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Spatial smoothing of onshore wind: implications for strategic development in Scotland

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Abstract

High levels of wind penetration is widely accepted as presenting problems for energy security. With increasing wind deployment this issue is well recognized in Scotland. Spatial smoothing of generation is seen as one method to enhance energy security in a high wind penetration system. This requires wind farms to be developed in a way to take advantage of this smoothing; however, this is not part of the UK/Scottish government wind deployment strategy – which is instead developer led.

This research seeks to contribute to a strategic approach to wind development in Scotland, taking into account spatial smoothing – which is shown in this study to be statistically significant within Scotland. Providing quantification of which pre-existing areas of large-scale wind development in Scotland should be the focus of further development and which are of least benefit. Wind farms in southern Scotland offer least in terms of energy security, due to over-concentration of deployment in this area, further development here should be in part considered in terms of export value, rather than utilization within Scotland. The two island areas modelled are shown to have high spatial smoothing value. This work should help inform current political discourse over grid connections to these areas.

Highlights

- A 30 year hindcast for onshore wind generation in Scotland is created.
- Areas of wind development of most benefit to generation smoothing are identified.
- Areas are identified where extra capacity has low value unless primarily for export.

Keywords

Onshore wind, spatial smoothing, strategic development

1. Introduction

Currently, onshore wind capacity in Scotland exceeds all other renewable resources combined, with over 5.6 GW being operational at the end of 2015 (DBEIS, 2017). However, onshore wind power can be highly variable (Sinden, 2007; Yang et al., 2016); this has implications for both short term security of electricity supply and system efficiency. Additionally, with increased penetration, wind curtailment can become more prevalent (Waite and Modi, 2016). These issues are well recognised; leading to many valuable UK focused studies of wind's integration into the electricity system. These studies are predominantly academic (e.g. Boehme and Wallace 2008; Dale et al. 2004; Le & Bhattacharyya 2011; Oswald et al. 2008; Sinden 2007) but there are also reports commissioned by government (e.g. Boehme et al., 2006), advisory bodies (e.g. Cox 2009) and NGOs (e.g. Milborrow 2009). The depth and breadth of literature highlights the importance of the issue. Yet, research tends to be rather generalised, focusing on the long-term trends and theoretical wind development, rather than actual wind farms.

Large-scale renewable projects, such as wind farms, in the UK were historically supported by the Renewables Obligation (RO), which in essence paid certified renewable generators a subsidy for each unit of electricity generated. The RO is being phased out and replaced by the Contracts for Difference (CfD) scheme. This operates in a similar way but with a bidding process attached. Neither of these policy mechanisms directly assigns additional value to renewable generators if they add to system security by having a different output regime to other generators. With onshore wind increasingly dominating the Scottish renewable portfolio this could become a problem. Much of the wind power development in Scotland is focused, and set to continue to be focused, in the South, see Figure 1. Consequently, there is limited geographic smoothing of wind generation – which can have a significant effect on wind power production (Buttler et al., 2016).

Figure 1. Wind farms of Scotland in 2016 either in operation or within the planning system. Wind farm data is from Scottish Natural Heritage (SNH, 2017). Crown copyright ©.

By identifying areas where wind development would be of greater benefit to the Scottish electricity system it would attach additional value to development in such areas. This could enable policy makers to either directly increase the subsidy to such developments, alternatively indirect assistance through mechanisms that encourage development such as greater grid connection to isolated areas.

This paper aims to provide initial quantification of the comparative benefits of additional onshore wind capacity in different areas of Scotland. Indicating where extra capacity would be of the greatest value for more reliable contribution of onshore wind to the Scottish electricity system; assisting with strategic development of onshore wind in Scotland.

2. Methodology

This study utilises a hindcasting methodology, taking historic wind speeds and using them to infer generation for onshore wind farms given past conditions. The longer the set of historic data, the greater the accuracy of the hindcast in its representation of how future renewable plants would have performed given historic conditions. A 30 year time series is desirable as it is classified as a climate normal period by the World Meteorological Organisation (WMO). The most recent climate normal period classified by the WMO is 1981-2010 and is the period used in this study. To hindcast onshore wind, measured wind speeds are the preferred data source for the UK; e.g. Früh (2015, 2013), Sinden (2007) and Boehme and Wallace (2008). Sharp et al. (2015) observe that these measured datasets perform better than modelled ones in high wind speed environments in the UK, such as Scotland.

2.1. Onshore wind data

For this work, data from the Met Office Integrated Data Archive System (MIDAS) was obtained from the British Atmospheric Data Centre's (BADC) website (BADC, 2013). This data archive uses measurements from an extensive network of weather stations across the UK, operated by the Met Office.

The data required cleaning, with the removal of repeat recordings for the same hour, removal of incorrect versions of the data, and the insertion of missing time-steps. The insertion of missing time-steps is required as when no recording is taken at a MIDAS station the whole hour is missing from the record, with the next time-step only being when the next measurements were recorded. This presents problems for analysis, as datasets are not uniform in length. The addition of missing hours only adds a time measurement; it does not attempt to infill missing wind parameters. This method adds no wind speed, i.e. no generation calculation will be performed, rather than adding a 0 knots wind recording which would result in zero output and have a greater impact on analysis. Details of the occurrence of missing values in the MIDAS stations used to model wind output is provided in Table 1. Further details of the MIDAS selection process and station characteristics is provided in Appendix A.

