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Preliminary assessment of climate change impacts on the UK onshore wind energy resource

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Abstract

Wind power is currently the fastest growing renewable technology and will play a significant role in constraining the extent of climate change. However, the very fact that its 'fuel source' is driven by the climate may leave it exposed as climate changes over the coming decades. In this preliminary assessment, the potential for changes in climate to affect the significant onshore wind resource in the United Kingdom (UK) is explored using the regional climate change scenarios published by the UK Climate Impacts Programme in 2002. The scenarios indicate seasonal changes in potential wind production with winter production generally increasing while summer decreases.

Keywords: climate change, United Kingdom, wind energy, wind climate.

1 Introduction

Wind energy is currently the fastest growing renewable energy source globally and will be a key contributor to future long term renewable energy targets. This is particularly true in the United Kingdom (UK) which possesses some of the best onshore and offshore wind energy resources in Europe. While the current installed wind capacity is of the order of 1 GW the potential is far greater (BWEA, 2006). In Scotland alone, the economically viable onshore potential is 11.5 GW, although a range of constraints, including network capacity, reduce the exploitable resource significantly (Garrad Hassan, 2001). Given this, and the potential of UK-based offshore wind, wave, tidal and biomass, the UK Government and Scottish Executive have, respectively, stated aspirational targets of 20% and 40% renewables by 2020 (Scottish Executive, 2002).

While low-carbon wind energy is being developed to assist in limiting the extent of climate change, its reliance on the natural environment means that it may be sensitive to changes in climate that result from rising carbon emissions. It shares this risk with other renewable sources including hydropower (Harrison and Whittington, 2002) and wave (Harrison and Wallace, 2005). With evidence of changing offshore wind speeds over recent decades (Watson *et al.*, 2001), closer examination of onshore wind impacts is justified.

Here, an analysis is presented that takes a preliminary look at the implications of the changes in wind speeds in the UK. Section 2 describes how changes in wind speed could ultimately affect production from, and the economic feasibility of, wind developments. The wind speed projections used in the study are taken from the 2002 scenarios published by the UK Climate Impacts Programme (Hulme et al., 2002) which are described in Section 3. The method taken to translate these into wind energy impacts is set out in Section 4 while Section 5 presents the initial results from this study; the implications of these are discussed in Section 6.

2 Climate Sensitivity of Wind Power

In addition to the well-known projections of a global rise in mean temperature of up to 5.8°C by 2100 (IPCC, 2001), climate models suggest changes in a wide range of climate variables including wind speed. This implies changes in the quantity and timing of the wind resource, leading to changes in turbine performance and energy production, and this may have an impact on the economic attractiveness of schemes.

With the growing importance of wind power, there is increasing interest in changes in wind speed and the possible impact on wind power production. Notable research includes that of Breslow and Sailor (2002) and Segal *et al.* (2001) for the United States, Pryor and Barthelmie (2004) for the Nordic and Baltic regions (as part of the Climate and Energy Project; CEP, 2006), as well as that for the UK by Harrison and Wallace (2005).

2.1 Production

Wind turbines harness the kinetic energy possessed by moving air. The wind power available is defined by the cubic relationship between power per unit area of flow (P, W/m^2) and wind speed (U, m/s) (Manwell *et al.*, 2002):

$$P = \frac{1}{2}\rho U^3 \tag{1}$$

where ρ is air density (kg/m^3). This basic physical relationship indicates that for a given percentage change in wind speed, there will be a proportionately greater impact on the power output of a wind turbine. Baker *et al*. (1990) report that a 10% change in wind speed could alter energy yields by 13 to 25%, depending on the site and season.

Wind turbines are designed and installed to suit prevailing climate conditions and can extract energy over a defined band of wind speeds, typically between 3 and 25 m/s. Outside this range the speed is either too low to allow the blades to turn efficiently or too high that the turbine shuts down in order to prevent damage from excessive gusts. The extraction of energy at higher wind speeds (>15 m/s) is constrained by the generator rating and in most modern devices is regulated by pitch control of the blades. An example of the production characteristics (or power curve) of a large wind turbine is shown in Figure 1.

2.2 Other climate factors

Other climate factors could impact on wind power production. Wind direction affects production, not only because differing terrain in each direction influences wind speed, but also due to its impact on wake interactions between individual turbines in an array. Air density is an important factor in the power equation (1) and, as density is inversely proportional to temperature, power levels will vary with temperature. Fortunately, the impact is relatively small with a 1°C rise in temperature lowering density and power by just one-third of a percent. Temperature and rainfall are important determinants of blade fouling which reduce aerodynamic efficiency although the extent of icing appears to be less significant in a warmer climate (Laakso *et al*., 2006). While these climate factors are clearly important, the cubic relationship between power and wind speed means that changes in wind speed are of most interest in examining climate impacts.

