ASSESSMENT OF A COMBINED OFFSHORE RENEWABLE ENERGY RESOURCE FOR IRELAND

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ABSTRACT

This paper attempts to assess if extracting energy from a combined offshore, wind, wave and tidal resource can reduce the difficulties envisaged from integrating a large volume of a single intermittent source into the current electricity system in Ireland. The paper concludes that the use of wave power and tidal power, in combination with wind power, has significant merit.

INTRODUCTION

All countries must increase the quantities of renewable energy in their electricity system due to the Kyoto Protocol and their own obligation to the environment, not to mention the desire to find alternative means of energy with the continuing increase in oil prices. With wind power being one of the world's fastest growing energy resources and Ireland's envious wind resource, wind power is set to fulfill most of Ireland's renewables target. However, the Irish electricity system is a small island system, and it is envisaged that the integration of large volumes of wind power into the system, will come with a number of technical, economical and environmental difficulties (ESBNG, 2004; SEI, 2004; Ó Gallachoir et al., 2004). These difficulties have been shown to arise form the variability and unpredictability of the wind resource. Technically, it is essential that the stability and security of the power system be maintained, while economically, the introduction of a highly variable source, albeit a free source, could result in higher electricity costs (due to surplus capacity, increased number of start ups and an inefficient stop/go operation of conventional plants). For these same reasons, it is also thought that savings in fuel and emissions will not be as high as originally estimated.

With a large wave power resource (often exceeding 70 kW/m width of oncoming wave) and with a number of viable tidal energy locations (as given in (SEI, 05)), Ireland has an option to include wave power and tidal power in its renewables energy mix. This paper attempts to assess if extracting energy from a combined wind/wave/tidal resource can reduce the difficulties mentioned above, and hence reduce costs and increase fuel and emissions savings. The assessment focuses on three specific aspects: variability, correlation and predictability, and is based on actual time series data from various locations around Ireland. A comparison between a single wind resource and a combined wind/wave renewable resource is presented and the results for the Irish case are documented. The issues are proven to be location specific, with appropriate locations showing the combined renewable source to be significantly less volatile and less intermittent.

DATA AVAILABILITY

The data used in this study is hourly measured data of wind speed, wave height and wave period, from the four locations given in figure 1. This data was collected by the Irish Marine Data Buoy Network (Marine Inst., 2005). M1-M3 are the labels given to the three buoys deployed at these locations, while FS1 represents the data collected form the Marathon Gas Platform, off the South coast of Ireland.

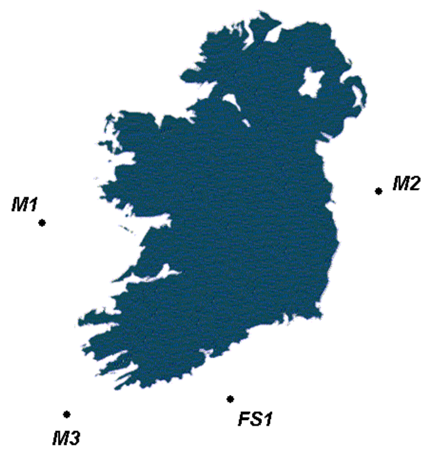

Figure 1 Location of Data Points

As there is no facility for measuring the tidal current velocity on board these data buoys, no tidal velocity time series is available. However, these are not the most appropriate tidal points anyway. As a result, initially, only the combination of wind power with wave power is considered. Combining tidal power with the two other forms of renewable power is considered in a later section.

To investigate the combined resource under the headings of predictability and correlation, the raw wind speed, wave height and wave period time series are used to calculate raw wind power and wave power time series. In the variability analysis, it is important to investigate the variability in the supply of power into the grid system, hence, the raw wind speed, wave height and wave period time series' are transformed to actual wind turbine (WT) and wave energy converter (WEC) power output. To convert the wind speed time series into a wind turbine power production time series, a power curve for an appropriately sized offshore WT, was used, with the wind speed data scaled to an appropriate height. Due to the relative infancy of wave power technology, details of actual power production at different wave conditions are not available for most WECs. However, details of power production from Ocean Power Delivery's, Pelamis WEC, the world's first commercial WEC (OPD, 2005a), is known. The power output, from the Pelamis, over a range of sea spectra, is indicated by the WECs power matrix (OPD, 2005b). The time series of wind power production and wave power production, obtained through the use of the power curve and power matrix, respectively, will provide the basis for the variability analysis in this paper. Some preprocessing of the two series was required to deal with a number of periods of missing data, in an appropriate manner, for the analysis.