Table 1. Details of MIDAS stations used for wind modelling. The wind capacity represented is either built, under construction or accepted as of June 2012. Missing values refers to if either the wind speed or direction, or both, are missing – as both elements are required for calculating wind farm generation.

The wind capacity listed in Table 1 is not evenly distributed within Scotland, this is illustrated in Figure 2.

Figure 2. Wind farms modelled and MIDAS stations used (text next to MIDAS stations indicates station ID). Crown copyright ©.

In this study only onshore wind farms which are either operational, under construction, or consented as of June 2012 are considered, the location of the wind farms modelled is displayed in Figure 2. Many of the wind farms either in planning or scoping, and thus omitted, are in areas which already have significant wind development, such as in Southern Scotland in Dumfries and Galloway. The wind farms used will therefore be representative of future wind farm installations.

The only area with large wind developments not modelled or mapped in Figure 2 is the Isle of Skye, which has 69 MW of installed capacity. The mountainous terrain of the island necessitates wind measurements to be made close to the wind farms, as the nearest suitable MIDAS station was on the mainland the error this would create was considered to be too high.

Small wind farms and individual turbines are not included as it is a very intensive process to integrate these developments. Orkney, which has the highest density of such developments, has a collective wind capacity of 45.75 MW, which is a very small share of overall wind portfolio modelled – 0.79%. Exclusion of developments such as those on Orkney thus makes negligible difference to Scotland's wind output on a national scale.

2.2. Modelling onshore wind generation

The Wind Atlas Analysis and Application Program (WAsP) was used to extrapolate wind data from the measured MIDAS stations to wind farm locations for the 30 years of MIDAS data. Other authors have used WAsP for similar applications (e.g. Boehme and Wallace, 2008; Boehme et al., 2006; Onat and Ersoz, 2011; Sinden, 2007), although typically not for specific wind farms.

The foundation of the WAsP model is the double horizontal and vertical extrapolation method. If there is measured wind data for one location and the roughness around the site is known, then the model can find the frictional velocity from the logarithmic profile and apply the geostrophic drag law to calculate geostrophic wind (Petersen et al., 1998). This process uses a flow model to account for the effects of local obstacles, terrain heights and terrain roughness. The result is a 'cleaned' set of measurements – called a 'Wind Atlas' – that are independent of site-specific conditions. The reverse of this procedure can then be performed to obtain the local wind climate at a different, unmeasured, location by reintroducing the height, roughness and obstacles.

The orographic data used was UK Ordnance Survey 'Profile', which provides contours at a very fine resolution of between 1m and 10 m intervals, depending on terrain, with extreme heights in terrain being measured to the nearest 1 m. This fulfills the criteria for accurate use of WAsP in complex terrain described by Mortensen and Petersen (1997).

The European land cover database Corine Land Cover 2006 (European Environment Agency, 2012) was used to derive surface roughness. This dataset is suggested as a useful source of information for roughness values in WAsP (Technical University of Denmark, 2012). The 100 m resolution falls between the original Corine dataset which has a 250 m resolution and Landsat data which has a 20 m resolution, both datasets were criticised by the makers of WAsP for being too coarse and too fine respectively (Nielsen et al., 2004). The surface roughness inferred by different land cover types is detailed in Table 2.

Table 2. Corine Land Cover (CLC) classes description and roughness lengths. The roughness lengths were determined independently for Scotland in this study, but are based on the work of Silva et al. (2007) with the roughness lengths suggested by the authors being verified and adjusted by the use of detailed aerial and satellite imagery and photography from Google Earth. The roughness length of water is usually treated as 0.0002 m, however, WAsP requires it to be assigned a value of 0 in order for it to be recognised as water.

WAsP can also take into account the wake effect of wind turbines, if their individual coordinates within a wind farm are available; these data were gathered from the developers themselves, the Ministry of Defence, and Scottish Natural Heritage. In some cases wind turbine heights were also provided; however, these were not always available, in these instances the default heights from WAsP for the selected turbine model were used.

Not all turbine models which are being/will be used in Scotland are available in WAsP. In these cases turbine information from the manufacturers were compared to turbines within WAsP and the closest match selected; for example, Vesta V80 2 MW turbines were used instead of Gamesa 80 2 MW turbines. The wide variety of turbines available within WAsP meant a close match could always be found.

Details of the use of WAsP are given by Mortensen et al. (2007). The methodology provided in Mortensen et al. (2007) can be used to create a power curve for each MIDAS site. This power curve specifies how much electricity is generated from the wind farms modelled for any given wind speed and any given wind direction. The power curve can then be applied to the hourly MIDAS data, giving hourly output figures over the entire length of the record (when wind speed and direction are available). In this way each of the 16 different regions of wind farm development in this study were modelled.

To account for downtime, a 2.5% loss is applied to the output from each hour in the output chronologies created using WAsP; this level of reduction is supported by operating data and literature (Ali et al., 2012; Blanco, 2009; McKenna et al., 2014). The electrical loss within the wind farm was applied in the same way, after losses due to downtime were accounted for. The level of electrical loss was taken to be 3%; in accordance with the upper end electrical losses identified in the literature (Ali et al., 2012; McKenna et al., 2014).

3. Results and analysis

The methodology described in Section 2 creates a hindcast of output for a 5779 MW wind portfolio, the distribution of the wind farms which make up this is capacity is detailed in Table 3. Due to the length of some wind records only 80.2% of this portfolio is hindcast for the full 30 years, 83.5% for

28 years, 92.7% for 23 years, 96.3% for 19 years, and the full 5779 MW is modelled for 12 years. So despite the limitations of some datasets the considerable majority of the portfolio has output figures for the whole 30 years.