2.3 Economics

Changes in energy production caused by changes in wind speed will undoubtedly impact on the revenue earned, particularly when changes coincide with periods of high energy prices, traditionally during winter in the UK. Despite low variable costs, adverse changes in revenue pose a potential risk to the ability of the wind installation to service its relatively high capital debt and will clearly impact on the investment performance of schemes. The economics of offshore wind farms have been shown to be sensitive to mean wind speeds (Harrison and Wallace, 2005). A similar analysis for an 80 MW onshore scheme has been performed here by applying the estimates for capital (£819/kW) and operational costs (5% of capital cost per year) set out in the 2006 UK Energy Review (DTI, 2006). Figure 2 shows project value (Net Present Value) as a function of mean wind speed assuming the farm has the production characteristics shown in Figure 1. It is apparent that with project value most sensitive to changes in wind speeds in the 6 to 10 m/s interval, the financial consequences could be significant. Indeed it could be argued that the additional resource uncertainty that stems from climate change appears to increase the potential risk for investors. However, the extent of this is yet to be fully quantified.

3 The UKCIP02 Climate Scenarios

In assessing the impacts of future changes in climate, it is regarded as scientific best practice to base analyses on the projections from general circulation models (GCMs). GCMs are complex numerical models of the atmosphere and oceans and provide information on a wide range of climate variables including temperature, precipitation, pressure, and, of interest here, wind speed. In 2002, the UK Climate Impacts Programme published a set of climate change projections specifically for the UK (Hulme *et al.*, 2002) that were based on regional climate simulations. They provide mean-monthly changes for a range of climate variables on a 50 km × 50 km model grid for three periods or 'time slices' representing conditions for 2011–2040, 2041–2070 and 2071–2100. These three periods are referred to as the '2020s', '2050s' and '2080s', respectively.

Projections were made for four scenarios of future greenhouse gases emissions corresponding to several from the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC, 2000). Referred to as 'low', 'medium-low', 'medium-high' and 'high', 'low' represents a 'greener' future with decreasing greenhouse gas emissions from 2050 onwards while the 'high' scenario represents a situation where fossil fuels are used intensively and emissions are more than triple current levels by 2050. The use of multiple scenarios reflects the fact that it is not possible to state that any one scenario is most likely.

Each emissions scenario is used to drive GCMs in order to simulate future climate. The UKCIP work used a sequence of three nested models developed by the UK-based Hadley Centre. Each model has progressively higher spatial resolution: HadCM3, a coarse resolution global atmosphere/ocean model, HadAM3 a higher resolution global atmosphere model and, finally, HadRM3, the 50 km resolution regional climate model. The high resolution HadRM3 is required since global GCMs give poor predictions of local climate as they cannot deal with sub-grid local weather effects.

The Hadley Centre models produced simulations of 'current' climate (based on the period from 1961 to 1990) as well as runs to 2100 with each of the emissions scenarios. Due to the computational intensity, a limited number of regional model simulations were performed: these were for 1961 to 1990 period and for 2071–2100 under a medium-high emissions scenario. Projections for the other time slices and emissions scenarios were generated by scaling each climate variable in the 2080s medium-high scenario by a factor based on the relative global temperature change suggested by each scenario.

Despite the much improved spatial resolution, Figure 3 shows that the modelled coastline of the UK is quite a poor match with reality. In addition, the topographical features of the UK are also coarsely represented in the model. Given that these features play a key role in governing wind speed and direction, much less confidence can be placed on the projections of wind speed as applying to a specific site. However, the projections may well be reasonable reflections of the background pattern of air flow. This view is supported by the work of Segal *et al*. (2001) who used the predecessor of the HadRM3 regional model in their analysis.

4 Assessment Methodology

Monthly mean wind speed data was extracted from the UKCIP dataset for the 50 km grid squares covering the UK land mass. The data included the model simulation for 1961-90 as well as the percentage change anomalies for each of the scenarios and time slices. The baseline data was multiplied by each percentage change anomaly to give projected monthly mean wind speeds for future periods. In each case, these monthly wind speeds were converted into estimates of energy production using the following method.

4.1 Wind speed distribution

Wind speed tends to follow a highly skewed spectra and it is common practice to fit the resource to either the Rayleigh or the Weibull distribution (Manwell *et al*., 2002). The Weibull distribution is often more representative as its two parameters (shape factor k and scale factor c) allow it to be tuned to specific sites. The simpler Rayleigh distribution is defined solely by mean wind speed and is therefore easier to apply across larger areas; indeed, many other studies considering wind climate have relied on it (Breslow and Sailor, 2002; Segal *et al*., 2001, Harrison and Wallace, 2005). The Rayleigh distribution is given by (Manwell *et al*., 2002):

$$p(U) = \frac{\pi}{2}\left(\frac{U}{\overline{U}^2}\right)\exp\left[-\frac{\pi}{4}\left(\frac{U}{\overline{U}}\right)^2\right] \qquad (2)$$

where $\overline{U}$ is the mean wind speed and $p(U)$ is the probability of occurrence of wind speed U. When modelled incrementally, (2) gives the probability and, for a given period, the duration of time for which each wind speed increment is experienced. Figure 4 shows the impact of 10% changes in mean wind speed on the Rayleigh wind distribution. Of particular note is the effect on the relative probabilities of operation at higher wind speeds and shut-down periods (defined by the shaded areas).