RESOURCE VARIABILITY

In this section, different combinations of combined wind and wave farms are compared on an equal mean output basis. The wind farm and the combined wind and wave farm are scaled to a size where they both produce the same 50MW mean output. So, for example, in figure 2, a 50% wind 50% wave combined farm would consist of a number of WTs producing a combined yearly mean power level of 25MW, along with a number of WECs also producing a yearly mean output of 25MW. With this as a basis, the variability in the different levels of combined farm output can be reasonable compared. Scaling a single point measurement to represent a farm output does introduce some error, due to the smoothing effect of different areas of the farm experiencing different conditions at different times. While Norgaard (Norgaard et al, 2004) has developed a methodology to generate an estimate of a wind farm output from a single point time series, no such methodology exists for the accurate estimation of a wave farm output. Therefore, to maintain a fair basis for comparison, no preprocessing to represent the smoothing effects of an aggregated output is carried out.

To assess the level of variation in the power time series, four measures of variability are used:

Absolute Hour-to-Hour Variation

Through summation of the absolute difference between consecutive samples of the combined power production time series, a measure of the hour-to-hour variation of power production can be made:

$$\text{var} = \sum_{i=1}^{n} \left| x_{i+1} - x_i \right|$$

where x_i is the combined power level (in kW) at hour i and n is the total number of samples.

Standard Deviation

The standard deviation, can also be used to inform about the variability of the hourly time series, defined as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}}$$

where $\bar{x}$ is the mean value of x.

Power Production Duration Curve

The power production duration curve is a graphical representation illustrating the number of hours that farm production equals or exceeds specified values. It is obtained by sorting into descending order the power production time series values. A less variable power source will produce a much flatter duration curve.

Hourly Variations Duration Curve

This duration curve illustrates the number of hours for which the hour-to-hour variation between consecutive power levels, described as a percentage of the mean power level, exceed a particular amount. This duration curve assesses the variability in the power production over a shorter timescale then the power production duration curve.

