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Breakdown of British Wind Curtailment using a Multi-Source Knowledge Graph Approach

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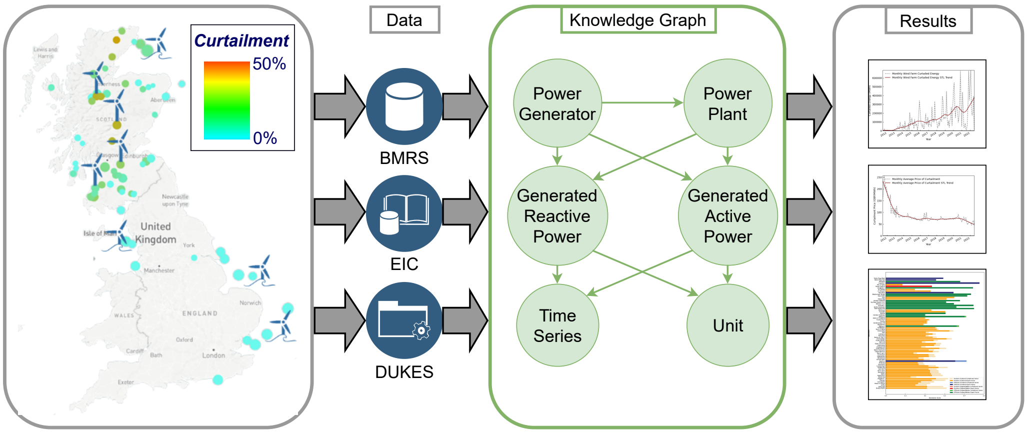
Abstract

Britain's mass adoption of wind generation technology has placed an increasing emphasis on understanding the nature and causes of associated energy losses due to curtailment. Previous investigations highlight cost structures (e.g. subsidies, fees, certificates) and transmission constraints to be curtailment's two leading causes, while also suggesting grid expansions may alter their influences. This paper settles these questions with a multi-source review and data-driven analysis into Britain's curtailment on a national, cost, and site specific basis. In particular, onshore and offshore wind farm sites from England and Scotland have their output and curtailment levels compared. Geospatial analysis concludes that despite significant energy grid expansions, transmission constraints are the primary cause of wind energy curtailment.



Highlights

- Analysis of British curtailment levels and costs.
- Geospatial breakdown of curtailment levels.
- Knowledge graph approach for multi-source data integration.

Contents

1 Introduction

Under its current pledge the UK government is committed to reduce emissions by 57% by 2032, and 80% by 2050. A key pillar in achieving this goal has been an expansion of renewables, particularly onshore and offshore wind energy generation. Future scenario estimates advise that the growth of wind generation seen over the past decade is expected to continue [22]. This transition has been paired with a variety of unique technical, economic, and policy challenges for onshore and offshore wind [3, 49].

Over the next 5 to 10 years base case scenarios from DUKES forecast a growth of both onshore and offshore wind energy generation in the UK [22]. Heriot-Watt University notes a 5x offshore capacity growth over the next decade [49]. Furthermore, the International Energy Agency predicts not only continued growth, but an increase in the wind installation growth rate worldwide [36]. This is consistent with historic trends from databases such as BMRS and DUKES (graphed in Figure 1) [8, 23]. In Figure 1 the growth of wind energy in the UK can be seen, particularly of offshore wind in recent years. Decarbonisation from renewables, however, requires fossil fuel use is displaced. This displacement cannot occur with energy that is curtailed, rather than making it to the consumer. Understanding curtailment is of significance to the UK and other global investors in variable renewable energy (VRE).