The hourly output chronologies created using WAsP enables characterisation of hindcast wind generation. Long term output statistics are initially examined in section 3.1, with spatial smoothing being analysed and discussed in Section 3.2.

3.1. Long term output

Hindcast capacity factors provide a useful initial gauge of how Scotland's wind fleet is likely to have performed in historic conditions, this provided in Table 3.

Table 3. Capacity and load factors for wind developments.

The overall capacity factor of 30.18% for Scotland's modelled wind fleet is higher than the UK average for 2009 to 2015 of 26.8% (DBEIS, 2017). This is to be expected with the greater average wind speeds in Scotland as well as the lack of curtailment in the modelled output.

The 30.2% overall hindcast capacity factor equates to an average hourly power production from the modelled wind farms of 1744 MWh, so on an average year 15278 GWh would be generated. To put this in context Scotland's highest annual demand, achieved in 2005, was 41923 GWh and the most recent year data is available for, 2014, had a total consumption of 32378 GWh (The Scottish Government, 2016). However, this level of generation cannot be relied upon year on year due to a high level of annual variation in wind output; this is illustrated by an examination of annual capacity factors in Figure 3. Examination of annual capacity factors will also enable it to be established whether, as inferred by Früh (2013), Scotland's exploitable wind resource has significantly decreased in the last few decades.

Figure 3. Annual capacity factor for modelled wind farms. 30 year records are plotted separately as the addition of sites not covering the full chronology provides a further variable which will impact capacity factor.

A general trend in lower annual wind capacity factors is apparent in Figure 3. The significance of this is confirmed by a Pearson correlation test of the relationship between time and capacity factor, which returned an r value of -0.415 for the areas with a 30 year record (p value 0.023); areas with a record under 30 years in length were not used as they alter the overall capacity factor.

In 2010 UK average wind speeds were the lowest this century (4.01 m/s), reducing onshore UK onshore wind capacity factors to 21.7% - one fifth lower than in 2009 (MacLeay et al., 2013). Average wind speed increased in 2011 by approximately 0.67 m/s from 2010, returning UK wind capacity factors to a similar level obtained in 2007 to 2009 (MacLeay et al., 2013). The presence of this anomalously low year for generation at the end of the chronology has considerable leverage on the relationship observed in Figure 3. If 2010 is excluded the strength of the relationship decreases with an r value of -0.330 (p value 0.081). Thus, as with Früh (2013), a decrease in exploitable wind energy over time is observed; however, the implications of this relationship wind development is questionable.

When examining long term output trends a quantification of the variability is useful in understanding the characteristics of this resource. Sinden (2007) examines variability by analysing the change in power output through the time series. For this analysis the change in power output of the hindcast was determined over both a 1 hour and 4 hour timestep, and the standard deviation of the resulting time series was calculated (Sinden, 2007). These two time steps were used as they were chosen by Sinden (2007) and will thus allow a direct comparison of the results between the two studies, giving an indicator as to how variability in Scotland differs from the UK as whole. Expressed as a percentage of the installed capacity of wind power, the standard deviation of the modelled wind power data was 3.3% at the 1 hour period, and 8.8% at the 4 hour period; these figures are compared to Sinden's (2007) study in Table 4.

Table 4. Comparison of 1 and 4 hour variability in wind output. Data is the standard deviation of the change in hindcast generation over different timesteps, displayed as a percentage of installed capacity.

The variability of in this study's hindcast, shown in Table 4, is shown to be similar to a study which covered the whole of the UK at the 1 hour ahead but noticeably less at 4 hours ahead. There are several factors which can contribute to this lower variability despite a smaller spatial diversity. The Sinden (2007) study, due to its timing, had to make assumptions over wind farm placement which causes different characteristics in the wind portfolio. The turbines used in this study are in the most part more modern and consequently have more efficient power curves. Scotland is windier than most of the UK, in particular England, and as such will have different characteristics to the UK as a whole. In addition, the impact of spatial diversity on overall wind output is complex; this is explored in Section 3.2.

3.2. Impact of spatial diversity

To determine the extent to which the spatial diversity of Scotland's wind fleet can smooth wind output, the relationship between the different areas modelled was examined. As in Stoutenburg et al. (2010) this was done using Pearson correlation analysis. This was undertaken for the 16 areas listed in Table 1 on the hourly output data and plotted against the distance between the MIDAS stations used to model each area's output, with the result being displayed in Figure 4.

Figure 4. An examination of the importance of distance between MIDAS sites in determining output correlation for areas of modelled wind output.

A report by the European Wind Energy Association (EWEA) shows the impact of spatial diversity of wind farms on wind fleet forecast output errors is very similar to the relationship displayed in Figure 4 (EWEA, 2012). As the distance between wind farms increases the accuracy of the overall pooled wind output forecast increases (EWEA, 2012), although, as in Figure 4, there is a case of diminishing returns as these distances increase. This suggests that smoothing of output through wind farm aggregation will also aid large scale integration of wind energy by increasing forecast accuracy.