In each case, the mean monthly value was used to generate a Rayleigh distribution which was then combined with the turbine production characteristics to estimate production. The turbine chosen for this study was the 3 MW Vestas V90 (Vestas, 2004; shown in Figure 1) as, despite the continuing trend towards larger turbines as a means of capturing economies of scale, it is likely that turbines of 5MW and above will only be routinely installed offshore. The V90 possesses a 90 m diameter rotor at 80 m hub height.

4.2 Height correction

With the UKCIP wind data available only at 10 m height, a correction was applied to translate it into higher speeds experienced at the 80 m hub height of the wind turbine. Rather than use the standard logarithmic wind profile which requires knowledge of the terrain surrounding each location, here, the simpler power law is used (Manwell *et al.*, 2002):

$$U_H = U_{10}\left(\frac{z_H}{z_{10}}\right)^{1/7} \quad (3)$$

where z_H and z_{10} are the hub and reference heights and U_H and U_{10} are the hub and 10m wind speeds.

4.3 Baseline case

To provide a means of comparing future wind speeds, the method was applied to the models simulated 1961–90 monthly-mean data. This results in the baseline annual wind speeds shown in Figure 5 along with the energy production estimates based on it. The model grid has been rotated to simplify presentation.

5 Preliminary projection of UK wind climate impacts

While all the scenarios have been extracted and analysed, only the most extreme scenario, for the 2080s under conditions of high greenhouse gas emissions, is presented here. In the following section, the results are analysed in three ways: firstly, as an average over all of the grid-squares of the UK on an annual basis; secondly, the data is presented as a set of maps showing the changes in each individual grid square both annually and seasonally; thirdly, greater temporal detail was gained by selecting five regionally diverse locations from around the UK. The results from these individual locations are presented as month-by-month graphs showing the range of changes throughout a whole year.

5.1 Annual changes

Looking at the average change over the whole of the UK annually, relatively minor changes are forecast with 2080s mean wind speed about 0.5% higher than baseline levels with a spread between –5 and +3%. The impact of these changes on production is modest and around 1.3% averaged across the UK as a whole. The seasonal changes, however, are more significant.

5.2 Seasonal changes

Figure 6 shows the simulated changes in winter wind speed and energy production by the 2080s. It indicates wind speed increases in the south and east of the UK of between 5 and 10%, with increases in the northern half of the country of up to 5%. The extreme north of Scotland and part of Northern Ireland are forecast to see slight reductions in mean speeds. In energy terms the impacts are larger, with increases of between 10–15% in much of the UK with a more modest 5–10% increase in the northern England. The changes for Scotland are mostly increases of up to 5%, with the reductions in the extreme north being of a similar magnitude.

Summer wind speeds tend to decrease with much of the UK experiencing reductions of 5 to 10% but with some areas, such as western Scotland and Northern Ireland seeing more significant drops of 5–10 and 10–15%, respectively (Figure 7). The far north of Scotland and the south coast buck this trend and show increases of up to 5%. Again, the energy impacts are more significant and appear more complex given the coarse intervals used in the figures. Across much of the UK, the production falls by up to 15%, particularly on the coasts. The far north and the south coast generally experience increases around 5 to 15%. The areas seeing the largest reductions in energy production are in western Scotland and Northern Ireland where the energy production appears to drop by up to a quarter.

The focus in this study is generally on winter and summer changes, since autumn and spring changes are more modest. Autumn sees a general decrease in wind speed of up to 5% and 5 to 10% for energy, with spring experiencing increases of the same magnitude. However, as Figures 8 and 9 indicate, there are some areas that experience the opposite trend.

5.3 Monthly changes

To explore the changes in more detail, five locations around the UK were selected to cover a range of different regions: two in England and one each in Scotland, Wales and Northern Ireland as indicated in Figure 10. On average, the locations appear to experience slight increases in mean annual wind speed of around 2%. The exceptions are Northern England which sees a smaller increase of about 1% while Northern Ireland sees a decrease of some

4%. The energy changes are more significant: Scotland and Wales see increased annual production of some 5%, the English locations increase by around 2.7% and Northern Ireland sees reductions of about 8%. The annual changes for the 2080s mask the considerable variation in monthly response (Figure 11) and in particular the significant differences between locations in the far north and far west.

The locations in England and Wales respond in a similar manner with wind speed increases of around 3.7 to 7.7% during December to March, smaller increases (1–3%) in late spring and decreases of between 2 and 5.3% in late summer. This represents a strengthening of the existing seasonal pattern. Northern Scotland experiences broadly the opposite trend with slight (0.6%) decreases in winter speeds, 4.5–6% increases in late spring/early summer speeds and modest (2%) changes in autumn speeds. This represents a modest weakening of the seasonal pattern. Northern Ireland appears to experience the most significant changes overall: despite relatively minor increases in winter, speeds drop throughout the rest of the year with the most extreme drop of 14% in late summer. This appears to indicate a strengthening of the winter/summer difference.

The energy production changes that result from these are shown in Figure 12 and, in many respects, are an amplified version of the wind speed changes. Monthly production in early summer in Northern Scotland could rise by up to 19% while that in Northern Ireland would experience decreases of up to 33%. The increases in winter production for the locations in England and Wales are of the order of 9 to 13% with late summer decreases of 5 to 14%.