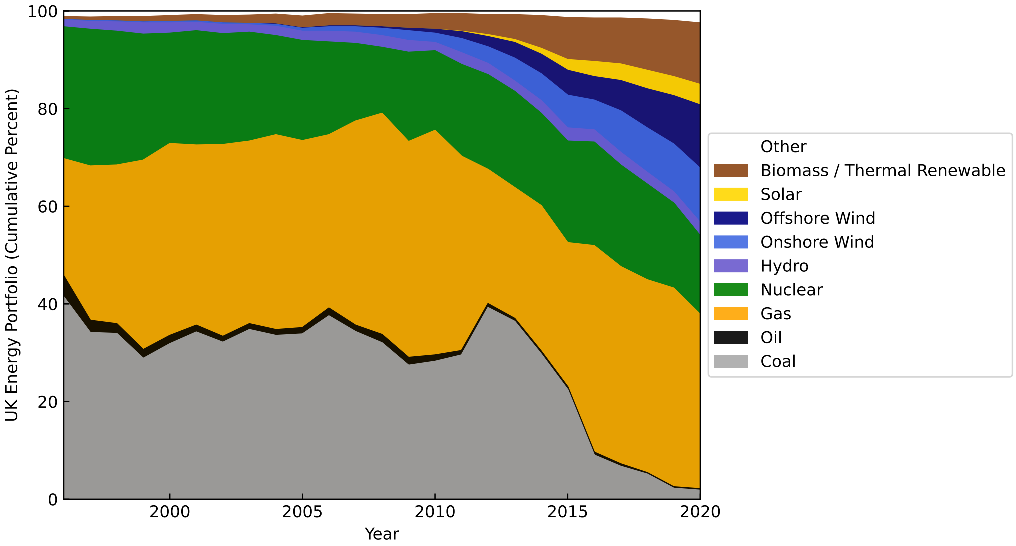


Figure 1: *Proportional generation type of energy (electricity), in the UK.*

Curtailment may occur due to a mismatch between supply and demand, network strength / stability concerns, or capacity constraints of transmission and distribution networks. As variable renewable energy penetration increases, so too will curtailment if compensation measures are not taken [29, 47, 62, 63]. These measures include complementary & rapidly dispatchable (peaking / fast ramping) generators, storage, and grid network improvements.

Presently, dispatchable technologies (such as gas in the UK) exist to resolve supply-demand imbalances, however further wind energy deployment has long been regarded as requiring expansions of storage and grid infrastructure [5, 65]. If theoretical alternatives such as rapidly ramping small modular nuclear reactors were sought, then Scottish anti-nuclear policy may impose additional transmission circumstances (this paper's investigation determining Scotland to be subject to significant existing transmission constraints) [43, 46, 75]. Storage may be expanded using battery, hydrogen, and/or hydro storage solutions. Specific investigations have been made into these respective fields.

Battery storage, including the scheduling of those in electric vehicles has been considered in the context of Great Britain, though these are subject to transmission and distribution constraints which may have themselves been the cause of curtailment [2, 13, 27]. On-site storage is therefore also considered [14]. Hydrogen storage has also been analysed as a potential solution for the UK as a cost-feasible solution, though the placement of facilities should carefully consider the aforementioned grid constraints, such as those faced by electric vehicle scheduling [77, 78]. Finally, long term storage (such as location dependant hydro-storage) is recommended at significant volumes as non-dispatchable renewable penetration continues to increase [64].

Given that many of these solutions are reliant on transmission and distribution, ongoing geospatial wind energy curtailment analyses are significant not only to transmission inquiries directly, but also to the complementary generation and storage measures the grid supports (or would be expected to support). Numerous countries, including the UK, have sought to expand transmission infrastructure to increase their network capabilities [52]. In addition, increased network integration, management, and improved prediction of renewable and demand levels have also been pursued [20, 37, 41, 53, 55, 72].

Alongside transmission constraints, renewable energy subsidy costs are also noted as a cause of wind energy curtailment [40]. These costs differ for onshore and offshore wind farms, however, while onshore wind capacity is overwhelmingly installed in Scotland, offshore wind capacity is disproportionately installed off the English and Welsh coast. As transmission constraints drive a north / south curtailment divide, these sources of curtailment are complementary.

Existing analysis notes transmission constraints and the structure of subsidies as the leading causes of curtailment, however the dominant cause remains unidentified [40]. With access to new data from major offshore Scottish wind farms, this paper compares the expected impacts of these causes to determine which is dominant. This is performed as part of a broader investigation into British wind energy curtailment.

