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The influence of the North Atlantic Oscillation on diverse renewable generation in Scotland

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HIGHLIGHTS

- Strongly positive correlation in October–March between NAO and renewable generation.
- In the highest energy months a positive NAO index increases renewable variability.
- High-energy positive NAO conditions leads to increased wave device cut-outs.

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ABSTRACT

The North Atlantic Oscillation (NAO) is an index measure of the pressure gradient between Iceland and Portugal, with the pressure gradient affecting the strength and track of storms across the North Atlantic and into Europe. This has implications for renewable generation, which are becoming increasingly important with higher renewable penetrations. To explore the impact of the NAO on renewables a hindcast of wave, onshore and offshore wind generation in Scotland was created for the most recent climate normal period (1981–2010).

These hindcast generation figures were compared to NAO monthly index values and showed a strong and significant positive correlation for the high energy portion of the year (October to March). The strength of this relationship is in some instances, most notably for wave generation, weakened by the higher energy positive NAO conditions causing increased device cut-out. The impact of the NAO was also modelled at a seasonal winter scale (December–March) as is usual in NAO analysis. The model showed the strongest influence on capacity factor for offshore wind, with each increase in NAO index of 1 causing a predicted increase of capacity factor of 3.17 (compared to 2.59 for onshore wind, 1.35 for wave, and 2.49 for the combined portfolio). In January and February, the NAO has a statistically significant impact on hindcast generation variability, at a 1–4 h time scale for all resources and 1–24 h timescale for onshore wind and wave, which will have implications for system management.

1. Introduction

Scotland's renewable energy potential allowed the Scottish Government in 2011 to set their ambitious renewable electricity target of generating the equivalent to 100% of Scotland's electricity demand from renewable sources by 2020 [1]. The word equivalent means not all the renewable electricity generated in Scotland will be used there. Therefore, whilst the target is a step forward in terms of renewable penetration it still means fossil fuels will be in the electricity mix. Full reliance on renewable generation for an electricity system is not seen as tenable or desirable by the Scottish Government, due to variability in renewable generation threatening security of supply. This variability can lead to large inter-annual changes in renewable generation, for example in 2010 the annual capacity factor for onshore wind power in the UK was 21.8% whilst in 2013 it was 28.8% [2].

1.1. The North Atlantic Oscillation

Large climate patterns can drive variation in renewable output on inter-annual scales. The strongest of these in the Northern Hemisphere is the North Atlantic Oscillation (NAO) [3]; which is the primary source of variability for the North Atlantic climate on annual to multi-decadal

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timescales [4–6]. Historically the NAO is defined as an index that measures the difference in surface pressure between Ponta Delgada in the Azores and Stykkisholmur in Iceland [7]; changes in this pressure gradient result in a shift in wind patterns [8]. With a particular correspondence between elevated values of the NAO and strong westerly winds [9]. NAO variations cause significant shifts of air-sea exchanges of heat [10], freshwater [11] and the track of storms and depressions across the North Atlantic Ocean and into Europe [7]. The storm track varies from winter to winter in both its strength and position. A particularly recurrent variation is for the storm track to be either strong with a north-eastward orientation taking depressions into NW Europe (a high NAO winter) [7,12]. Or weaker with an east-west orientation taking depressions into Mediterranean Europe (a low NAO winter) [7,12]; the former resulting in stormier conditions in Scotland, and the latter calmer conditions. Associated with these changes in weather conditions are altering generation levels from weather dependent renewable developments, such as wind farms, having implications for electricity system performance and security of supply.

A study by Curtis et al. [13] found the NAO to have a significant impact on monthly mean wind speeds, wind power output, and consequently carbon dioxide emissions from the entire Irish electricity system. The NAO impact on emissions depended on the level of wind penetration within an electricity system, but the study indicates emissions intensity within the Irish electricity system could vary by as much as 10% depending on the NAO phase within the next few years [13]. Scotland's renewable targets are more ambitious than Ireland's making improved understanding of the potential impacts of the NAO a pertinent issue.

Earl et al. [14] note recent wind industry discussion of the low-wind year of 2010 (which was strongly affected by a very negative NAO) requires further supporting analysis and discussion of the wider context of the NAO. Ely et al. [15] also argue it is important to understand the impact of the NAO on European electricity systems. Recent research by [16] corroborates the impact of the NAO on wind patterns in Scotland. With low-pressure systems between Greenland and Scotland being steered by stronger sea level pressure, occurring during positive phases of the NAO and causing the W-SW winds rise around 60 °N [16].

