Published paper
Drake, B. and Hubacek, K. (2007) *What to expect from a greater geographic dispersion of wind farms? - A risk portfolio approach,* Energy Policy, Volume 35 (8), 3999 - 4008.

What To Expect From A Greater Geographic Dispersion Of Wind Farms?

- A Risk Portfolio Approach

1. Introduction

Increased greenhouse gas emissions are suspected by scientists of contributing towards the recent increase in mean global temperatures witnessed since the middle of the 20th century (IPCC, 2001). To counter this recent trend towards higher global temperatures, some industrialised countries have placed explicit limits upon the amount of CO_2 that can be released into the atmosphere. Indeed the UK, as part of the Kyoto protocol, has agreed to reduce its level of CO_2 emissions by 2008-2012 to 12.5% below 1990 levels (Black, 2005). In an effort to meet its Kyoto obligations, the UK has set itself another target; to ensure that 10% of its electricity supply comes from renewable sources such as wind farms by the year 2010 (DTI, 2002).

However the variable nature of wind power generation currently prevents it from being widely adopted within national electricity systems. Therefore in an attempt to overcome the problem of wind power variability, this paper will attempt to show how a wider spatial distribution of UK wind farm sites will succeed in delivering lower overall variations in wind power output. This hypothesis will be explored by using portfolio theory which will identify the most efficient allocation of wind power capacity amongst 4 simulated wind farms with the aim of delivering the least amount of wind power variability per unit of power generation. Portfolio theory itself is used widely within financial markets whereby fund managers use such theory to decide how much of a particular stock to include in their investment fund based upon a stock's risk and rate of return. For instance fund managers seeking to minimise the risk (variance) of their investment fund for a given target rate of return would use portfolio methods to tell them exactly how much of a particular stock to include in their fund to achieve this aim. By extension this paper will be using the same principle to decide what allocation of wind power capacity each simulated wind farm should have in order to minimise aggregate wind power variability per unit of power generation.

The paper is structured as follows: in section 2 we describe previous studies' attempts to mitigate for wind power variability. In section 3 we provide scenarios and the likely effects that should be expected in the event of a wider spatial distribution of UK wind farm sites. Section 4 details the results whilst the implications and shortcomings of this study are discussed in section 5 with a conclusion provided in section 6.

2. Attempts to Overcome Wind Power Variability

Combined Hydro-Wind Power Systems

In an effort to counter wind power variability, academics have introduced the idea of combining wind power with a storage medium such as hydroelectric power (Gastronuovo and Lopes 2004, Bueno and Carta 2004). Essentially the storage of wind power is achieved by using excess wind power to pump water up from a lower reservoir to an upper reservoir. Such excess wind power could occur in situations whereby demand for electricity falls short of the amount of electricity generated by a wind farm or if the generation of electricity rises above a predetermined maximum limit that was agreed with the network operator.

Overall there are three beneficial effects to using a combined hydro-wind system versus using wind power exclusively. The first benefit arises from the ability to sell electricity that would otherwise have been wasted due to the electricity generation exceeding demand. Secondly it will be possible to sell this stored wind power at times of peak load when prices for electricity are high thus enhancing revenues. Indeed (Castronuovo and Lopes, 2004) found that annual profits from a combined hydro-wind power operation rose by 11.92% when compared to a stand-alone wind farm site. This can be attributed to the inherent flexibility of hydroelectric power insofar as enabling the sale of excess supplies of electricity in addition to being able to sell a greater proportion of electricity at peak times during the day. Finally reduced variations in power from a combined hydro-wind system will enable intermittency charges levied by electricity network operators to be reduced in comparison with a wind only scenario. For instance (Bueno and Carta, 2004) witnessed a lower variation of wind power as a result of its linkage to a hydroelectric facility which in turn led to an increase in the penetration rate of renewable energy in Gran Canaria from 4.72% to 6.65% as a percentage of total annual electricity generation. Due to the intermittent nature of wind power and its effect upon the stability of Gran Canaria's electricity network, restrictions are currently in place with the intention to limit further penetration of wind power.

However in cases whereby hydroelectric power is used alongside wind power but without the use of a pump to store excess wind power, it was found that variations in wind power prevented it from replacing energy sources with fast ramp up times[1]. For instance Bélanger and Gagnon (2002) simulated an 11% increase in electricity demand for Quebec which could either be accommodated by building a new 56MW hydroelectric power plant or by building 98MW of wind power capacity plus 48MW of backup hydropower capacity. In effect the second option translates into only 8MW of hydroelectric capacity being displaced despite a relatively large 98MW of wind power being constructed. The authors site the need for large amounts of hydroelectric backup capacity as being the result of fluctuations in wind power generation (Bélanger and Gagnon, 2002).

Adding wind power to a hydroelectric facility can also have detrimental effects upon aquatic eco-systems, river corridors and wetlands. This is primarily due to the high fluctuations in power output often associated with wind power. For example Bélanger and Gagnon (2002) found that the yearly minimum flow rate of the local river during the summer months could fall by up to 53% while the hourly flow variations increased 2-3 fold with negative effects on aquatic wildlife.

Combined Solar-Wind Power Systems

[1] Ramp up times can be defined as the time it takes for an energy source to dispatch power once a decision to dispatch power has been made.

In contrast to combined hydro-wind power systems, which attempt to mitigate wind power variability by using a storage medium, solar-wind power systems instead aim to reduce wind power variability by using two power sources that are relatively uncorrelated with one another in terms of when generation takes place. One could hope that in the event of a slowdown in the generation of wind power, solar power might cover the shortfall and vice-versa. Such compensation in power production is most readily observed over the course of a year, as was the case when a recent study into combined solar-wind power systems in Turkey discovered that during the summer months an increase in solar power generation made up for a fall in electricity generated from wind power (Ozdamar et al., 2004).

Despite solar power complementing wind power over the course of a year, it is not possible to tell what kind of relationship exists on an hourly basis between solar and wind power. Compensating for wind power variability through the use of solar power was only achieved at very small scales. For example, Yang et al. (2003) successfully managed to mitigate variations in wind power by adding solar power by deploying a battery pack as a storage unit. The combined solar-wind-battery powered system was designed to supply power to a telecommunications system in addition to four buoys of 40 watts. However due to the small size of the combined solar-wind-battery power system, especially in relation to the battery pack, the implementation of such a system on a larger regional scale does not seem to be feasible at the moment. In summary there does not appear to be any evidence to date that suggests hourly variations in wind power can be mitigated in this way.