An 'arms race' between the expansion of renewable and transmission infrastructure renders curtailment investigation a moving target. Mapping numerous data sources facilitates more sophisticated investigations into the energy landscape [69]. Using knowledge graph technology to facilitate a multi-source analysis, the current state of these dual expansions will be analysed and it shall be determined whether transmission constraints or the structure of subsidies are the dominant cause of wind energy curtailment. The purpose of this paper, therefore, is to quantify the current and changing state of wind energy curtailment in Britain and therein determine if transmission constraints or subsidy costs are the leading cause of where they are incurred (region, onshore vs offshore).

Analysis will specifically be performed with respect to:

- Curtailment volumes;
- Curtailment costs;
- Onshore vs Offshore wind farms (generation type), and,
- Geospatial (transmission constrained) curtailment distinctions.

This will permit an updated outlook on British wind energy, and wind energy curtailment. New insights into unsettled and emerging trends will be discussed. This paper's methodology, as well as its insights, should serve to guide planned expansion and ongoing research in the British energy transition.

2 UK Curtailment and Transmission Overview

As global wind penetration levels increase, associated curtailment has been of increasing interest. National and comparative studies exist for the United States [67], China (quite extensively) [16, 17, 39, 44, 45, 57, 70, 76], and Europe [4]. Given the prevalence of wind power generation in Europe, curtailment costs and transmission constraints have been core focuses of existing literature [15, 21, 30, 48, 50]. Among multi-national studies, the following two are of note, due to their British data [28, 79].

An extensive 2018 review of wind curtailment in Britain (analysing data up to 2016) summarises the state of British wind energy curtailment with a focus on balancing costs and mechanisms [40]. In more recent years, given the expansion of wind generation, curtailment volumes 2-3 times higher are prevalent [58, 59]. Note that this persists in 2021 and the months of 2022 examined at the time of writing, and is not exclusive to the potential outlier year of 2020 (owing to lock-downs and other macro influences on demand, though the wind load factor was at an all time high) [26, 71].

2.1 Curtailment Volumes and Data

In terms of curtailment as a percentage of wind energy generation, this growth is less extreme (with % wind energy curtailed either slowly growing or remaining consistent) [40, 74]. Differences between sources (deriving from both curtailment and notably, generation figures), however, are significant in their own right. These are calculated as per:

$$\text{Curtailments}_{\%} = \frac{\text{Curtailments}_{\text{MWh}}}{\text{Curtailments}_{\text{MWh}} + \text{Exports}_{\text{MWh}}} \tag{1}$$

Where:

$$\text{Generation}_{\%} = \text{Curtailments}_{\text{MWh}} + \text{Exports}_{\text{MWh}} \tag{2}$$

Table 1: *British Annual Wind Energy Curtailment (% of total wind energy generated). As per Imperial College London (ICL) [40], Wind Europe [74], Kyoto University [79], and the University of Strathclyde [28]. Note that data is not provided or obtained for all years from all sources/papers.*

Year	ICL	Wind Europe	Kyoto	Strathclyde
2012	0.44	0.4		
2013	2.39	2		
2014	3.58	3.1	2	2.8
2015	5.68		0.7	4.2
2016	5.64		2.9	4
2017			2.9	4
2018			2.6	3.9
2019			3	
2020			4.2	

Table 1 displays such a comparison for curtailment, in volume and percentage terms. Even where differences in curtailment volumes (TWh) are similar, greater differences can be found between the curtailment percentages (being the result of differing generation datasets used). These metrics, including percentage curtailment metrics, while subject to the differences of the data used to calculate them, are still extremely useful in analysing curtailment during a period of mass wind generation expansion. A year-on-year comparison within a percentage curtailment timeseries, for example, would provide such an insight.

This primarily explains Kyoto University's lower curtailment % due to their higher generation results (seen in Table 4), which fall more in line by those of DUKES [25]. By comparison, the summed generation from individual BMRS reported sites is lower [8]. Further comparison on wind curtailment and generation differences is discussed in Appendix A.1. This difference in methodology for calculating annual wind generation also explains why curtailment results from the remaining sources (and this paper) are broadly more consistent (as they use wind generation from more selective ranges of wind farms for which curtailment data is also available).