In Figure 4 the strength of correlation increases the closer together the MIDAS stations used to model output are. However, Figure 4 suggests there is diminishing additional value to be had by spacing wind farms far apart in Scotland – this is in part shown by an exponential trend line providing the best fit to the data (this trend line is included in Figure 4). This relationship between wind correlation and distance between areas is corroborated by and consistent with two UK wide studies which utilised a larger number of MIDAS stations (Früh, 2015; Sinden, 2007).

Some areas of wind development close to each other do exhibit relatively low correlation of output in Figure 4. The trend line in Figure 4 has an R^2 value of 0.642 (p value < 0.001), lending support to factors beyond proximity, for example topography, impacting the correlation of wind generation between different areas of Scotland. To observe the relationship between the different sites in more detail than Figure 4, the correlations between the 16 different areas of wind generation and the overall portfolio is presented in Figure 5, the correlations between the different wind areas on a site by site basis is presented as a series of 16 maps in Appendix B.

Figure 5. The correlation of output (capacity factor) between the modelled wind generation areas and the combined wind portfolio. The MIDAS station ID is provided for each area with the corresponding r value in brackets. Crown copyright ©.

The most isolated MIDAS station, station number 9 (Lerwick), exhibits the weakest correlations with the overall wind portfolio, when coupled with the area's high capacity factor (Table 3) this makes the area most valuable to the smoothing of wind output in Scotland. The map examining MIDAS station 9 in Appendix B shows that the area surrounding station 32 has the strongest correlation of wind output to station 9, suggesting that if wind development in Shetland is unable to go ahead – due to issues like interconnectors to the mainland – that the value of wind generation in the station 32 area is likely to increase. Figure 5 also shows that the four largest areas of wind development (the areas modelled using stations 268, 1023, 982 and 1039) have highly correlated output to the overall portfolio, suggesting that further development in this area will be of limited value. Leading from this a generalised observation from Figure 5 is that areas in the south of Scotland tend to exhibit greater correlation to the overall wind portfolio than areas in the north. Consequently, this infers a higher security of supply value on further capacity in higher latitudes. In addition there is some degree of an East/West separation visible in the maps in Appendix B, which is to be expected from the manner weather systems track across Scotland.

With different weather conditions the relationship between sites is likely to change; this is explored in Figure 6, with detailed breakdowns by area in Appendix C. Wind generation varies significantly with time of year – consequently the different months of the year are used to breakdown the data set into different conditions; in general winter months are the windiest whilst summer months experience the lowest wind speeds and levels of generation.

Figure 6. Box and whisker plot of correlation of output between the different hindcast wind areas for different months of the year. Due to the number of sites (16) there are 120 r values for each month.

Correlation between wind areas is generally higher in high energy winter months and lower in the low energy summer months; although September exhibits the strongest correlation. From a system management perspective the greater spatial smoothing during summer is beneficial as it is at this time of year where shortages in wind generation would be expected, due to the lower wind speeds. A likely driving force behind the lower correlations in the mid-summer months (particularly June and July) seen in Figure 6 is the greater dominance of local thermally induced winds at this time of year (Sinden, 2007). Conversely, in the winter larger weather systems are more dominant acting to reduce spatial smoothing.

The weakness of correlation in summer grows very pronounced in some cases; in the case of MIDAS areas 9, Lerwick (on Shetland in the far North East), and 908, Machrihanish (in the South West), the correlation between the two generation areas falls below 0.1 during June and July (this can be seen in Appendix C). Analysis of correlation between sites by month highlights the importance of Shetland (area 9) to smoothing of wind output; only MIDAS area 32 in ten of the months and areas 132 and 137 both in one month (September) exhibit correlations with this area greater than 0.5 (see Appendix C for details).

3.2.1. Generation peak smoothing

The greater difference in correlation between geographically diverse areas, shown in Figures 4, 5 and 6 and appendices B and C, suggests that continued wind deployment in some areas will help to increase smoothing. In other areas greater development will increase the variability of Scotland's wind generation profile, potentially creating issues for system management. Identification of areas which cause the greatest smoothing of generation is a useful policy tool for strategic and secure wind development. It can help determine which locations, from a short temporal scale system management perspective, would be most beneficial to develop in the future. The changes caused by excluding different areas from the wind portfolio is quantified in Table 5 using the same standard deviation methodology as described for the creation of Table 4.

When carrying out this standard deviation analysis unweighted output figures are examined; these are output figures where only capacity factors are examined with no context of installed capacity. The use of unweighted capacity factors helps reduce the impact of times of no recording on the results, as the distorting effect when a high installed capacity area (such as that modelled using the Salsburgh MIDAS station) has no recording is lessened.

Table 5. The impact of excluding different areas of wind development on the 1 and 4 hour standard deviations of Scotland's wind output. The capacity factors are un-weighted, that is they do not take into account the differences in installed capacity in the various areas but instead use the hourly capacity factors from different areas to calculate the overall capacity for different wind portfolios. Only the 12 years of hourly capacity factors where all areas have wind speed recordings were used in the standard deviation calculations so as not to bias certain areas, it should be noted that these alterations in methodology create changes in standard deviations for the whole portfolio when compared to Table 4.

A higher standard deviation suggests there are times where a larger portion of electricity generated cannot be utilised; this would result in wind farms having to potentially curtail output – creating a more wasteful and less efficient electricity system. Table 5 shows that excluding MIDAS area 9 would have the largest negative impact of standard deviation of wind generation in Scotland and that areas 908 and 54 being excluded would have a large negative impact. In general Table 5 shows adding an area makes a positive contribution to reducing the standard deviation. However, there are two important observations which would necessarily have been expected. First, areas 982 and 1039, which are generally shown in much of the analysis in this paper to be of low value, noticeably decrease the standard deviations in generation. This is in part due to the areas having a very high level of capacity spread over wide geographic extents, meaning there is some within area smoothing. So whilst these may not be of high value for most measures of energy security they do smooth output over short time scales.