Spreading Wind Farms Over A Wide Geographic Area

Another option discussed in the literature to mitigate for the variability of wind power is to disperse wind farms over a wide geographic area. As the distance between wind farms widens, it is argued that wind speed correlations between different wind farms will begin to fall (DeCarolis and Keith, 2004). Indeed it should be remembered that low correlations between wind farm sites are good insofar as they reduce the variability of aggregate wind power generation. This is primarily achieved through wind power variations in one part of the country balancing out variations in wind power in another part of the country. For instance it was discovered that errors in predicting wind power fell by 9% if wind power predictions were made for Denmark as a whole compared to making separate predictions for East and West Denmark (Holttinen, 2004). For example one study into variability on UK wind farms Power, (2001) found that the hourly correlation coefficient between sites fell to approximately 0.1 over distances in excess of 120 km. In terms of meeting the conditions for absorbing intermittent electricity generation onto electricity networks, more specifically the UK network, it was found in all scenarios i.e. the installation of 3.5GW, 5.6GW and 7.3GW worth of wind capacity by 2010, that the National Grid's[2] criteria[3] for accepting intermittent electricity generation had been satisfied with respect to hourly and 3 hourly periods (Power, 2001). Reductions in the intermittency of wind power that result from a wider dispersion of wind farm sites may also be responsible for the direct trade-off between high-pressure underground storage technologies and the geographic dispersion of wind farms (DeCarolis and Keith, 2004). For example when the number of wind farms in the simulation increased from one to five, increases in wind power reliability rendered high-pressure storage systems uneconomic (DeCarolis and Keith, 2004). However one caveat to the latter study is the fact that geographically dispersed wind farms only became economically viable after carbon taxes of US$300 per ton, which was considered unrealistic at that point in time (DeCarolis and Keith, 2004).

Although only a few studies have been conducted to date regarding the geographic dispersal of wind farms, evidence that geographically dispersed wind farms in the UK can be compatible with electricity transmission standards may provide some hope that the inherent problems of wind power intermittency can eventually be overcome. Combined hydro-wind power systems, in the context of the UK, suffer from a lack of potential hydropower sites from which to accommodate variations in wind power. With respect to combined solar-wind power systems, the lack of analysis regarding hour-to-hour variations casts doubt on whether solar and wind are indeed good

[2] National Grid is the company responsible for operating the UK electricity network in the UK.
[3] Such intermittency criteria consists of not exceeding output changes of the order of 1,000 MW per hour and also not exceeding output changes of 2,000 MW over the course of a 3 hour period (Power, 2001).

complementary power sources. Consequently for the purpose of this research we focus on measuring the precise effect on wind power variability from a wider dispersion of UK wind farm sites.

3 Methodology

Two Alternative Scenarios

For this study we construct two scenarios: the first scenario involves the construction of a 2.7GW (Giga-Watt) wind farm off the coast of Stornoway, Scotland with enough capacity to supply 1.75% of UK electricity demand during the year 2005 (DTI, 2006). In determining the output of the Stornoway wind farm site, it is assumed that offshore wind farms typically operate at 30% of capacity on average. This assumption can be viewed as being rather conservative as other studies of offshore wind farms use higher capacity factors[4] (see e.g. DTI, 2002).

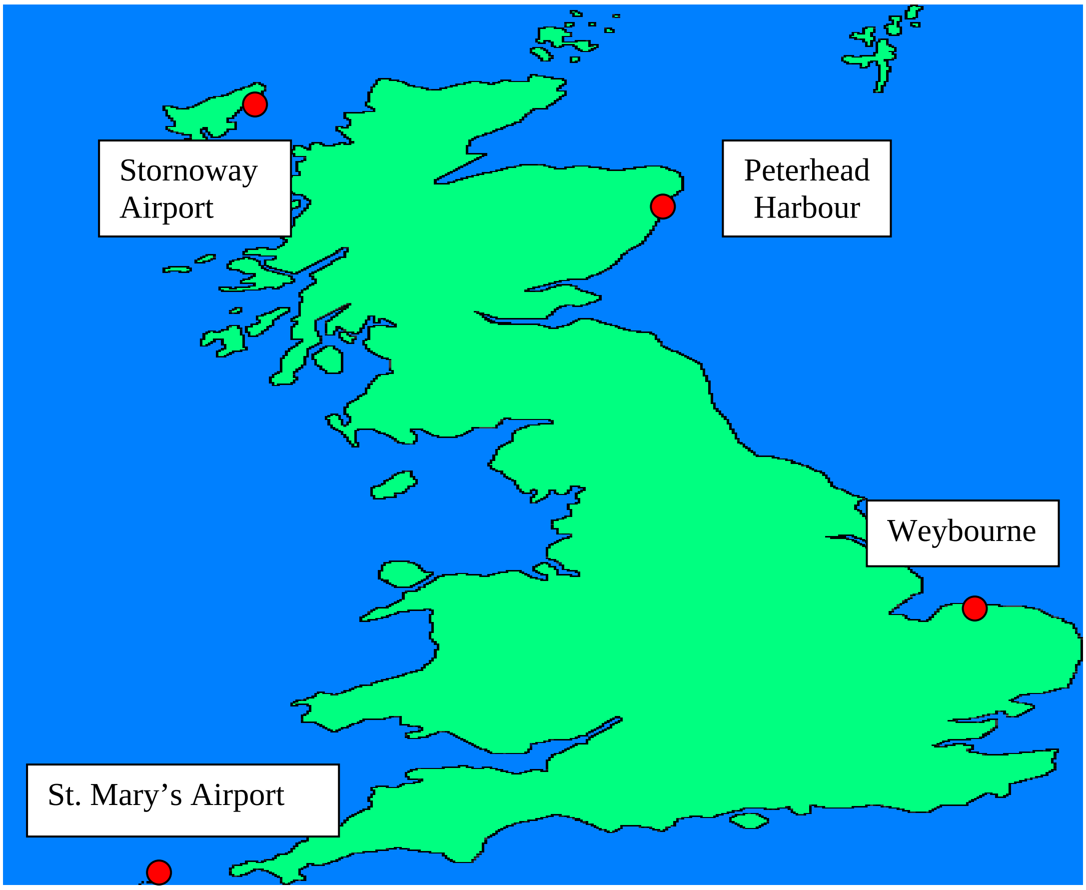
The second scenario consists of a total of four wind farm sites, as can be seen from figure 1, including the Stornoway wind farm site used within the first scenario. Additional wind farm sites include sites located off the coasts of St. Mary's, Weybourne and Peterhead[5]. The location of the four wind farm sites is made in such a way as to maximise the geographic dispersion of wind farms within UK territory.