As different curtailment figures may be obtained due to differences in base data and methodology, a robust mapping process is greatly beneficial. Many sites may have multiple generators or expansions under different labels. Using a process to keep track of various identifiers (IDs) for plants, stations, or generators is therefore a key focus of power plant data management. The Power Station Dictionary, for example, maintains a record which maps between various IDs from different data sets [69]. A data mapping approach will also be required by this project to associate station names with energy identification codes (as some sources use one or the other) [6–10, 24, 60].

2.2 Curtailment Costs

Due to the historically higher onshore wind rates of curtailment, the average cost of curtailment has been dominated by the costs of these curtailments. Where this data was first available in 2012, onshore wind curtailment costs exceeded those of offshore curtailment, but this has since inverted. Over the past decade, onshore average curtailment costs have experienced periods of decline and consistency, while offshore wind curtailment subsidy costs have steadily increased [61]. As a result offshore wind curtailment subsidy costs are now greater than those of onshore farms [60, 61]. From a policy standpoint, for wind farms participating in the balancing mechanism 2 Renewables Obligation Certificates are granted per MWh for offshore wind energy curtailment as opposed to 0.9 for onshore curtailments, with the former therefore demanding higher compensation and thus being less likely to be curtailed [40].

The combination of these overlapping practical and policy factors is a disincentive from curtailing offshore wind energy. Differing subsidy costs are therefore a potential explanation of the aforementioned trend of increased onshore curtailment. This incentive further aligns with a concentration of onshore wind in Scotland (and offshore off the coast of England), resulting in increased transmission constraints on onshore Scottish wind farms. In recent years, however, large-scale offshore wind expansions has been deployed off the Scottish coast, providing data for a more direct comparison of transmission constraints independent of differing price incentives (by comparing offshore Scottish and English site curtailments).

2.3 Transmission Network Expansion

Scottish wind farms have consistently faced higher rates of curtailment than their southern peers. These concerns have been significant enough as to motivate on-site battery attachment investigations for Scottish wind farms as to lower reliance on the transmission network at a single point in time [14]. As mentioned above, this is due to a combination of greater curtailment costs for (disproportionately southern) offshore wind farms, along with increased transmission difficulties directing Scottish energy to English loads. Expansions in grid infrastructure have been expected to lower associated constraint costs [40], warranting a review of the energy network and its expansions.

In 2012 the University of Edinburgh (using data from the University of Strathclyde) released a 29 bus model of the UK grid [73]. This model has been used as a basis for modelling the British transmission network [13], as this paper will also briefly verify. The combined Scottish-to-English line transmission capacity noted in this model sums to 8,880 MW. Since the creation of this model, and the prior discussed British curtailment investigations, however, the Western High Voltage Direct Current (HVDC) Link has been rolled out.

Connecting Scotland to England/Wales this cable adds an additional 2,250 MW of transmission capacity (an approximately 25% increase). As it was rolled out incrementally from 2017 to 2019 (following which was the outlier year of 2020), it is difficult to pinpoint an exact impact from this installation against the ongoing wind generation expansion of this same period. With respect to the above expectation [40] of infrastructure expansions being expected to result in lower curtailment costs, this paper will, however, broadly investigate the changes in these costs. While net curtailment costs have increased, costs per MWh have declined (predominantly driven by Scottish onshore wind curtailment cost reduction given the trend of offshore curtailment costs increasing per MWh [60, 61]). At present, Scottish wind capacity remains in 'substantial excess' of cross-border transmission capacity despite grid reinforcement [19, 33]. Finally, at the time of writing, an Eastern HVDC Link (2,000 MW capacity) is also planned and conditionally approved [66].

3 Methodology

Multi-source geospatial renewable studies [38] allow for both a greater volume of data to be used, as well as compared. Given the significance of differing input data sources when calculating British curtailment (Table 1), this approach will be of particular importance. In this paper, curtailment data from Balancing Mechanism Reporting Service (BMRS) market ([7]) and export ([11]) data is used to calculate curtailments (in net and percentage terms). Information from the Renewable Energy Foundation (REF) on an aggregate ([58, 59]) and site specific [60] level (for comparison with BMRS data) is also used. To enable the geospatial mapping of this information, internal, Digest of UK Energy Statistics (DUKES), and Energy Identification Code (EIC) data is also used as described below (Mapping and Ontology 3.1).