The second observation is that some areas, which are otherwise shown to be of high value for development in this study, raise the standard deviations of the wind portfolio through their inclusion. This is most notable in the case of area 48. In this instance there are several contributing factors behind this increase in standard deviation. These include relatively few wind farms modelled in the area (three as opposed to 17 for area 982) - meaning there is little within area smoothing; this is coupled with high capacity factors, which means the output profile has a large impact on the overall wind portfolio. It is likely that the mainland location causes these factors to increase standard deviations, unlike the otherwise similar - in terms of security and smoothing contributions - island areas 54 and 9.

It is useful to consider the findings presented in Table 5 in the context of a similar Great Britain wide study by Früh (2015). The study found that the hourly variation in wind generation is more affected by localised events than large-scale weather systems (Früh, 2015). This demonstrates that variability in wind generation over a typical weather regime will affect the nationally available wind power (Früh, 2015). Associated with this are implications for system management, such as the amount of reserve needed. However, Früh (2015) considers it might be possible to smooth out short-term power fluctuations from individual wind farms by aggregating them with other wind farms. The results presented in this study, with Table 5 being particularly pertinent, suggest this is likely to be achievable at some level with strategic wind development. Finally, as concluded by Früh (2015), this could result in power quality and short-term energy storage issues stemming from large scale wind integration into the transmission system not being too severe an issue.

3.2.2. Impact of wind areas on achieving fleet stability

The impact of different wind development areas on the overall portfolio is further assessed in Table 6. Details of how this analysis was undertaken is provided in Appendix D. However, to summarise Table 6 presents how the exclusion of different wind areas alters the frequency of different capacity factors being achieved. As in some other analyses in this study unweighted capacity factors were used, so all areas make an equal contribution to the portfolio in this instance.

Table 6. The impact of excluding different areas of wind development on hourly unweighted capacity factors (cf). The impact of area exclusions are highlighted with a sliding colour scale, dark blue shows a lower capacity factor whilst dark orange shows exclusion results in a higher capacity factor. The whole portfolio performance is also included to provide an indication of frequencies, although due to missing data this whole portfolio performance will vary slightly in each of the 16 cases.

The areas which are identified as most beneficial to Scotland's wind portfolio are those with a high number of dark blue cells and a low number of dark orange cells in Table 6. The lower capacity factor bins, i.e. those below the 30% overall capacity factor of the wind fleet, are of most interest as they represent the occasions when output is below the average capacity factor – and can thus be considered to represent a low wind generation event.

The blue cells represent times when the exclusion of the listed area increases the percentage of occasions a given capacity factor is not exceeded. MIDAS station 9 (Lerwick) is the most valuable area for wind development in terms of phasing of output. This is due to the large increase in percentage share of the 5% to 30% capacity factor bins when it is excluded; these represent instances when capacity factor is lower than the 30 year average. The high value of including Lerwick is due to two factors: firstly, it is the most isolated area, providing most spatial phasing; secondly, it is the windiest area with the highest capacity factor, meaning output is always likely to be higher than other areas. The high energy wind regime is likely to be responsible for the light orange cells observed at Lerwick in the 80% to 90% capacity factor bins. When other areas are experiencing their highest levels of output, high wind speeds are likely to cause wind turbines to shut down in Lerwick area; as this area is naturally windier, causing a slight increase in the times capacity factors fall in the 75%-90% bins of Table 6 when Lerwick is excluded.

High capacity factors have a major influence on the impact an area's exclusion has on the wind portfolio. After Lerwick Table 6 shows Kinbrace Hatchery (48), Loch Glascarnoch (67), Lossiemouth (137), Machrihanish (908), Stornoway Airport (54), Dyce (161), and Wick Airport (32) to be beneficial; all of these areas have high capacity factors, see Table 3. However, capacity factor is not the only influence on providing benefit to the portfolio. Machrihanish has the same capacity factor as Kinbrace Hatchery, yet Table 6 suggests that it is less beneficial to Scotland's wind portfolio in this context (although the opposite was true for Table 5).

The high value of Lossiemouth to the wind fleet is somewhat unexpected due to the close proximity of Kinloss, so the areas are likely to experience the same weather systems. It thus seems likely that the low capacity factor experienced in Kinloss has inflated the value of the inclusion of Lossiemouth.

The four largest areas of wind development: Charterhall (268), Eskdalemuir (1023), Salsburgh (982) and West Freugh (1039) offer very little improvement to the overall wind output in Scotland; this is despite having capacity factors not much lower than the overall wind portfolio. Given the disproportionally large installed capacity represented by these four areas of development, over 50% of the entire wind fleet modelled, this suggests no further wind development should take place in these areas (unless there is a large export market) – the limited value of further development in these areas can also be seen in Figure 5. The three most preferential areas for further development are around Lerwick (9), Machrihanish (908), Stornoway Airport (54) as all analyses show these to have a positive impact. After these three areas Kinbrace Hatchery (48), Loch Glascarnoch (67), Lossiemouth (197), Dyce (161) and Wick Airport (32) are the next best for development. Although some of these sites increase or are of little benefit to the standard deviations in the wind portfolio they do act to enhance security in supply of wind output in other ways (e.g. see Figure 5, Appendix B, Table 6).