6 Discussion

This work represents a first step in exploring the potential changes in UK wind speeds and their implications for wind power production and the broader issue of long-term security of supply. The approach has been deliberately simple in order to rapidly quantify the magnitude of energy production changes implied by the UKCIP projections. Given the direct use of the climate model simulations as a baseline for energy production estimates, the bias in the climate model will be present in the baseline energy change projections. As such, the results of this study can only be regarded as indicative of what the UKCIP scenarios imply.

The analysis has shown that UK wind speeds are very seasonal with the highest speeds occurring in winter, coinciding with peak demand for electricity. With much of the UK potentially experiencing 5–10% increases in winter production by 2080 this is a broadly positive trend despite the slight reduction in production in the north of Scotland where a significant proportion of wind farms may well locate to harness the currently higher wind speeds. With summer production already much lower than winter, the summer changes appear to indicate lower summer turbine capacity factors at the same time as demand is likely to rise as cooling loads increase due to the warmer temperatures. Reductions in wind speed on the scale projected for Northern Ireland would have a significant impact on the economics of wind farms located there. In saying that, investors are more likely to be concerned about nearer term conditions rather than those in the 2080s; further analyses must meet this requirement.

Whilst climate models are being continuously improved, models at a sufficiently high resolution to be able to accurately represent local topography are not available and, even using current technology, infeasible to run. Without this topographical detail, it is difficult to be precise in projecting localised wind speeds at a scale that is useful for site analysis. In order to bridge this gap, other methods of wind speed projection are being considered, for example, exploring the relationships between mean sea-level pressure and local wind speeds and applying this to climate model pressure projections. Another possibility would be to apply the wind speed projections from a regional climate model to an established higher resolution baseline wind climate. At present this is lacking as the UK-wide NOABL dataset (Burch *et al.*, 1992) offers only annual mean speed while a temporally and spatially detailed on and offshore wind dataset developed by Boehme *et al.* (2006) covers Scotland alone. Future work by the authors and others is planned to develop this resource.

The use of several simplified relationships in the study places limits on the accuracy of the results. The Rayleigh distribution was chosen over the often more common Weibull distribution due to the lack of site-specific parameters. Whilst it is common for sites in Northern Europe to have a k parameter equal to 2, as in the Rayleigh distribution, individual locations will, of course, deviate from this average value and thus using site-specific Weibull distributions could give more precise results. Also, the use of a simplified method to scale the wind speeds to the 80m turbine hub height required implicit assumptions about the boundary layer stability conditions which may not necessarily hold into the future.

Despite these shortcomings, the work represents a sound first attempt at quantifying the potential changes in the UK wind climate and its implications for energy production. Given the magnitude of some of the seasonal changes, further, more detailed research is warranted.

7 Conclusion

This paper represents a preliminary exploration of the potential magnitude of changes in onshore wind speeds UK-wide and the implications for wind power production. The UK

Climate Impacts Programme regional climate change scenarios for the 2080s suggest a slight overall increase in annual mean wind speeds of 0.5% averaged across the UK. This disguises significant trends in seasonal wind speeds and energy production: winter production rising by up to 15% in the south and falling in the north; summer production would tend to fall by up to 10% although some areas would experience more severe reductions. Given the magnitude of some of the seasonal changes, the work indicates that further, more detailed research is warranted.

8 Acknowledgements

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Figures

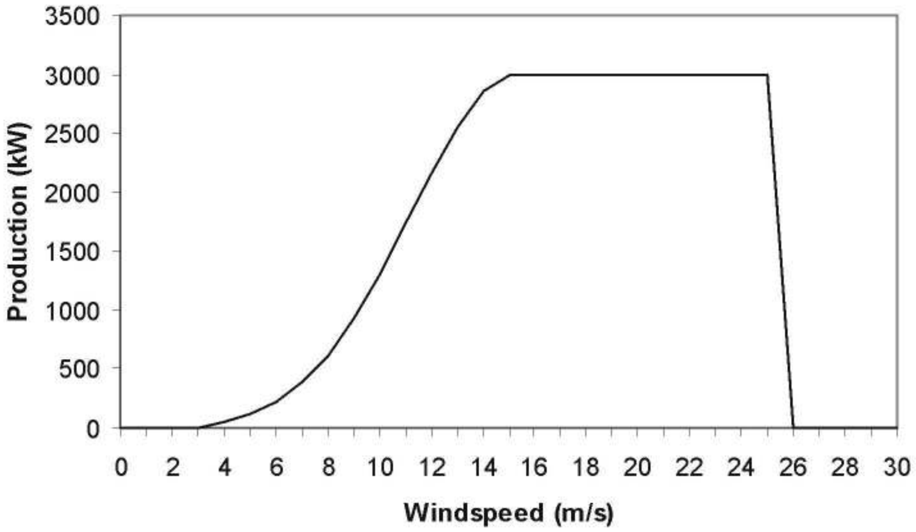

Figure 1: Power curve for Vestas V90 3 MW wind turbine (Vestas, 2004)