3.1 Mapping and Ontology

A mapping process was performed using a knowledge graph system. Ontologies can be used for energy and utilities system modelling [12, 32, 35, 42]. By facilitating the interconnection of concepts they may assist with standardising information across (potentially inconsistent) databases [31, 54].

Data mapping was required between BMRS and DUKES to expand the data available for use in this study [6–9].

Firstly, there should be a connection made between power plants and their power generators. This connection may be established using both the naming convention, as well as (ideally) explicit definitions from the EIC database, while manual review may also be performed.

Secondly, there should be an association made (where possible) between DUKES and BMRS entries [10, 24]. An intermediary EIC database was used to assist this process as it contained both name (not identical to DUKES) and EIC data [51]. With this performed a script was run to attempt mapping using the name, capacity, year, and technology type of power plants.

Finally, to obtain the types of the marginal seller, the type of a noted generator could be checked directly (as well as its power plant / station), but BMRS data did not always note a type (for power generators or their assigned power plants). In these cases the DUKES type (where mapped) could also be used (or used for verification).

This was performed using a knowledge graph approach, employing the structure visualised in Figure 2.

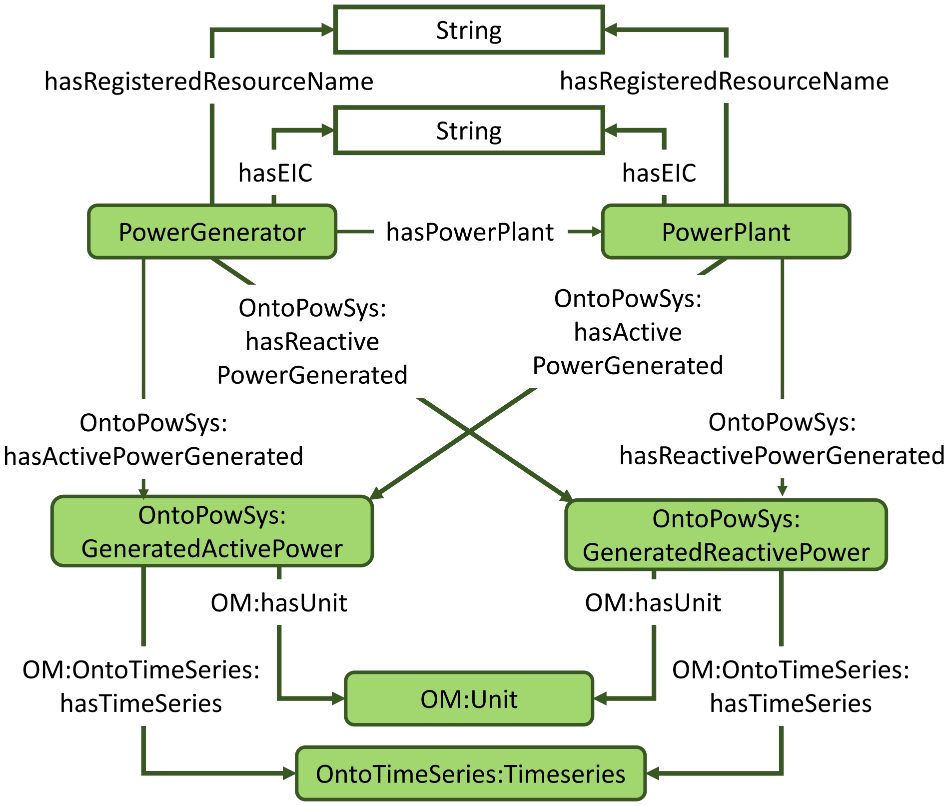


Figure 2: *Visual representation of ontology structure for power plant and power generator labelling.*

3.2 Trend Identification

While the Mapping and Ontology 3.1 methodology is used for individual site data, aggregate data from REF ([58, 59]) is also used to create various nationally aggregated figures (in conjunction with BMRS data [8]). For these, trends are required to assist in the readability and understanding of results. The Seasonal-Trend decomposition using LOESS (STL) method is a tested and commonly used methodology for trend identification, de-noising, and prediction [18, 56].