Within the second scenario the aim is to identify the most efficient mix, i.e. the percentages of total capacity (2.7GW) allocated to each wind farm so as to minimise standard deviation subject to a number of differing power generation targets. For this we apply an optimisation tool to create an efficiency frontier showing all the points at which the standard deviation is minimised for every single power generation target. Based on this we are able to identify which point on the efficiency frontier represents the best value in terms of maximising power generation per unit of standard deviation.

[4] The capacity factor represents the percentage of wind capacity that is used during the year on average.
[5] Offshore wind sites will hereon after be referred to by the name of the nearest coastal town even though they are located some 1-2 miles offshore.

It is precisely this point on the efficiency frontier that is used when making comparisons to the centralised production scenario on the basis of differences in standard deviation and power generation.

<u>Figure 1: Map Of Simulated Wind Farms Used Within The UK</u>



From the outset we expect a reduction in the standard deviation of wind power when moving from a limited geographic dispersion of wind farm sites (centralised production scenario) to a situation involving a widespread dispersal of wind farms. This expectation is based on the fact that over large distances, the weak correlations that exist between wind farm sites serve to reduce the fluctuations in aggregate wind power.

Secondly it is expected that losses associated with electricity transmission lines will remain the same when moving to a situation involving geographically dispersed wind farm sites. This is due to the inclusion of wind farm sites that are located at both greater and shorter distances from their respective demand centres compared to the distance found to exist between the Stornoway wind farm site and its demand centre.

Onshore Versus Offshore Wind Farm Sites

At the outset it was decided to simulate offshore wind sites in order to take advantage of less variable wind speed patterns in comparison to onshore sites (DTI, 2001). Also locating wind farms onshore has recently encountered increasing opposition and has resulted in a greater proportion of wind farm applications failing to get planning permission. Opposition to onshore wind farms has primarily come from people who enjoy recreational activities in the great outdoors and who are concerned about how a wind farm may affect the surrounding landscape (The Economist, February 2005).

Another reason for choosing to include offshore wind sites within this study is to recognise the huge potential the UK has with respect to offshore wind energy. In a recent study conducted by the UK government's DTI (Department of Trade and Industry) it was estimated that the UK, due to its long coastline, has an offshore wind power potential of 3,213 terawatt/hours per year (DTI, 2002). When compared to UK energy demand of 405.9 terawatt/hours for the year 2005, it seems extremely relevant to try and incorporate offshore wind sites into this study (DTI, 2006).

Obtaining Hourly Wind Speed Data

For this study hourly wind speed data[6] for the year 2004 was used from a number of coastal weather stations based at different corners of the British Isles (The Meteorological Office, 2005). Wind speed data from buoys located 1.5-3 km offshore would have been ideal for the purposes of this paper although the only offshore data

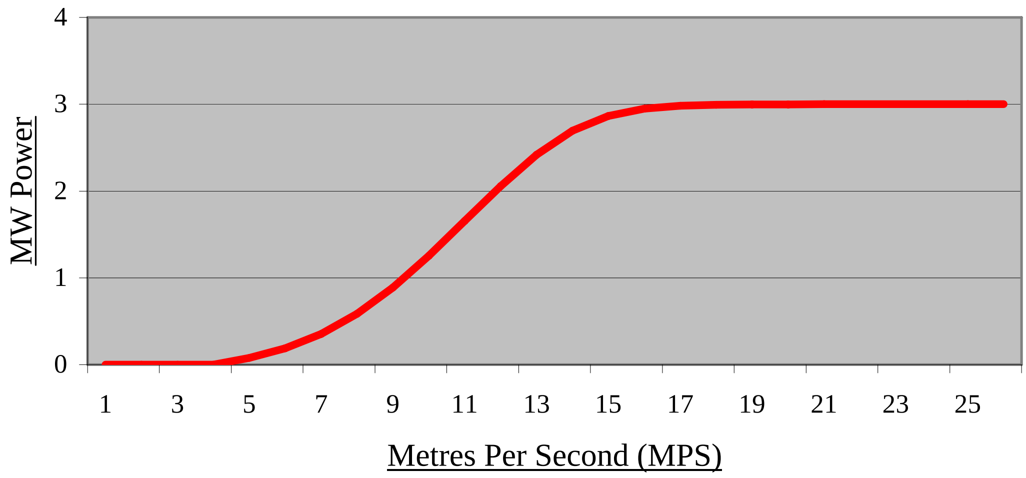
[6] Courtesy of the UK Meteorological Office. Missing wind speed data totalled only 534 hours for the year 2004.

available at the time was from buoys located at least 40 km from the nearest coastline. Such distances are clearly unsuitable for the construction of offshore wind farm sites due to the extraordinary cost of locating wind turbines in deep-sea areas. Indeed DTI (2002) estimated a doubling in the cost of connecting a 1 GW wind farm to the UK's National Grid when seeking to locate 60 km offshore as opposed to 20 km offshore. Therefore we use wind speed data from coastal stations as a proxy for actual offshore wind speeds.

Calculating Output of Wind Farms Using Power Curves

Once a particular type of wind turbine has been selected for use within this study, the next step involves obtaining power curve data for the turbine in question. Data on power curves simply detail what level of power generation is reached for any given wind speed. Power curve data concerning the Vestas offshore V90-3.0MW wind turbine was subsequently obtained as shown in figure 2 below (Vestas, 2004).

Figure 2: Power Curve For A Vestas V90-3.0MW Wind Turbine



Comparing hourly wind speed data with power curve data enabled hourly values of wind power generation to be obtained for each of the 4 wind farms. In calculating hourly power generation figures[7], each wind farm was given 2.7GW worth of capacity. Although there will only be a total of 2.7GW of wind power capacity to be shared out amongst 4 wind farms in the second scenario, giving each wind farm the same capacity will enable an easy comparison to be made between the standard deviation and the average level of power generation for each of the different wind farms.