Results

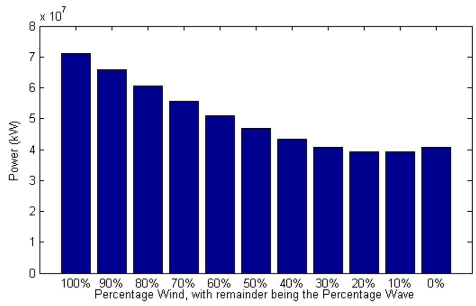

Figure 2 Total Absolute hr-to-hr Variation, Location M1

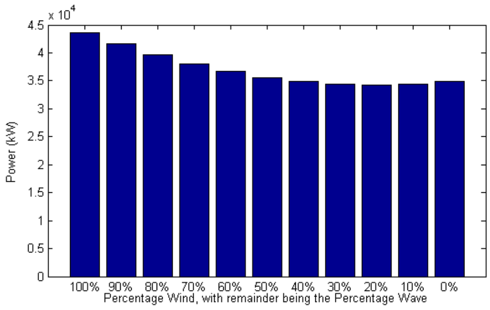

Figure 3 Standard Deviations, Location M1

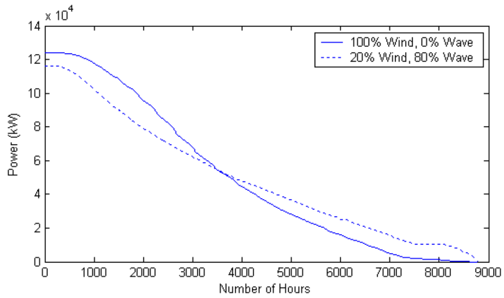

Figure 4 Power Production Duration Curve, Location M1

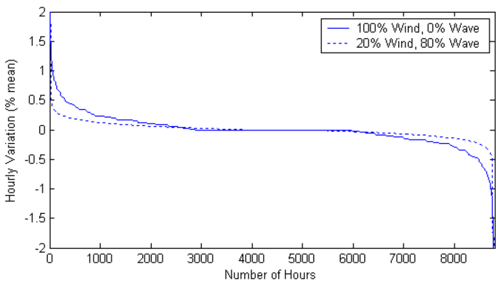

Figure 5 Duration Curve of Hourly Variations, Location M1

Figures 2-5 illustrate the results of the variability tests for the west coast location. Figures 2 and 3 show a reduction in the hour-to-hour variations and the standard deviation, as the percentage of wave power in the combined farm increases. Figure 4 shows that a combined 20% wind 80% wave farm has a greater spread of production across the total number of hours in the year, with the stand-alone wind farm having almost no power production for over 1500 hours. Finally, figure 5 shows that the hourly variations, for the combined farm time series, only exceed ± 0.25% of mean power production for 7% of the total number of hours. However, in the case of the stand-alone wind farm time series, this is 23% of the hours. It is clear from these results, that in terms of variability, a stand-alone wind farm is significantly inferior to a wind/wave option.

Figures 8(a) – 8(d) show the results of the variability tests for the east coast location, M2. In this case, the trend has totally reversed from the west coast location results. Now the most variable power output comes from a stand-alone wave farm, with the optimal combination coming from a combined 90% wind 10% wave farm. The difference between the two locations is primarily due to the fact that the wave resource is much greater on the west coast then the east coast.

Figures 8(e) – 8(l) show the variability test results for the south and southwest coast. In these cases, there is no clear trend towards any one resource. Interestingly, the total absolute hour-to-hour variation analysis and the hourly variation power curve show a slight tendency towards the wave resource being less variable. On the other hand, the standard deviation analysis and the power production duration curve show a tendency towards the wind resource being less variable. In conclusion, over a shorter timescale (hour-to-hour) the wave resource is less variable, with the wind resource being less variable over the longer timescale (production over the year, as indicated by the flatter power production duration curve and smaller average deviation from the mean). Considering this, and the individual results, it is clear that a combined farm would be the best option at these locations.

RESOURCE CORRELATION

In the previous section, the level of variability in a single source and a combined source was assessed. It is also important to assess the co-incidence of this variability. Ideally, when one resource diminishes, the other resource would increase to compensate. To assess this, the statistical correlation between the two time series, raw wind and wave power, was investigated. Statistical correlation can be thought of as a measure of how much one variable depends on another and is calculated as:

$$cor(X,Y) = \frac{\operatorname{cov}(X,Y)}{\sigma_X \sigma_Y}$$

where

$$X = x_1, x_2, x_3 \dots\dots\dots x_n$$
$$Y = y_1, y_2, y_3 \dots\dots\dots y_n$$

with σ_X and σ_Y being the standard deviations of the variables X and Y, and $cov(X,Y)$ is the covariance between the variables, given as:

$$\operatorname{cov}(X,Y) = E[(X-\mu_X)(Y-\mu_Y)]$$

with μ_X and μ_Y being the mean values of X and Y.

The result of the calculation is a correlation coefficient with a value between –1 and 1.

Table 1 Interpreting the Correlation Coefficients

Correlation Coefficient	Interpretation
0	No relationship between the variables
1	Perfect positive correlation
-1	Perfect inverse relationship

To assess the level of correlation between the wind power and wave power produced at a specific location, it was decided to calculate the correlation coefficients over a number of different periods of interest (6hrs, 12hrs, 24hrs and 72hrs). The yearly time series of wind power and wave power at a specific location is broken into sections, representing the current period being investigated (e.g. 6hr blocks), and the correlation coefficient was calculated across each section. The results are described graphically in the following probability density diagram.