4. Discussion of grid implications

In Scotland the transmission system, operated by the National Grid, is well developed to serve the major population centres in the Central Belt. However, the distribution system, operated by Scottish and Southern Electric Power Distribution and Scottish Power, is very congested. This allows limited amounts of local power generation to be absorbed and transmitted. This can create transmission bottlenecks; with many of the highest value areas in terms of spatial smoothing being at the extremities of the transmission system congestion and associated curtailment could become a potentially significant issue (Coker et al., 2013). This existing high voltage infrastructure in Scotland is one of the major reasons behind the imbalance of wind farm deployment across the nation.

Whilst this issue is a national problem it will be discussed in an island context as these areas (i.e. MIDAS stations 9 and 54) are identified in section 3 as some of the highest value locations for spatial smoothing. Furthermore, being at the extremities of the grid they are particularly strongly effected by transmission constraints.

Under the current regulatory model, Scottish Hydro Electric Transmission plc (SHE-T) is responsible for financing and developing island grid links (Snodin, 2014). Prior to development approval is needed from the UK's central regulator for the electricity industry – Ofgem – for the costs involved in doing so (Snodin, 2014). Ofgem will grant an "allowed revenue" to SHE-T which it can then be certain it will receive (with conditions) once it has commissioned the grid link; this process of SHE-T applying for funding from Ofgem is called the "needs case" process and involves SHE-T submitting a fully costed and justified proposal (Snodin, 2014).

There are currently three proposed island links in SHE-T's portfolio (including to Lewis and Harris (MIDAS station 54) and Shetland (MIDAS station 9)), combined these projects are worth more than the company’s current total asset base (Scottish and Southern Energy Power Distribution, 2012; Snodin, 2014). From this it is easy to see that these projects presents a risk to SHE-T, with any cost overruns or reductions having a significant impact on their whole business.

When approving construction of island links it is in Ofgem’s remit to ensure SHE-Ts activities are adequately financed, and that it is acting in the interests of consumers (Snodin, 2014). With the risks attached to island connections it is questionable whether it is in the interest of consumers for SHE-T to take these risks that threaten the integrity of its business. In a report commissioned by the Scottish and UK governments Snodin (2014) considers that this separation of the party with the control (Ofgem) from the party required to manage the risks (SHE-T) is leading to major difficulties for island generators.

An additional problem with this set up, for the marine renewable industry, is developing a “needs case” can be complex and SHE-T may build up a case for several years (Snodin, 2014). Ofgem estimate once a “needs case” has been submitted and accepted as competent it can take 12-15 months to approve a scheme (Ofgem, 2013). Consequently the lead in time for island grid links is very long, and once this is combined with the actual construction time the process runs into a timeframe of several years. To quantify this, in 2009 Scottish and Southern Energy (SSE is the parent company of SHE-T) stated that it would take a minimum of four years to make the network upgrades necessary to accommodate any additional generation in Shetland, the Western Isles, Coll and Tiree, and Islay and Kintyre (The Scottish Government, 2010). It should be noted the situation in most of these areas has not changed greatly since 2009, so with the 12 months required by OFGEM five years for grid reinforcement and connections could be expected to integrate large scale marine developments in these areas; even if SSE had all the necessary funds available.

Due to the risks attached wind farm development in Lewis and Shetland at the scale modelled in this study is unlikely to occur until the regulatory process for grid development is complete and construction is underway. The two processes can’t happen in conjuncture as a grid link needs to be secured before a developer will commence construction, as otherwise there is no guaranteed market for the electricity.

As discussed grid strengthening has high costs attached. Consequently they are not currently a priority for the grid operators. Instead, cheaper electricity management strategies are being explored, such as demand side management (DSM) and Smart Grid initiatives. Früh (2014) explores and compares the benefits for energy security of these short-term temporal smoothing approaches and spatial smoothing (through extensive grid infrastructure). What this study adds is a method to calculate the benefits of upgrading the grid for the country as whole, in particular remote locations with high capital costs attached but high security of supply of value. This should assist with policy makers' decision making process, providing a more considered basis than just the investment costs of grid upgrades.

5. Discussion of non-resource considerations

When creating a strategy for onshore wind development there are factors to consider beyond resource. This section discusses some of the key elements to consider in Scotland, pertaining to the findings of Section 3.

5.1. Planning Considerations

There are a number of policies and plans at a national, regional and local level which deal with the planning of onshore wind developments. The National Planning Framework 3 (The Scottish Government, 2014a) considers Scottish development and investment over the next 20-30 years. The Framework is a statutory document and a statement of policy with a major aim of realising Scotland's renewable potential. The Scottish Government also sets out policy on the locations of wind farms in its Planning Policy (The Scottish Government, 2014b) which sets out that planning authorities should consider the merits of an individual proposal and that they will be carefully considered against the full range of environmental, community, and cumulative impacts. Local development plans created by local authorities also set out strategic local areas that can indicate specific sites that are suitable for wind farm development. When considering onshore wind applications the Scottish Government and local authorities do this by placing the applications into one of three main groups, these are summarised in Table 7.

Table 7. Planning categorisations for onshore wind development in Scotland. Reproduced from Scottish Government Scottish Planning Policy (The Scottish Government, 2014b).