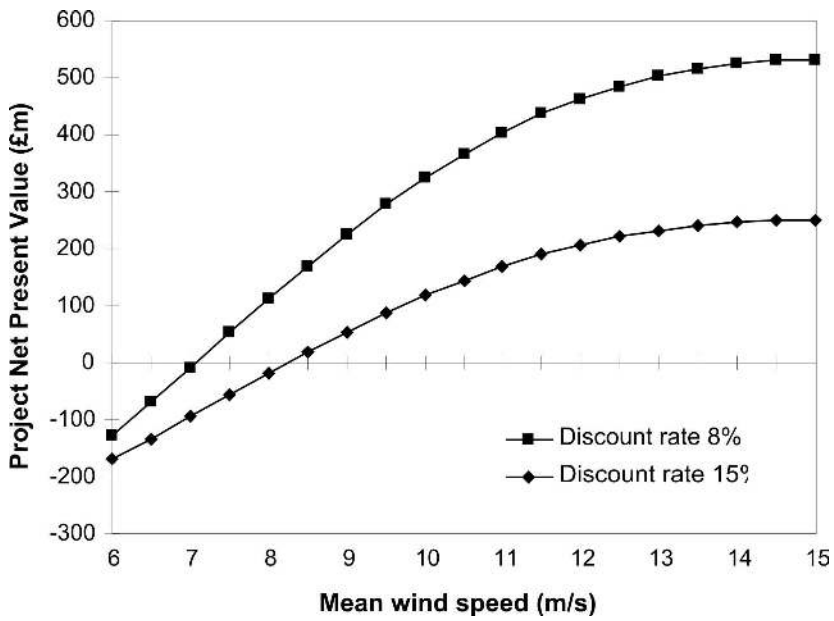

Figure 2: Project value with mean wind speed for 80 MW onshore wind farm

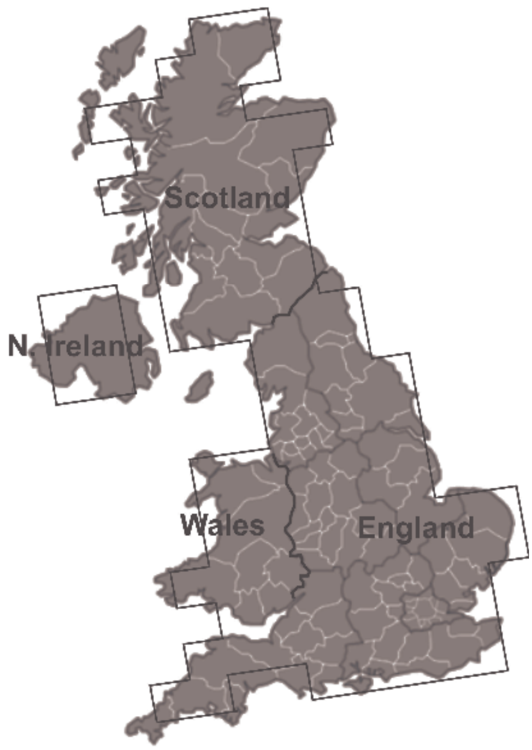

Figure 3: Regional map of the UK and the HadRM3 50 km grid outline

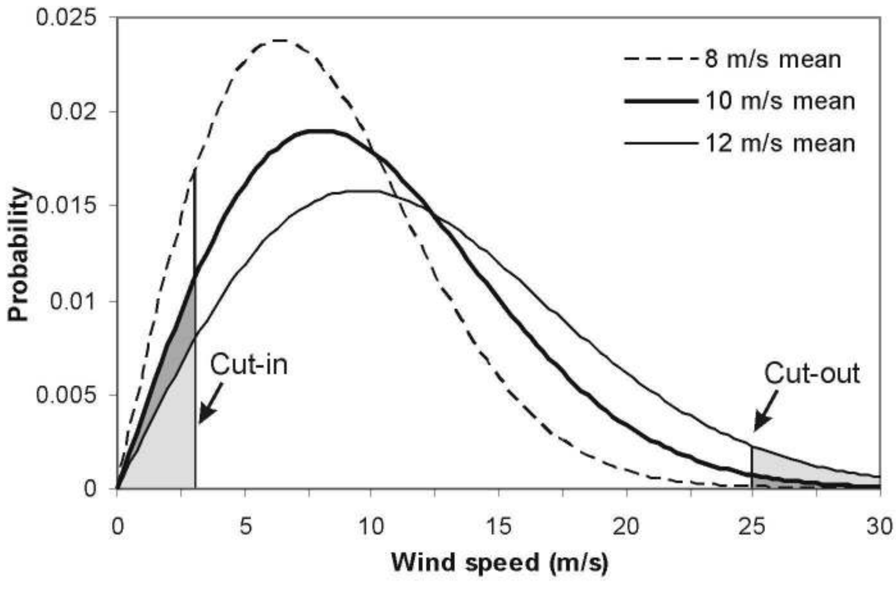