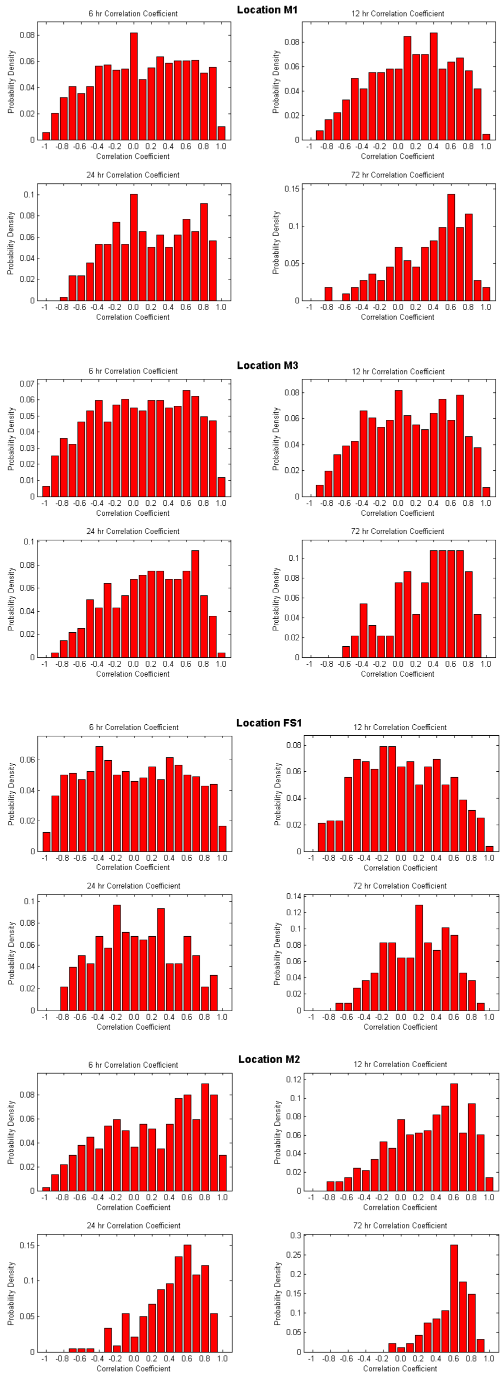

Figure 6 Probability Density of Correlation Coefficient

The probability density for the 6 hour periods, at location M1, is centered just right of zero, pointing to a reasonable amount of anti-correlation between the two resources. It can be seen, that as the time period over which the correlation is calculated increases, the overall correlation increases (the probability density tends towards unity). This is explained by the fact that, ultimately, the ocean waves are caused by the wind. There is also a noticeable change in the probabilities as you move from the west coast location, down along the south coast and around to the east coast (M1 to M3 to FS1 to M2). The correlation coefficients increase (probabilities tend towards unity). The increase is due to the fact that there are relatively low levels of swell waves (rather wind waves) on the east coast. The relatively high levels of anti-correlation at the west, south and southwest locations point to the use of a combined resource at these locations. However, the high correlation between the resources at the east coast location, indicate a situation where there will be a large number of occasions when both resources will be low.

PREDICTABILITY

Accurate forecasts of wind and wave power are important to the successful integration of large volumes of either power source into the electricity system in Ireland. The forecasts are crucial to system operation and planning, and to the overall efficient running of the electricity system. In the case of wind power prediction, up to 2-3 hour ahead forecasting can be achieved fairly well through simple persistence forecasting (what happens now will happen in 2-3 hours from now). Improvements on this can be made through the use of statistical regression of wind farm outputs (using time series models, e.g. Kalman filter models, ARMA models). Beyond 3 hours, forecasts are based on data from the National Meteorological Offices 'Numerical Weather Prediction' (NWP) models, with site-specific forecasts achieved through both statistical and physical methods.

This study is interested in comparing the short-term predictability of raw wind and wave power. Actual power production is not predicted as obtaining the actual power production time series involves use of the highly non-linear operation of the power curve and power matrix. Forecasts were made in two ways:

- Forecast future values of the individual variables: wind speed, wave height and wave period, and then calculate raw power values,
- Directly forecast future instantaneous raw power values from previous raw power values.

This means all the forecast errors are in terms of power and can be easily compared. For each location, the yearly time series is divided into 8 sections, with each section being further divided into training, validation and test data. This allows for the prediction models to be tested across 8 sample sections, spread across the year, and for average prediction errors to be calculated. A persistence model and a set of auto-regressive models are used for the forecasts. A nonlinear neural network model was also tested, but it was found that it gave no advantage over the linear extrapolation models. Giebel (Giebel, 2003) notes that for short term prediction of wind power, the improvements attainable through the use of neural network was usually deemed not enough to warrant the extra effort in training a neural network. It must be remembered that this study is only looking for an appropriate model to do a fair comparison between the predictability of wind power and the predictability of wave power. It must be stressed, that the best model, with minimal prediction errors, is not necessarily required.

Persistence Model

$$y(k) = y(k-1)$$

where *y(k)* is the value being predicted, and *y(k-1)* is the previous value.