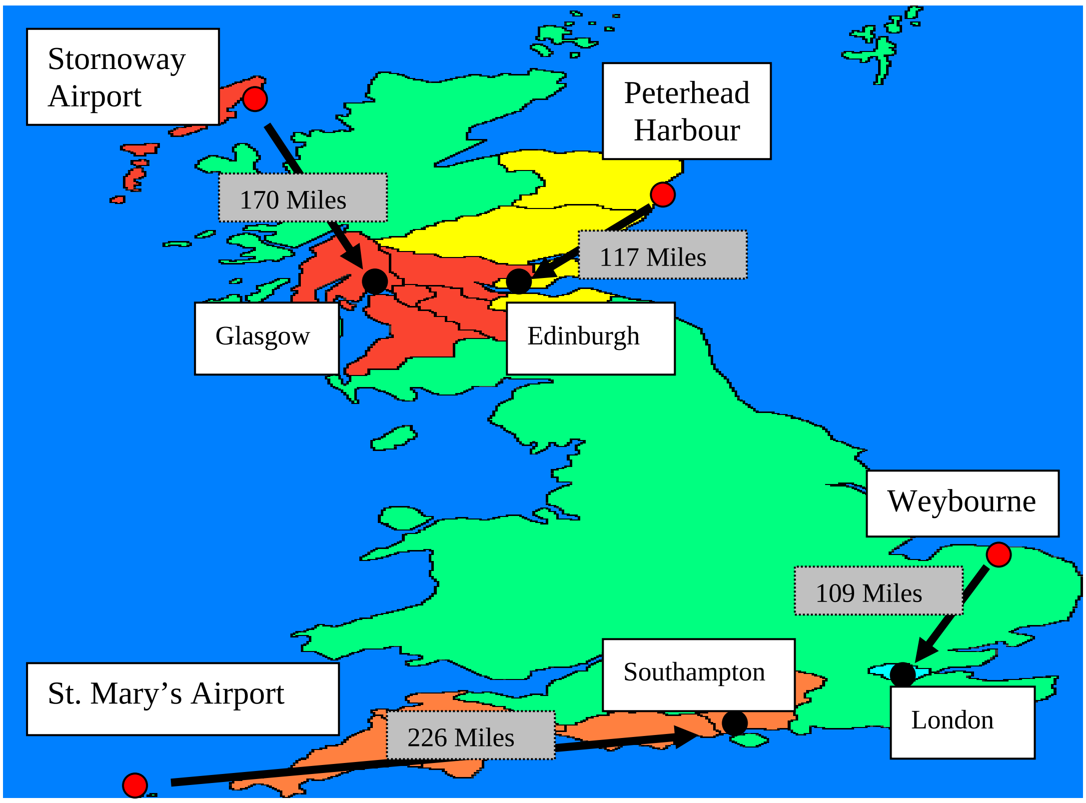
Wind Farm Sites and Demand Centres

The location of demand centres in relation to wind farm sites can undoubtedly impact upon the amount of electricity that may be lost in transport. For instance the greater the distance between a wind farm site and its respective demand centre, the more electricity is lost from power lines. For this reason it was necessary to identify demand centres that are in close proximately to each of the four designated wind farms in order to minimise transmission losses. In the case of the first scenario, only one transmission line is needed whilst for the second scenario all 4 wind farm sites have their own respective demand centres with one respective transmission line. Before choosing demand centres for each individual wind farm, it is necessary to firstly calculate the average annual expected output of each wind farm based upon a 30% capacity factor. The first step involved multiplying the number of wind turbines per wind farm (900) by the generating potential of each wind turbine (3MW) to arrive at a figure representing the maximum generation possible per wind farm (2,700MW). Multiplying this figure by an average load capacity of 30% and by the number of hours per year results in some 7 million MW/hours of power generation to be expected from each wind farm.

[7] Wind speeds below 4 MPS were given a power generation figure of zero as were wind speeds in excess of 25 MPS. For the type of wind turbine used throughout this study, wind speeds below 4 MPS are insufficient to generate power while wind speeds over 25 MPS force the turbine to closedown for fear of damage.

Next we identified appropriate demand centres capable of taking in such power. This is based on statistics regarding county populations in England and Scotland which aided in the search for appropriate demand centres capable of absorbing electricity produced at the designated wind farm sites (Registrar General for Scotland 2006; Office of National Statistics, 2002, 2005; The British Wind Energy Association, 2005). Despite a conscious effort to limit the distances between wind farms and demand centres using ordinance surveys, transmission distances of over 150 miles were still incurred by two of the four wind farm sites as shown in figure 3 (Ordinance Survey, 2005).

Figure 3: Map Of Simulated Wind Farms Used Within The UK And Distances From Wind Farms To Demand Centres