Figure 4: Wind speed distributions at several mean wind speeds

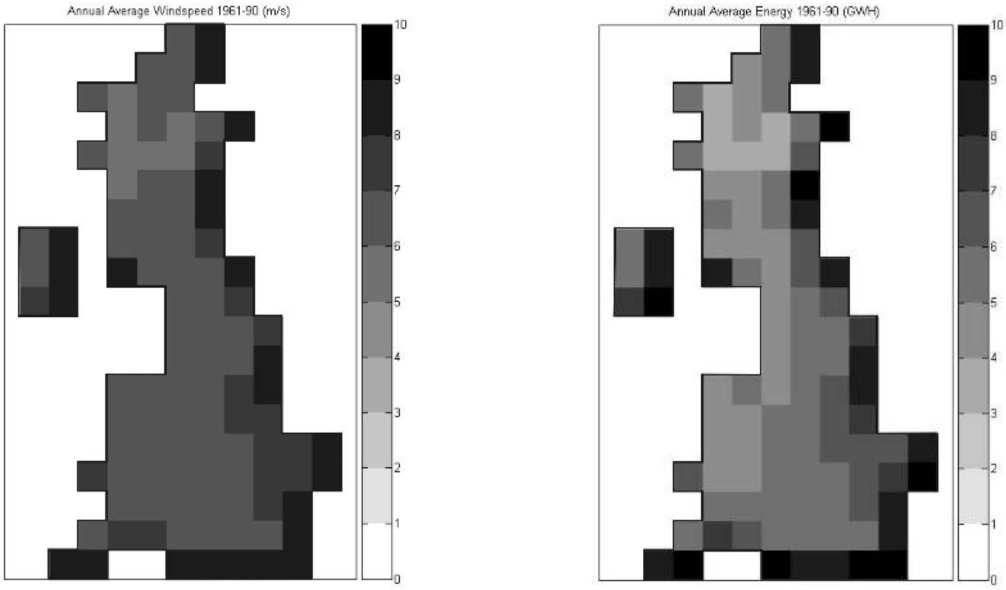

Figure 5: Baseline (1961-90) annual (a) wind speed and (b) energy production on UKCIP grid

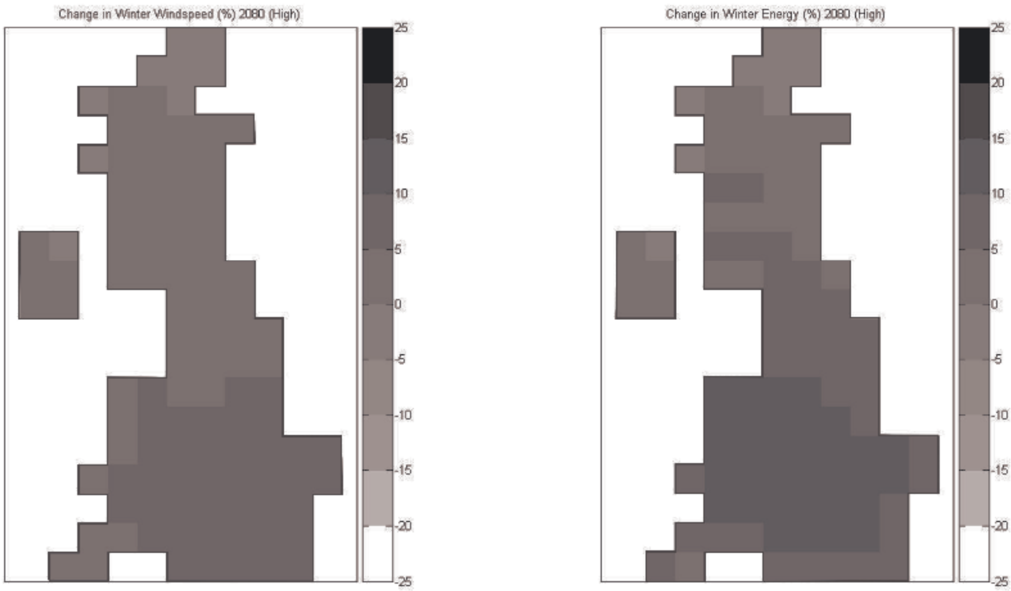

Figure 6: Winter changes by 2080 in (a) mean wind speed and (b) energy production