Auto-Regressive Model

$$y(k) = -a_1 y(k-1) - a_2 y(k-2) - \ldots\ldots\ldots\ldots - a_{N_A} y(k - N_A) + e(k)$$

where a_i, $i=1,\ldots,N_A$ are the auto-regressive coefficients, N_A is the order of the system, and *e(t)* is the modeling error. A loss function analysis returned $N_A = 2$ as most suitable. The auto-regressive coefficients where estimated through the use of a least squares algorithm.

Results

Figure 7 illustrates the average multi-step ahead forecast errors for wind and wave power over the eight sample sections taken from 2004. The solid lines and dotted lines represent the wind and wave power prediction errors, respectively, and the star, circle and cross, represent the persistence model, indirect AR power predictions (via the variables wind speed, wave height and wave period) and direct AR predictions of power, respectively. In the persistence model case, predicting the wind speed, wave height and wave period variables and then calculating the power, gives the same results as predicting the power directly. The error function used, is a variation on the typical mean absolute percentage error (MAPE) function, with the variation being that the x_i have been taken out of the denominator in the summation in the typical MAPE function and replaced by the mean value $\bar{x}$ outside the summation in the new MAPE* function. The reason for this is that some of the x_i values go to zero, giving a large absolute percentage error even though the error in terms of power could be relatively small.

$$MAPE^* = \frac{100}{N.\bar{x}} \sum_{i=1}^{N} \left| x_i - \hat{x}_i \right|$$

where, N is the number of data points, x_i is the actual value at period i, $\bar{x}$ is the mean value of x, and $\hat{x}_i$ is the forecasted value at period i.

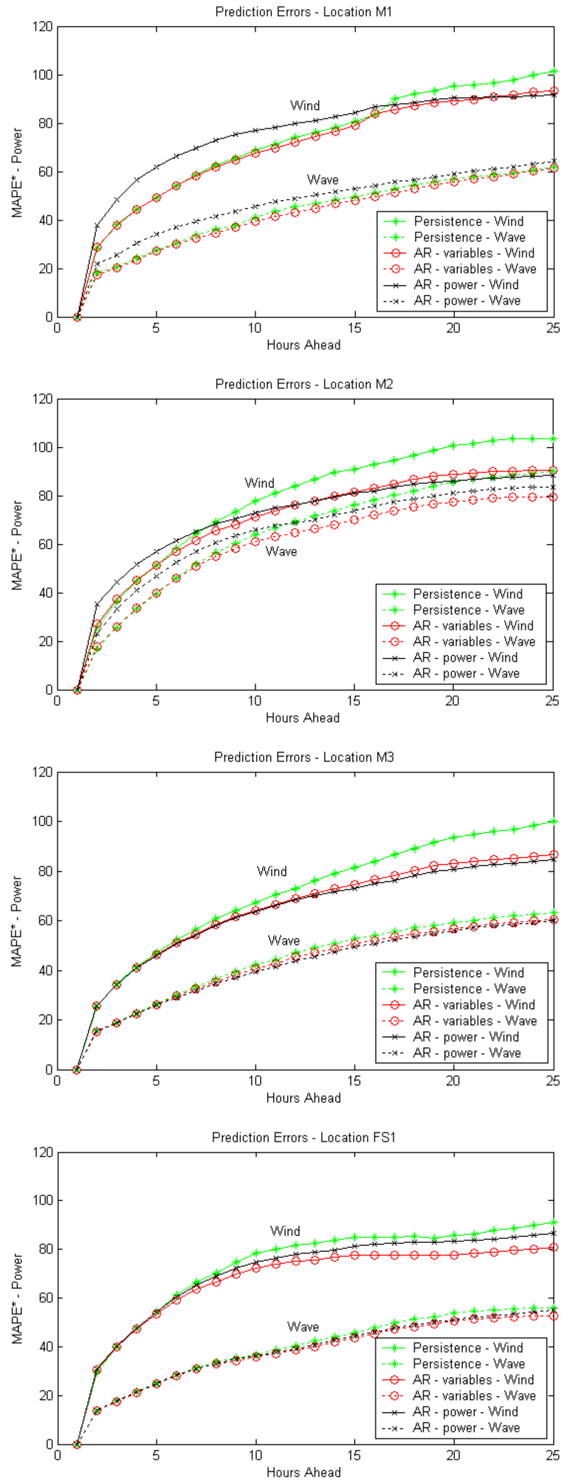

Figure 7 Forecast errors

Overall, the wind forecast errors are greater then the wave forecast errors, illustrating that wave power ,in general, is more predictable then wind power. It can be seen that wind power prediction errors vary only slightly over the different locations while wave power prediction errors vary significantly from location to location, with significantly greater prediction errors at the East coast of Ireland. Evidently, this is directly linked to the variability results, with the highly variable wave power on the east coast giving the greatest prediction errors. It can also be seen that the AR model out-performed the simple persistence model, though not to a significant extent.

