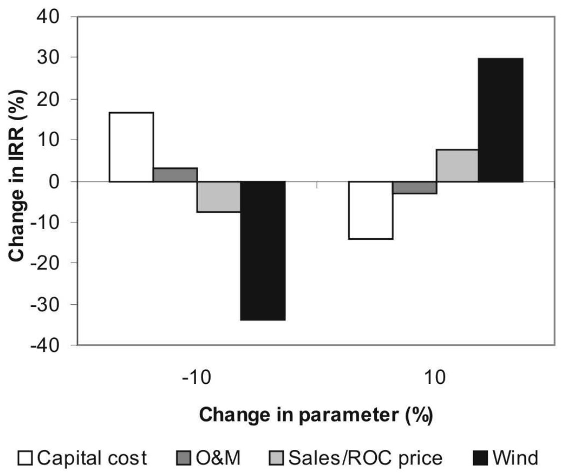

Figure 3 Financial sensitivity to wind speed and key parameters (after Harrison and Wallace, 2005)

The authors believe that this study is the first to address how global warming-induced changes in wind climate will influence the production and economics of wave energy devices. A deliberately simple approach has been taken in order to get a quantitative appreciation of the potential changes. As a result, several important aspects are not considered:

1. Swell and monthly variations in wave climate,
2. Survivability in extreme waves, and
3. Sensitivity of alternative WECs.

The Pierson-Moskowitz spectrum takes into account only wind generated waves and ignores swell. Swell waves are larger, longer wavelength waves produced by distant extra-tropical cyclones (storms). The intensity and frequency of these storms are of major importance to the wave energy resource of Western Europe and the Pacific Northwest, particularly in the winter months. In the North Atlantic and Pacific the storm tracks tend to move in a northeasterly direction and, as the storm rotates anti-clockwise, the southern part of the system continuously feeds energy into the waves. With the storm effectively moving with the waves, very large energetic waves are produced. When the storms weaken, the waves continue to travel (with minimal energy loss) in a north-easterly direction, arriving as swell a few days later. By ignoring swell, the PM spectrum tends to underestimate wave energy which explains the lower than expected device performance. Furthermore, the PM spectrum is only validated for wind speeds of up to 20 m/s as few higher speed spectra were available in the original study [16]. Given the very low probabilities attached to the higher wind speeds the approach is believed to be acceptable.

Despite its limitations, this study has been a useful start in defining the extent to which wave energy conversion may be vulnerable to changing climate. More sophisticated approaches relating climate to wave conditions and driven by current and future climate as projected by GCMs will be necessary for detailed examination and the application of a range of analyses including scenario and risk analysis to this issue.

CONCLUSION

This paper has shown how to prepare a paper for submission to the 6th European Wave and Tidal Energy Conference, Glasgow 2005 . Good luck with your paper. Hope to see you in August.

ACKNOWLEDGMENT

This document is a summary of various documents from previous Conferences.

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