This study uses the Python 'Statsmodels' Library to perform STL decompositions for the purposes of trend identification [34, 68]. These decompositions will be shown alongside their base data in relevant trends, while their decompositions are provided in Appendix A.3. By using this methodology a greater understanding of curtailment on a national level may be understood before investigation continues on a site specific basis.

3.3 Transmission Network Formulation

Section 2.3 estimated the transmission network's expansion with respect to overland powerline capacity and the undersea cable capacity of the Western HVDC link. Specifications for this model are provided by the University of Edinburgh (using data from the University of Strathclyde) [73]. This model simplifies the British transmission network into a number of nodes (buses) connected by lines (branches). The specific geographic coordinates used for the buses in this model were estimated in Appendix A.2 by the location of physical infrastructure. Power generators were then clustered to nearby buses using their centroid coordinates.

While this paper predominantly focuses on curtailment on a site specific, or national level, the integration and visualisation of the transmission network model will serve as meaningful starting point in the discussion of British transmission constraints.

4 Results and Analysis

Results are discussed on both a national, and individual wind farm basis.

4.1 Transmission Network Verification

Firstly, the transmission network model discussed in Section 2.3 will be verified, as per the methodology discussed in Section 3.3.

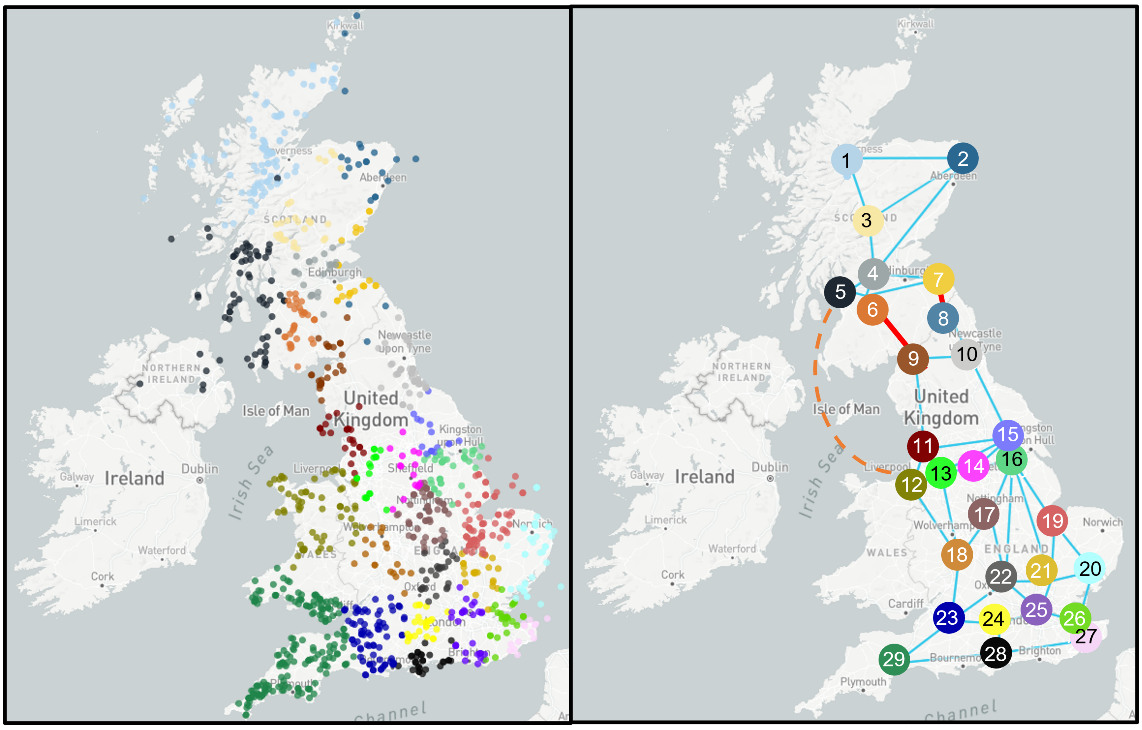


Figure 3: *29 Bus model of Britain's energy grid.*
Left: Generators colour coded by their clustered buses.
Right: Colour coded buses and connecting branches. Scottish-to-English lines (branches) are highlighted in red (6 to 9, and 7 to 8 - with a combined 8,880 MW transmission capacity). Finally, the 2,250 MW transmission capacity Western HVDC Link is displayed as a dashed orange line.