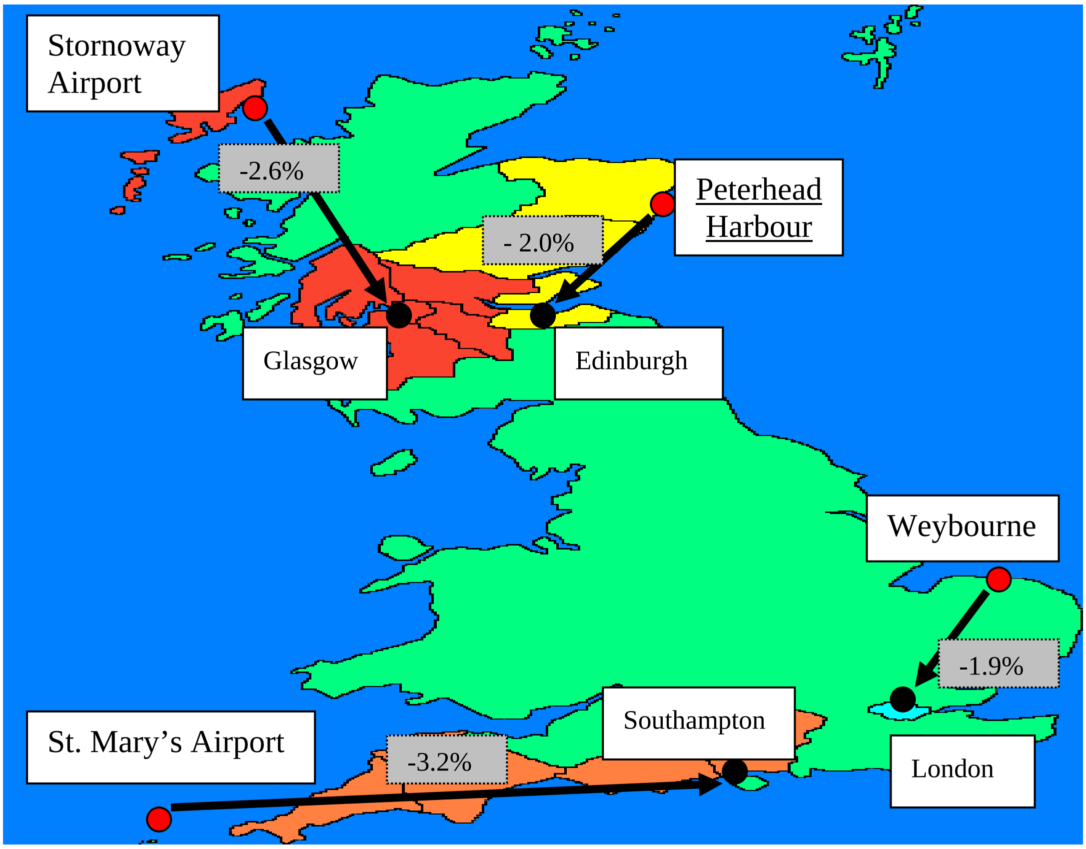


Transmission Lines

Once the distance between wind farms and demand centres is determined, we can decide what type of transmission line is used to distribute electricity. From the outset there are two choices on offer; AC (alternating current) transmission lines and HVDC (high voltage direct current) transmission lines. Typically for distances in excess of 170 miles, HVDC line losses start to undercut the losses to be had from using AC transmission lines (ABB Group, 2005). Likewise it can be seen from figure 3 that the only wind farm to possibly benefit from using HVDC lines is St. Mary's wind farm.

Given the distances involved between wind farms and demand centres, the decision was made to adopt AC transmission lines to transmit electricity from all 4 wind farms. This is not to say that HVDC transmission lines do not have their uses. Across the great plains of the America, HVDC lines are commonly used to transmit electricity at distances that would render AC lines useless. However AC transmission lines in the context of a relatively small geographic area like the UK still prove to be more efficient than HVDC transmission lines. Given the distances involved, the decision to use AC transmission lines resulted in known electricity losses of 0.55% per 100 mile distance of transmission line (ABB Group, 2005). Figure 4 illustrates these losses.

Figure 4: Map of Simulated Wind Farms Used within the UK and Transmission Line Losses as a Percentage of Wind Farm Output



Consequently it is shown in figure 4 that whatever weights are allocated to individual wind farms in the distributed production scenario, transmission line losses will be higher compared with the first scenario of limited geographic dispersion.

4. Results

Simulated Wind Farm Performances

Upon calculating hourly power generation figures for all 4 wind farms, each wind farm's performance was estimated as highlighted in table 1 below.

Table 1; Average Power Generation And Standard Deviation Per Wind Farm

	Stornoway	Weybourne	St. Mary's	Peterhead
Average Power *(MW/Hours)*	641.8	542.8	610.6	477.6
Standard Deviation	726.1	637.9	725.6	648.6

Note; Wind speed data was converted to metres per second (MPS) and then compared to power curve data in order to calculate power generation for each wind farm (Vestas, 2004).

According to the simulations there exists a great potential to reduce the standard deviation of wind power by dispersing wind farms to the UK's more eastern regions, more specifically Weybourne and Peterhead wind farms. Over the course of a year, standard deviations from these wind farms averaged levels approximately 10-12% lower than was found at Stornoway wind farm. However although these eastern wind farms exhibit lower standard deviations compared to the Stornoway wind farm, such wind farms also display lower rates of electricity generation. It must be remembered though that even if Stornoway wind farm did indeed have the highest level of average power generation *and* the lowest standard deviation compared to the other wind farms, the reliability benefits to be had from weakly correlated wind farms may mean a geographic dispersion of wind farms is still preferable to a limited dispersion. Table 2 below illustrates the correlation coefficients that exist between the different wind farms.

Table 2; Wind Farm Correlation Coefficients Between Sites In Relation To Hourly Output Changes

Weybourne (SE)	St. Mary's (SW)	Peterhead (NE)	
0.1	0.2	0.5	**Stornoway (NW)**
	0.4	0.2	**Weybourne (SE)**
		0.3	**St. Mary's (SW)**

As can be seen from the above table, the strongest correlation coefficient occurs between the 2 northern wind farm sites, Stornoway and Peterhead, with a figure of 0.5. The 2 southern wind farm sites, Weybourne and St. Mary's, are also moderately correlated with a correlation coefficient of 0.4. In general there appears to some correlation between sites with similar latitudes whereas sites with similar longitudes are weakly correlated due to the relatively small distances that exist between wind farms of similar latitudes compared to the distances that separate wind farms of similar longitudes.

Finding weakly to moderately correlated coefficients between all the wind farm sites gives great potential to using a wider dispersion of wind farm sites as a means to reducing aggregate wind power variability. For instance if power generation was found to be highly correlated between all 4 wind farm sites, there would hardly be any scope for wind farms to be relied upon to cover one another's generation shortfalls. However this is unlikely to be the case as there are no strong correlation coefficients between any wind farm sites in the distributed scenario thus enabling some wind farms to cover generation shortfalls in other wind farms and vice-versa.

Utilising Optimisation Techniques to Identify the Efficiency Frontier

The efficiency frontier shows all combinations of wind farms that produce the lowest variance for any given level of power generation. Similarly, investors use portfolio theory to calculate efficiency frontiers with respect to different types of shares and bonds with the aim of selecting combinations of securities that yield the least risk for a given level of return (Wilmott, 2001). For the purpose of this paper we use exactly the same techniques to calculate an efficiency frontier for wind farms that an investor would use to calculate an efficiency frontier for his or her investments. Following this logic wind farms can be seen as assets that can be interchanged with varying combinations.

Combining data already collected on the 4 wind farms regarding average wind speeds, standard deviations and correlation coefficients, it is possible to calculate such an efficiency frontier. The optimisation model used simply establishes the minimum standard deviation (portfolio risk) that exists for any given rate of average power generation (portfolio return) that is inputted into the model. Once a whole range of average power figures had been optimised for, an efficiency frontier is constructed. All points on the efficiency frontier are illustrated within table 3 with a graphical display available in the results section of this paper.