1.2. Study scope

This study seeks to increase the understanding of the significance of the NAO in the context of a renewable electricity system; going beyond establishing long term links between the NAO and energy influx or examination of one of extreme events (such as the winter of 2009/2010). This is particularly important given recent changes in the NAO, including increased winter variability, observed in recent studies [17]. Scottish renewables are an informative context in which to pursue this increased understanding, due to strong government targets for renewables and, associated with this, large levels of built, consented or leased areas of renewable development. In previous studies focusing on electricity generation and the NAO in northern Europe onshore wind has the resource predominantly explored [13–15,18,19]. In addition to onshore wind this study also examines offshore wind and wave power. Scotland has been a pioneer in this latter and immature technology since Salter's Duck in the 1970s, through to the establishment of the European Marine Energy Centre (EMEC) in 2003, to the world's first commercial scale leases for wave developments in 2010. A recent study notes that since the NAO exhibits considerable inter-annual variability, it is important that this variability is captured by any wave resource assessment in Scotland [20]. Given the current immature state of the industry this variability has only been explored in terms of generating technology on one occasion [21], this study seeks to expand this knowledge base.

Initially this study seeks to examine the relationship between and quantify the impacts of the NAO on renewable generation, on monthly and seasonal scales. There are studies examining onshore wind in this context, however, we are unaware of studies examining a mixed portfolio such as is done here. Of particular novelty is the inclusion of wave power, whilst other studies have examined links between raw wave characteristics and the NAO (e.g. [22]) this study takes the novel step of applying power matrices for wave technologies which have seen extensive sea trials – to give a better indicator of actual device performance. A further novelty is the wave power modelled is for areas and capacity leased for wave development. Similarly, for onshore and offshore wind only existing, consented or leased wind farms are modelled, further details are provided in Section 2. Consequently, it is possible gain a novel insight into what renewable generation might look like in the next decade in Scotland.

This study also explores the relationship between the NAO and short-term variability of renewable generation (at 1, 4, 12 and 24 h time scale). Understanding these short-term fluctuations is important in designing sustainable energy systems, in order to account for factors such as reserve capacity and ramp up flexibility. Ramping events are recognised as one of the most problematic issues for network operators to manage [23], however, the short term variability which often causes them is underexplored in the context of the NAO. Only one recently published study explores this (for onshore wind in Ireland, which has a lower capacity than Scotland) [23], the greater renewable capacity and diversity modelled within this study aims to improve the understanding of this relationship in a wider renewable context.

A further novelty examined in this study is the relationship between the NAO and renewable shutdown due to high-energy conditions. Whilst it is generally recognised that there is an increase in energy availability in northern latitudes with a positive NAO index, there are not studies questioning whether this additional available energy can be effectively exploited. With new and emerging technologies, like wave harvesters, it is important to establish how effectively devices will function in high energy conditions associated with positive NAO conditions. This is not only for system operators but also device developers and generators, as if devices are unable to function in high energy conditions it can lead to a loss of income. In general, the impact of the NAO on the economics of renewable generation is not well understood [24], to improve this understanding the relationships modelled between the NAO and generation are contextualised in impact upon income.

2. Methodology and study data

Much of Scotland's potential renewable capacity is yet to be built. In order to characterise how such a renewable portfolio would perform hindcasting was utilised; taking historic wind and wave conditions to infer generation for existing and future potential renewable capacity. Data from a 30 year time series (1981–2010) was used in this study, as the World Meteorological Organisation classify this as the most recent climate normal period [25].

2.1. Onshore wind

To hindcast onshore wind, measured wind speeds are preferred to modelled datasets in the UK; e.g. [26–28]. There are two main reasons behind this, Sharpe et al. [29] observe that alternative satellite reanalysis datasets do not perform as well in high wind speed environments in the UK. Secondly, Dragoon [30] notes weather models are more highly correlated in space than actual wind speeds. Given the complex terrain of Scotland could be a potentially major issue, particularly in examining the links between variability of output and the NAO on a fine temporal scale.

2.1.1. 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 [31]. This data archive uses measurements