There are two separate approval systems that control the development of onshore wind in Scotland. Both systems are applicable to the developments highlighted in this paper. The approval system that applies depends on the generating capacity of the proposed development. Proposals for large scale development with installed capacity in excess of 50 MW are considered and authorised by Scottish Ministers under provisions set out by Section 36 of the Electricity Act 1989 (UK Government, 1989). Proposals that lie below the 50 MW threshold are considered and consented by the relevant planning authority under the Town and County Planning (Scotland) Act 1997 (UK Government, 1997).

Sites included in this study vary in size and fall under both planning systems. There are a number of sites that would be considered under the planning categorisations found in Group 2 in Table 7. Development around MIDAS stations 48, 32 and 9 are located in areas with high concentrations of carbon rich soils and deep peat. Developments around MIDAS stations 113, 67, 38, and 32 would have faced more scrutiny against new wild land protection had they been built post 2014 (The Scottish Government, 2014b). The planning system evolves with time and will continue to shape the pattern of development across Scotland in the future.

5.1.1. Social Considerations

Social acceptability has an important role in the spatial planning of wind power. Planning decisions can become a focus of opposition, which can lead to problems in meeting renewable targets and the implementation of wind power. The rapid roll out of wind power in Scotland in an effort to meet climate change targets has seen growing disquiet about the cumulative effects on landscapes (Cowell, 2007).

Whilst all wind developments have a social backdrop, there are a number of sites in this study that should be considered in a greater social context. Whilst local opposition is present, the Shetland wind farm (station 9) offers continued socioeconomic benefit in an area where the oil and gas industry’s influence will diminish. The high concentration of wind farm developments in the Highlands and south Scotland, as shown in Figure 2, is of interest as these areas show the lowest support for wind development in Scotland, although there is still a majority who support developments (STV, 2015). A YouGov poll showed 64% those surveyed in south Scotland and 66% in Highland supported wind development – compared to 71% in Scotland as a whole (STV, 2015).

5.2. Environmental considerations

Environmental impacts are often associated with wind energy development. This paper does not seek to integrate such factors into the analysis. Instead, development areas are briefly examined as case studies; to highlight the importance of considering these factors in future studies. For example, an understanding of where wind potential is saturated (such as in areas like that surrounding station 982) and where is most appropriate for new development would allow conservationists, regulators and developers to work together to find the most sustainable solution. This may include combining wind-smoothing, environmental monitoring and post-construction data to inform future development. Following a national plan of wind-smoothing may also allow for the potential to assess cumulative impacts at regional and national scales.

5.2.1. Avian impacts

It has been suggested that among the environmental consequences of developing wind farms is an adverse impact on birds (Wang et al., 2015). The Shetland, represented by station 9, have been highlighted as the most valuable area for future development in terms of smoothing; however, thought should be given to the ornithological significance of Shetland. Shetland is known to host 95% of the UK breeding population of whimbrel (*Numenius phaeopus*) (Massey et al., 2016; Richardson, 1990), a wading bird, which caused contention in previous wind farm planning proceedings (Caine, 2015; Woolley, 2015) and a vital consideration for any future development. Additionally, some of the smaller Shetland isles host internationally important assemblages of breeding seabirds (Mitchell et al., 2004). Whilst potential adverse impacts on these colonies and species should be thoroughly quantified and minimised, consideration should also be given to the economic revenue these colonies generate for Shetland and understanding how this value may be affected by renewable energy developments would warrant investigation; particularly if wind development in Shetland were to progresses beyond that considered in this study.

The Isle of Lewis, represented by station 54, was also shown as a promising location for further development and indeed plans for a 36 turbine wind farm are under review. Lewis has a high density of breeding golden eagles (*Aquila chrysaetos*) (Eaton et al., 2007) and there is evidence to suggest that golden eagles are vulnerable to both displacement and collision effects (Smallwood and Thelander, 2008; Walker et al., 2005). Efforts to quantify golden eagle behaviour in relation to wind farms in Scotland noted shifts in the ranging behaviour of eagles that were consistent with avoidance of the wind farm (Walker et al., 2005). Potential impacts of future renewable energy developments on golden eagles in Scotland should be considered within the context of other known constraints on populations; namely persecution (Whitfield et al., 2004a, 2004b) and the potential for populations to remain viable in the face of potential additional mortality.

Overall, at the planning or scoping stage of development, from an avian conservation perspective, a number of useful tools exist for planners and developers, most notably sensitivity maps produced by conservation agencies (Bright et al., 2006); and more recently there has been a movement towards conservation charities proactively suggesting areas for renewable development (RSPB, 2016).Whilst such tools do not negate the need for pre-construction surveys they offer locational guidance with a view to minimise potential conflicts and maximise resources, and can be regarded as a preliminary step in mitigation strategy.

5.2.2. Flora

Windfarm developments necessitate the installation of certain infrastructure that will affect the quality of the habitat that remains. Estimates of directly impacted land for windfarms have been calculated at between 0.2 and 0.5 hectares/MW of power generation, with access roads for maintenance accounting for 79% of this space (Denholm et al., 2009). Flora will permanently be excluded from these areas, with alterations to drainage and nutrient availability resulting for the surrounding areas. The turbines themselves have the potential to cause changes in microclimate, altering the ecosystem around the base of the turbines (Armstrong et al., 2014). The sensitivity of plant species varies, so increases or decreases in moisture, nutrient availability, and temperature, may cumulatively have a positive or negative effect for two different species that presently coexist in the same habitat.