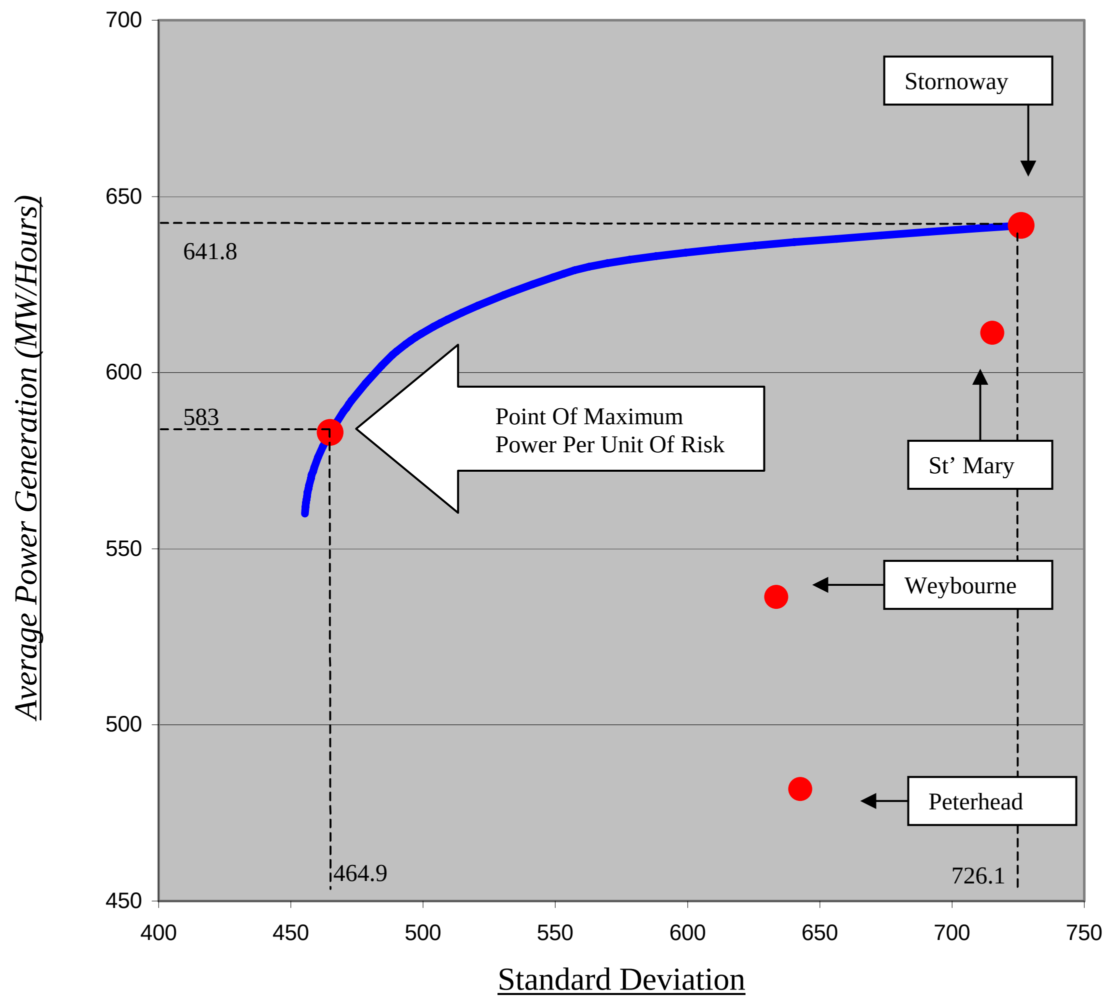
Out of all the points that represent the efficiency frontier, one point along this frontier must be chosen so that a direct comparison between the centralised production and distributed production scenarios can take place. Maximising power generation per unit of risk (standard deviation) will be the key decision criteria that will be used to determine this optimal point. Power generation per unit of risk calculations are shown in the third column located within table 3.

Table 3; The Efficiency Frontier And Return Per Unit Of Risk

Portfolio Return *(Average MW/Hours)*	**Portfolio Risk** *(Standard Deviation)*	**Return Per Risk Unit**
570	457.6	1.2456
571	457.9	1.2470
572	458.4	1.2478
573	458.8	1.2489
574	459.3	1.2497
575	459.8	1.2505
576	460.3	1.2514
577	460.9	1.2519
578	461.5	1.2524
579	462.1	1.2530
580	462.8	1.2532
581	463.5	1.2535
582	464.2	1.2538
583	**464.9**	**1.254033**
584	465.7	1.254026
585	466.5	1.254019

Located along the blue line within figure 5 are all the combinations of average power and standard deviation that represent the efficiency frontier. Basically the efficiency frontier illustrates those combinations of power and variance that are possible whilst varying the weights allocated to each wind farm. Any point located along this frontier also represents a combination of wind farm weights that minimises standard deviation for any given level of average power.

Figure 5; The Efficiency Frontier And The Location Of Individual Wind Farm Sites With Respect To Average Power And Standard Deviation



As can be seen from figure 5, improvements in variance are realised when moving to a scenario involving a greater geographic dispersion of wind farm sites. For instance in a situation whereby all wind power capacity is located at Stornoway wind farm (centralised production scenario), power generation averaged 641.8 MW/Hours with a standard deviation of 726.1 MW/Hours. However when the allocation of wind power capacity is spread out amongst a further 3 wind farms, standard deviation falls to 464.9 MW/Hours although average levels of power generation decrease to 583

MW/Hours[8]. For the majority of wind farms, except for Stornoway wind farm, it is impossible to obtain the combinations of power and standard deviation that are found on the efficiency frontier. Only by implementing a geographical dispersal of wind farm sites can one hope achieve a position on the efficiency frontier and by implication a point yielding maximum power per unit of risk.

Transmission Losses

Once the optimum point along the efficiency frontier has been identified, it will be possible to view the weights each wind farm has been assigned in relation to this optimum point. The optimisation model, for any given level of power generation, not only calculates the minimum possible level of risk but also display the weights used per wind farm. These weights are then combined with data showing the average level of generation as well as associated losses in electricity transmission for each wind farm in order to calculate aggregate transmission losses.