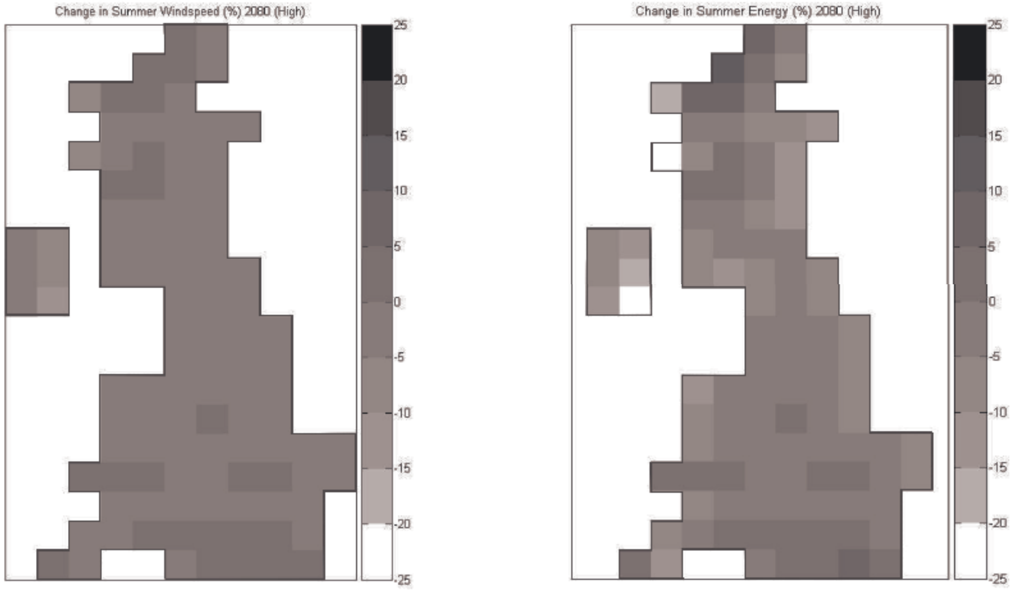

Figure 7: Summer changes by 2080 in (a) mean wind speed and (b) energy production

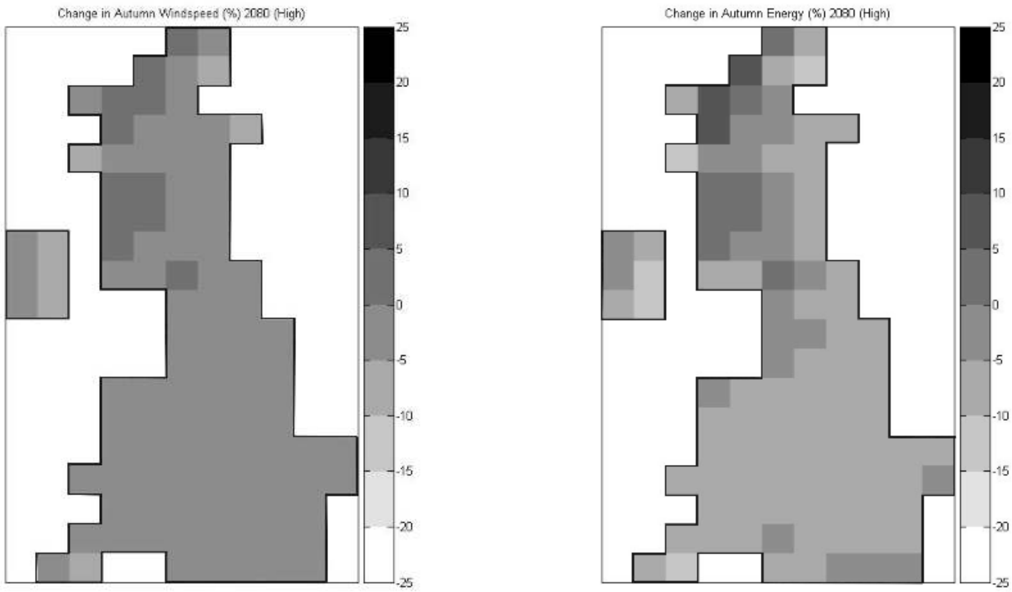

Figure 8: Autumn changes by 2080 in (a) mean wind speed and (b) energy production

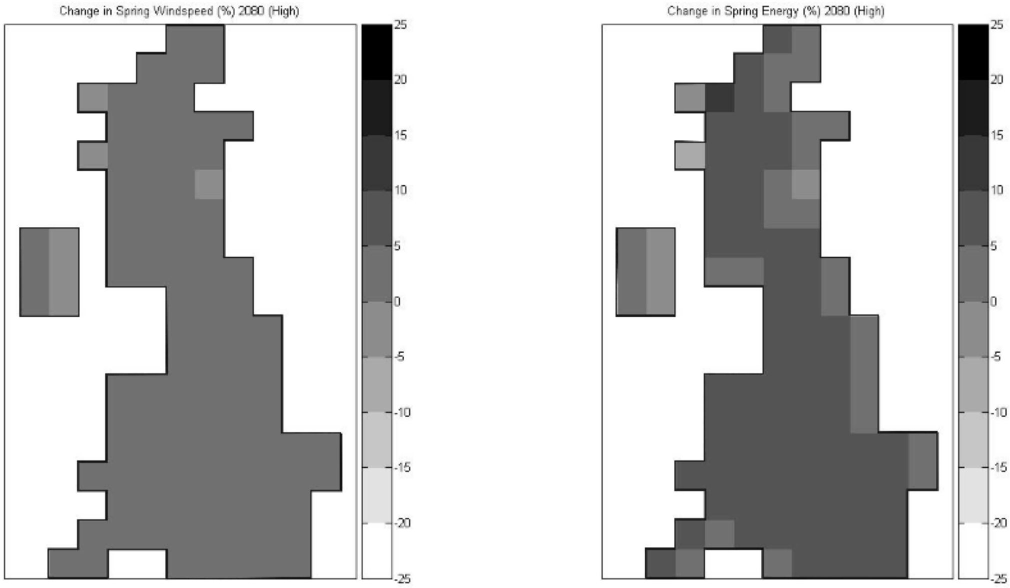

Figure 9: Spring changes by 2080 in (a) mean wind speed and (b) energy production