With respect to two of the sites that could benefit smoothing of wind energy the most, the Shetland Islands, station 9, and the Isle of Lewis, station 54, host a number of endemic and rare species. The Shetland Islands are home to four threatened species, including Unst's endemic Cerastium nigrescens (H.C.Watson) Edmonston ex Watson, the 'Shetland Mouse-ear', and seven Sites of Special Scientific Interest (SSSIs). The Isles of Lewis and Harris are home to one threatened subspecies, *Euphrasia officinalis* (L.) ssp. *anglica* (Pugsley) Silverside, English Eyebright, four SSSIs, and five important plant areas (IPA), and large areas of machair grassland (Plantlife, 2017). Other sites on the mainland that are home to fragile ecosystems include those around Dunstaffnage, station 918, and the Mull of Kintyre, around station 908. These correspond with areas that include epiphyte rich temperate rainforests (Ellis et al., 2015) already threatened by climate change (Ellis and Eaton, 2016). Development across any of these sites will need to be sensitive to the needs of the flora found there, and the ecosystem services they provide in terms of food, breeding grounds, and hunting grounds for the fauna of the region.

5.2.3. Water quality

A further environmental consideration with onshore wind is the potential to impact upon stream water quality within catchments, where turbine construction occurs (Waldron et al., 2009). Although generally, these impacts have been mostly found to be associated with the felling or mulching of conifer plantations (Smith, 2015), which often are present in areas chosen for windfarm development. A study investigating impacts of Whitelee Windfarm (modelled using station 982) found increased stream phosphorus concentrations and export following clear felling of trees for subsequent habitat restoration, as part of the habitat management plan for the windfarm (Murray, 2012). As peat has a poor retention for phosphorus (Asam et al., 2012), it is easily leached to downstream watercourses (Rodgers et al., 2010). However, with appropriate controls such as felling small percentages of catchments (< 30%), impacts of nutrient enrichment on stream ecology can be minimised (Palviainen et al., 2014). Additionally windfarm construction has been associated with increased suspended sediment in streams (Grieve and Gilvear, 2008), although mitigation measures such as the use of drain blocking and settling ponds can prevent impacts on suspended solids (Murray, 2012).

As peat and conifer decomposition produces dissolved organic matter in watercourses, there is concern for increased carbon losses from peatland systems which may be otherwise acting as net carbon sinks (Waldron et al., 2009). To date, increased carbon losses associated with windfarm construction have been found by some (Grieve and Gilvear, 2008), although others have not found increased in losses of aquatic carbon (Murray, 2012; Smith, 2015). However, increased dissolved organic concentrations associated with windfarm disturbance and felling (Muller et al., 2015; Murray, 2012) are problematic where catchments used for drinking water due to increased risk of forming toxic by-products during the water treatment process (Ritson et al., 2014).

Although water quality monitoring is often included in the environmental statement new windfarm developments in place in Scotland, there are often site specific impacts of construction or felling e.g. increased Aluminium in streams flowing into salmon fishing rivers (Gaffney, 2016). It is therefore important to consider water quality on an individual windfarm basis and take into account important factors such as soil type and depth, percentage of catchment felled, which can be important predictors of water quality impacts (Gaffney, 2016; Murray, 2012; Smith, 2015), as well as the key ecosystem services of the catchment.

6. Conclusions and policy implications

An overarching strategic approach to wind development, in terms of energy security, has not been historically exercised in Scotland. This is a consequence of developers driving where wind farms are built. The lack of incentive means developers favour areas where installation cost are lower due to better infrastructure, hence the bias towards developments in the south of Scotland. Figure 1 suggests this bias is set to continue, with the vast majority of wind farms in application or scoping being in southern Scotland, in close proximity to the wind farms modelled by the Charterhall, West Freugh, Eskdalemuir and Salsburgh MIDAS stations. The findings of this study shows that further development in these areas is of limited value, unless infrastructure and markets allow for increased export. If the Scottish wind portfolio is considered in isolation these areas offer little in terms of energy security, having highly correlated generation patterns.

The study identifies the wind farms modelled using the Lerwick, Machrihanish and Stornoway Airport MIDAS stations to be of most value for security of supply. Additional deployment around the Kinbrace Hatchery, Loch Glascarnoch, Lossiemouth, Dyce and Wick Airport MIDAS station areas also shows some security of supply value; i.e. they show a lower correlation to Scotland's overall wind fleet and raise the occurrence of high capacity factor generation. However, in some of these areas development may increase or be of little benefit in reducing standard deviations of generation. Modelling additional generation to better account for within area spatial smoothing is seen as a priority for assessing the value of further development in these areas.

Development of wind power in Shetland (modelled using Lerwick, station number 9) is shown to be particularly high value. This raises issues concerning grid connection, as currently Shetland is not connected to mainland Scotland. There are also similar issues for the Isle of Lewis (modelled using Stornoway Airport, station number 54), where there is very limited grid connection to the mainland. The issue of grid connection in Scotland is already an area of discourse in the political arena (Snodin, 2014; UK Government, 2016). This study helps identify the value greater island grid connection has to the Scottish electricity system as a whole; and should be considered in this political discourse.

These island areas are among those highlighted in Section 5.2 as being environmentally sensitive. Incorporating information such as environmental and societal factors into this energy security based analysis is an important area for future research, further contributing to a more proactive siting approach to onshore wind in Scotland.

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