For instance if the average power (MW/Hours) of each wind farm is multiplied by the weight it is assigned at the optimum point, then the individual contribution of each wind farm will become known. Each wind farm's contribution to aggregate wind power is then multiplied by its own percentage transmission loss so that actual transmission losses in MW/Hours can be determined. Summing all individual wind farm losses result in an aggregate figure for transmission losses. Dividing aggregate wind farm transmission losses by the aggregate level of power generation yields a figure representing the proportion of total electricity that is lost through transmission. Comparing this figure to the transmission losses associated with Stornowaywind farm site in the centralised production scenario provides a measure of the change in the proportion of electricity that is lost in transmission when moving to a scenario of geographically dispersed wind farms.

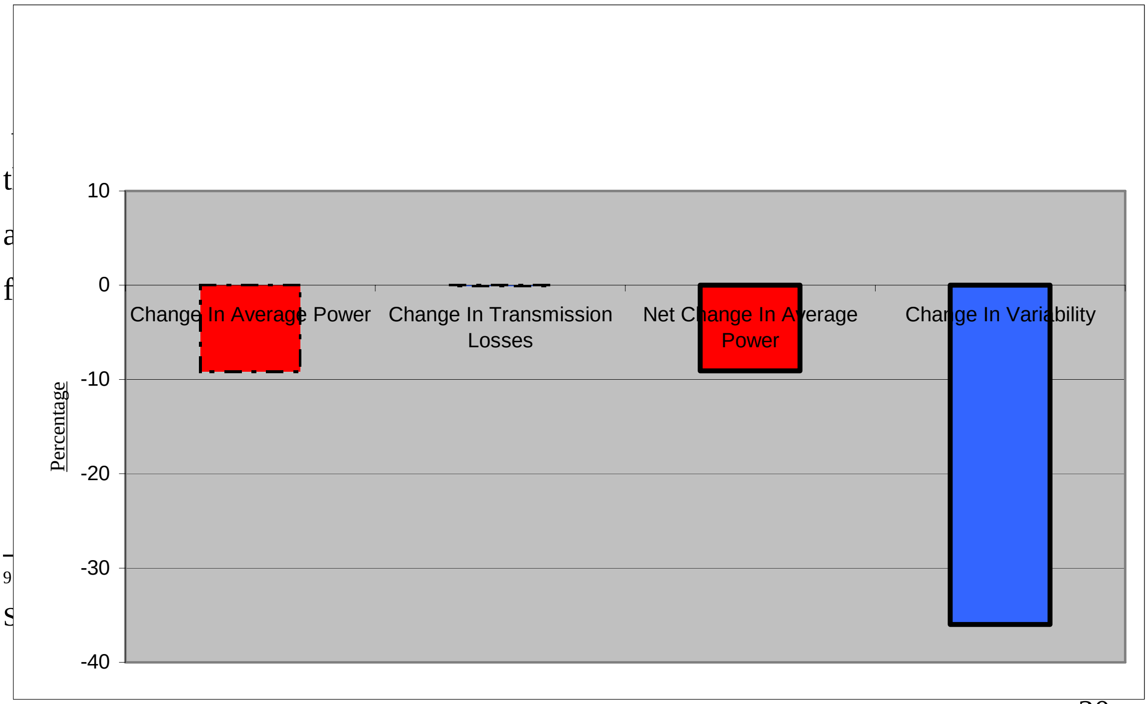
As a proportion of total electricity generated, transmission losses were largely unchanged between the two different scenarios. This finding was as expected given

[8] Assuming that the optimum point on the efficiency frontier (maximum power per unit of risk) is chosen to represent a scenario of geographically dispersed wind farm sites.

the fact that the additional wind farms used in the distributed production scenario consisted of wind farms with both greater and lesser distances to demand centres compared with the centralised production scenario. Likewise within this paper transmission line losses were found to decrease marginally from 2.6% to 2.5% of wind power production when moving to a distributed production scenario.

When analysing the change in wind power variability that occurred as a result of moving from a limited to a widespread distribution of wind power capacity, it can be shown from figure 6 that variability falls by 36%. However in terms of electricity generation, it can also be shown from figure 6 that distributing wind power capacity (distributed production scenario) results in a lower level of average electricity generation. For instance a 9.2% decrease in annual electricity generation was recorded when moving to the optimal point[9] on the efficiency frontier compared to a situation whereby 100% of capacity (2.7GW) was located at Stornoway wind farm. In terms of the relationship between transmission line losses and average power, it appears that the reduction in transmission line losses has had little effect in terms of compensating for the reduction in average power.

Figure 6; Comparing Net Changes In Average Power And Variability When Moving From A Centralised Production Scenario To The Optimum On The Efficiency Frontier



- Such a combination of wind farm weights also resulted in an decrease in average levels of power generation, net of transmission losses.

5. Discussion

Results in Relation to prior Hypotheses

When reviewing the results of this study, it can safely be said that most of our prior expectations have been fulfilled. For instance the correlation coefficients that were found between the 4 respective wind farms are broadly in line with what was expected given the distances involved. Weak correlation coefficients are also indicative of different wind farms being subject to separate weather systems for most of the time. For example on any given day, one part of the UK may be affected by a low-pressure system whilst another part of the country could be under the influence of a high-pressure system.

Weak correlation coefficients can also be used to justify the inclusion of Peterhead wind farm site at the optimum point on the efficiency frontier. Compared to Stornoway wind farm, which was the wind farm used in the centralised production scenario, Peterhead wind farm has inferior levels of power generation. Therefore inclusion of Peterhead wind farm in the second scenario can mostly be attributed to the effect it has on lowering aggregate variance.

However the reduction in the variance of wind power that was achieved when moving to a scenario of geographically dispersed wind farm sites was as expected. The reduction in variance by 36% was primarily achieved through the weak correlation coefficients that were exhibited by wind farms as a whole. Indeed a reduction in variance would have been impossible had strong correlation coefficients been evident as all other wind farms had higher levels of variance compared to Stornoway wind farm. Thus when it came to spatially distributing wind power capacity, aggregate power generation was found to display significantly less variation in comparison to the wind farm located at Stornoway.

The small change in transmission line losses as a result of seeking to increase the spread of wind farms was also expected. However the size of any change in transmission line losses is largely dependent upon the distances between wind farms and their respective demand centres as well as the performance of the alternating current (AC) transmission lines.