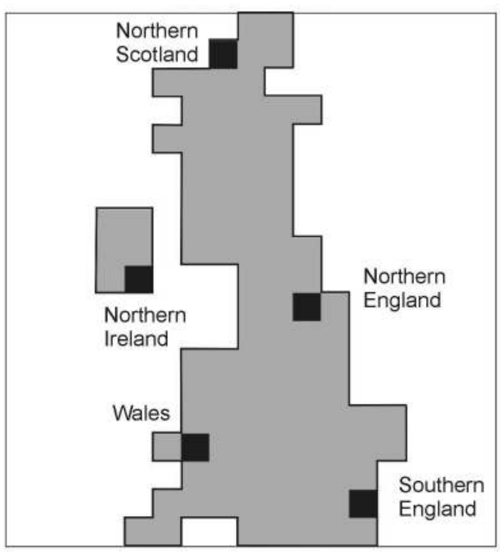

Figure 10: Locations for monthly analyses

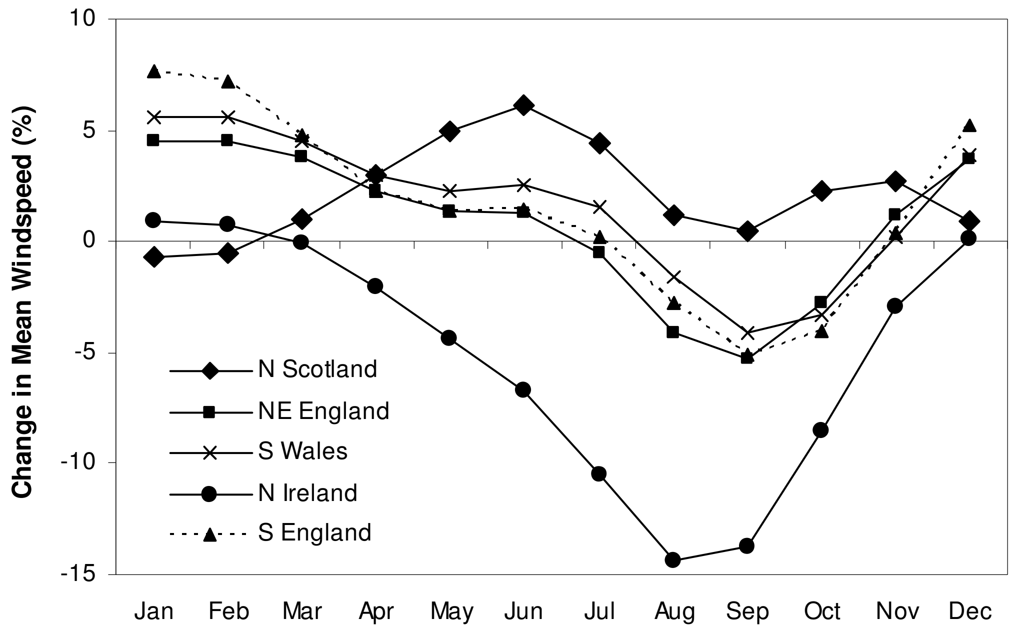

Figure 11: Change in monthly mean wind speed at five locations by 2080

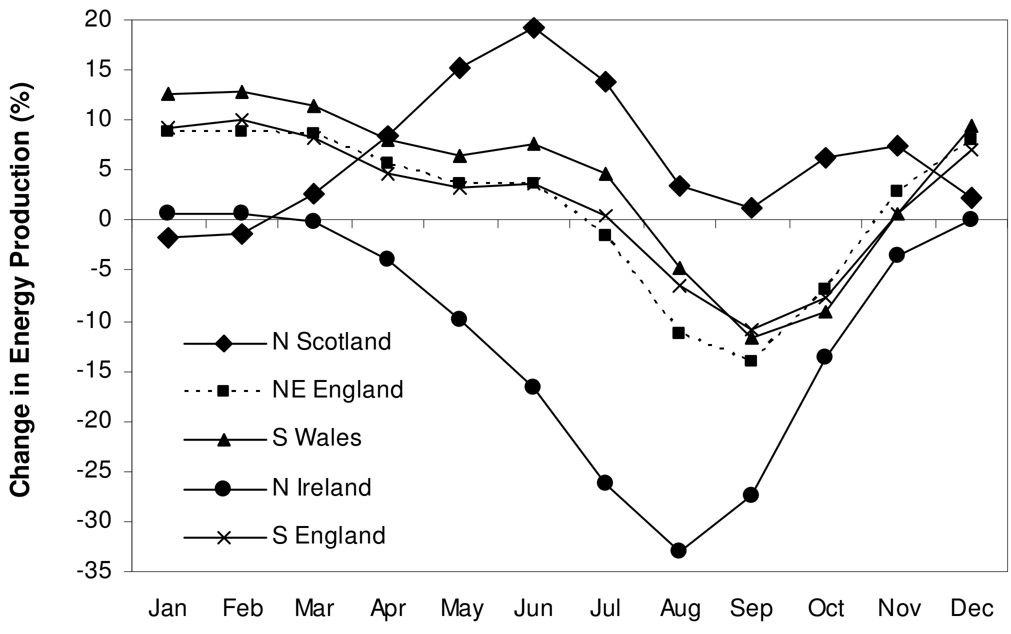

Figure 12: Change in monthly production at five locations by 2080