TIDAL ENERGY

A report by Kirk McClure Morton, for Sustainable Energy Ireland (SEI, 2005), found that Ireland had a theoretical tidal resource of 230 TWh/year. However, considering technological limitations, and physical, environmental and commercial constraints, this reduced to a viable resource of 0.915 TWh/year. However, with the continuing technological development of tidal energy extraction this viable resource could become significantly larger.

The Kirk McClure Morton report also notes that a significant proportion of the tidal resource around Ireland is found along the east coast, with suitable locations including Copeland Island, Strangford Lough, the Codling and Arklow Banks, Tuskar Rock and Carnsore Point. The resource on the west coast is mainly concentrated in the Shannon Estuary.

In terms of the short term variability of power production, the tides follow a diurnal 12.4 hourly cycle caused by the rotation of the earth relative to the moon and the sun, with the result that the marine current velocity will reach 0 m/s four times a day. For a period around these null points, the power production from a tidal turbine will be zero or very low, until the marine current velocity picks up to a 2m/s level. The length of this period is dependent on the specific location and on the design of the tidal turbine. However, the variation in the power production is entirely predictable, and on the east coast, observing the time spread of high and low tide (7 hours), there appears to be a definite opportunity to extract energy from different locations in order to remove production variability and possibly produce a relatively constant energy production.

Tidal energy offers variable but predictable electricity generation, as tides and marine currents are predicted accurately from the gravitational effects of the Moon and Sun.

In terms of correlation between the tidal resource and either of the wave and wind resources, there is little correlation, as the effect of the local winds and waves, on the tidal stream velocity, is largely insignificant relative to the effect of the change of tides.

Essentially, tidal energy gives highly predictable power production and should be considered as part of the combined renewable resource off the East coast of Ireland.

CONCLUSIONS

Ireland is set to introduce a large volume of a single intermittent source (wind power) into the current electricity system, creating some technical and economical difficulties. The objective of this paper was to assess if extracting energy from a combined, wind, wave and tidal, offshore renewable resource, could reduce these difficulties.

It has been shown that harnessing energy from a combined wind and wave renewable resource along the South and South-West coast of Ireland will provide significantly less variable power production, than harnessing energy just from the wind resource. The hour-to-hour variations and the overall spread of power across the year will improve. The power production from a combined farm will also be more easily predictable. The net result will be cheaper electricity generation and increased savings in fuel and emissions from conventional plants.

On the East coast of Ireland, results show that combining the wind and wave resource is less attractive. However, combining the wind resource with the entirely predictable tidal resource would have significant merit.

ACKNOWLEDGEMENTS

This research was funded by Enterprise Ireland under the Research Innovation Fund scheme (Project IF/2002/309).

REFERENCES

ESB National Grid (ESBNG). 2004. Impact of Wind Power Generation in Ireland on the Operational of Conventional Plant and the Economic Implications.

Giebel G. 2003. The State-of-the-Art in Short-Term Prediction of Wind Power - A Literature Overview. Project ANEMOS.

Irish Marine Institute Website. [Last accessed May 2005]. Irish Marine Data Buoy Network. Available from: http://www.marine.ie/ scientific+ services/data+services/data+buoy/

Norgaard P, Holttinen H. 2004. A Multi-Turbine Power Curve Approach. Proc. Nordic Wind Power Conference, Gothenburg, Sweden.

Ocean Power Delivery (OPD, 2005a) Website. [Last accessed June 2005]. Press Release: Order Signed to Build World's First Wave Farm in Portugal. Available from http://www.oceanpd.com/

Ocean Power Delivery (OPD, 2005b) Website. [Last accessed June 2005]. Power Prediction. Available from http://www.oceanpd.com /Pelamis/Powerpredictions.html

Ó Gallachoir BP, Gardner P, McKeogh EJ, Snodin H. 2004. The Grid Connection Moratorium in Ireland. Proc. European Wind Energy Conference.