Implications of findings

From the electricity generators' perspective, the reduction in wind power variance could lead to substantial cost savings. Each time a generator fails to meet a contract to supply, the network operator imposes ancillary charges in order to cover the cost of balancing supply and demand within the system. Such charges could be reduced by up to 36% when attempts are made to geographically distribute wind farms around the UK. Assuming that these falls in ancillary charges are proportional to the fall in variance, reductions of 36% in ancillary charges levied could be realised by wind farm generators in the distributed scenario. Overall it can be said that substantial cost benefits exist for wind farm generators willing to locate their wind farms over large distances.

The findings contained within this study also have implications with respect to the UK government's stated target of supplying 10% of electricity from renewable sources by the year 2010. As highlighted previously, variability of supply is the main barrier to the widespread adoption of wind power in the UK and indeed elsewhere. The reduction in aggregate wind power variability that was achieved when dispersing wind farms over a wide area can only help to reduce the costs of integrating large amounts of wind power into the electricity network. For instance at low levels of penetration, changes in the output of wind farms can be balanced out with existing mechanisms embedded within the electricity network. However as wind power begins to make up a larger and larger share of electricity supply, the normal balancing mechanisms of the electricity network will increasingly be unable to cope with this amplification effect with respect to variations in wind power. Therefore the reductions witnessed in wind power variability as a result of dispersing wind farms can help in extending the limits to which wind power can be successfully integrated into electricity networks. This is especially relevant to the current situation in the UK whereby the government has set ambitious targets for the generation of renewable energy.

Despite improved wind power reliability being realised as a result of dispersing wind farm sites, there were days when aggregate wind power generation across all 4 wind farms fell to zero[10]. In Denmark, a country which has a high penetration of wind power, shortages in electricity generated through wind turbines are made up by importing electricity from either Norway or Germany (The Economist, July 2004). However the UK electricity network is not set up to accept large amounts of electricity in the same way as Denmark is. In our view the only other option that exists in accounting for these periods whereby aggregate wind power generation falls to zero, would be to develop conventional capacity in the form of gas turbines. Gas turbines, due to their fast ramp-up rates, are able to respond to changes in wind power generation much more quickly compared to coal or nuclear power stations (DeCarolis and Keith, 2004).

Overall the diversification of wind farm sites across large areas has been shown to improve the reliability of aggregate wind power generation on a scale that is simply not possible in the UK with combined hydro-wind power systems due to geographical realities. Likewise the viability of combined solar-wind power systems has not yet been proven to alleviate the problem of wind power variability. Until technological progress leads us to the development of advanced storage systems capable of storing hydrogen for instance, it is likely that dispersing the location of wind farm sites may currently be the only way to counteract some of the inherent variability that is found in wind power.

[10] In total there were 202 hours out of 8,250 recorded hours whereby aggregate wind generation fell to zero.

Analysis Shortcomings

Despite a conscious effort to provide an accurate picture as possible with regards to analysing the effects of a greater spatial dispersion of wind farm sites, several shortcomings are noticeable. The first point of contention relates to the hourly wind speed data that was used as the backbone of this study. Whilst wind data measured in hourly intervals is a bare minimum in relation to investigating wind power variability, intervals of 5 or 10 minutes would have been more appropriate in order to capture a more accurate picture of wind power variability.

Additionally the wind data that was used throughout this study was recorded at a much lower height than the 80-105 metres height of the Vestas V90-3MW wind turbine that was used throughout the study (Vestas, 2004). Consequently this may have somewhat biased levels of power generation downwards due to the existence of higher wind speeds at greater altitudes. Such bias may be evident by looking at the capacity factors[11] that were recorded for all wind farms used within this study. For instance prior to undertaking this study, it was assumed that average capacity factors for all wind farms would be in the region of 30%, although the study later revealed capacity factors ranging between only 18% and 24%. This difference between figures may be as a result of taking for granted (wrongly) that wind speed measurements close to the ground are a good proxy for wind speeds at heights of 80-100 metres.

Similarly it is not clear as to whether using wind speed observations close to ground level has had any affect upon wind power variability. However there is good reason to believe that wind power variability may have been biased upwards as wind flow is known to become smoother with altitude. Smoother wind flows at higher elevations are often caused by the wind encountering less resistance due to the absence of buildings, trees, hills, etc.

Also of some concern is the assumption that coastal weather stations are representative of offshore wind conditions. Such an assumption had to be made due

[11] The capacity factor represents the level of wind power capacity that is utilised on average.

to the lack of available offshore wind data. One can only hypothesise that some differences may exist between coastal and offshore wind conditions due to the effects of sea breezes. Such sea breezes are caused by differences in the temperature of the land relative to the sea such that during summer, cool air from the sea blows inland whilst in winter the process is reversed. Obviously the effects of these sea breezes diminish the further offshore one travels. Bearing in mind the fact that all simulated wind farms will be located approximately 1-2 miles offshore, there is some reason to believe that the coastal wind data obtained may not be truly representative of conditions some 1-2 miles offshore.

Another point of contention in relation to the wind speed data set concerns the time frame from which recorded data could be obtained. Although an annual data set was able to capture all the seasonal changes that impacted upon wind speeds, obtaining data sets over 3 years in duration would have been preferable in order to mitigate for the possibility of exceptionally windy or calm years.

The final area of concern regarding the mechanics of this paper lies upon the power curve that was used to calculate levels of power generation. Although this power curve has been constructed and technically assessed by the turbine manufacturer, doubts remain with respect to the performance of the turbine in real life (Power, 2001). Ideally instead of utilising a power curve provided by the manufacturer, real wind farm generation data could be combined with actual wind speed data in order to create a power curve based on real data (Power, 2001). However such an undertaking is beyond the scope of this paper.

6. Conclusion

In concluding this paper, it can be said that moderate reductions in the variability of wind power are possible given a widespread dispersion of wind farm sites. Such reductions are of great importance when seeking to increase the penetration rate of wind power with regards to domestic electricity generation. However despite the reduction in wind power variability that was witnessed when moving to a scenario of geographically dispersed wind farms, large amounts of conventional power are still required as a backup capacity to mitigate for variations in wind power.

Further research, using wind speed data with a resolution of 5-10 minutes, is needed in order to ascertain a more accurate picture of wind power variability. In addition it would be interesting to see if such research could be undertaken on a larger geographical scale, for example on a European level, in order to see if an even greater reduction in wind power variability could be achieved.

7. References

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