Sustainable Energy Ireland (SEI), Kirk McClure Morton. 2005. Tidal and Current Energy Resources in Ireland.

Sustainable Energy Ireland (SEI). 2004. Operating Reserve Requirements as Wind Power Penetration Increases in the Irish Electricity System.

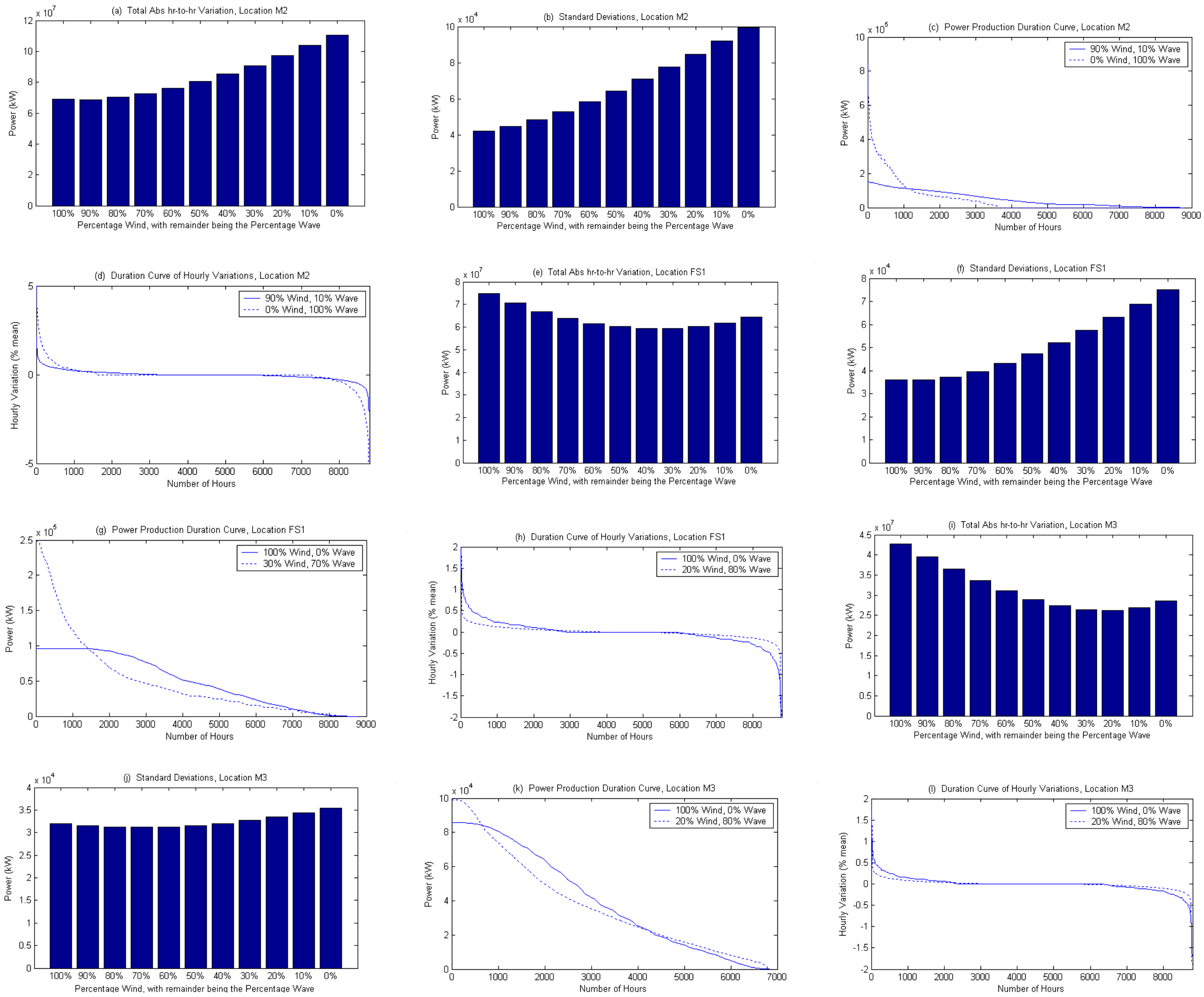

Figure 8 Variability Results