Figure 3 displays the 29 bus transmission grid model of Britain. This model's geographic breakdown of the British transmission network appears to be sensible, with generators locations also appearing to be reasonable. The prior discussed approximate 25% expansion in transmission capacity provided by the Western HVDC link (2,250 MW in addition to the prior 8,880 MW) should be considered with respect to the further discussion of wind farm curtailment; in particular in regards to the expansion of wind generation infrastructure.

4.2 National Curtailment Profile

Data from the Renewable Energy Foundation regarding wind farm curtailments in Britain was used to create Figures 4, 5, 6 and 7 [58, 59]. STL decompositions were also performed to provide trend lines for readability. Figure 7 also uses export data from BMRS [8, 9].

Total curtailment and cost levels are graphed in Figures 4, and 5.

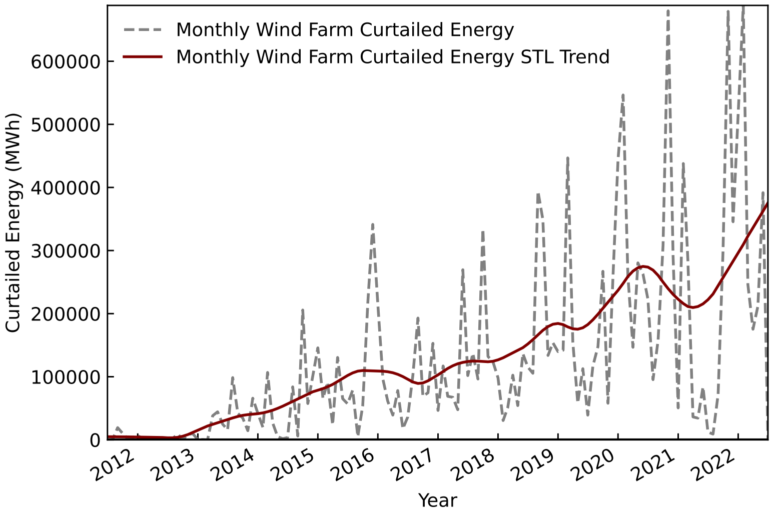


Figure 4: *Monthly energy curtailments from British wind farms.*

In Figure 4 a considerable upwards trend may be observed in wind energy curtailment volumes. While the year of 2020 was abnormally high, with a subsequent drop in 2021, 2022 levels are at an all time high.

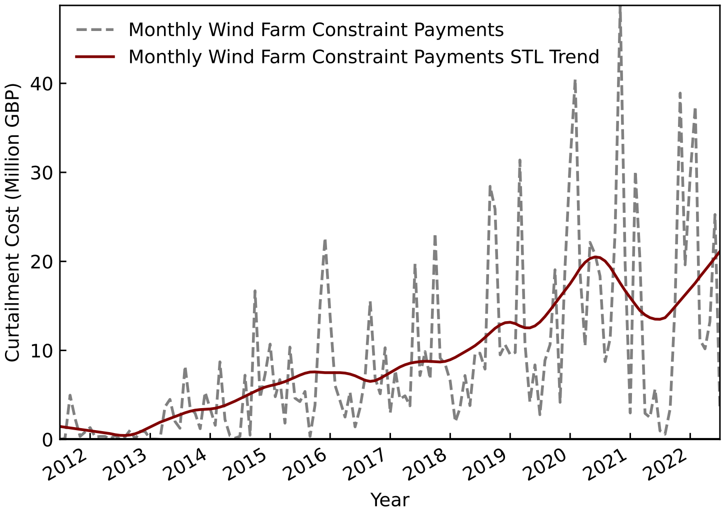


Figure 5: *Monthly constraint payments for energy curtailments from British wind farms.*

Figure 5 displays curtailment costs. This also displays an upwards trend, though it is not as steep as that of curtailment volumes in Figure 4. An abnormally high 2020 level is also observed, which is similar to that seen in 2022.

Given the backdrop of expanding wind energy generation curtailment and cost levels on a per MWh basis are shown in Figures 6, and 7.

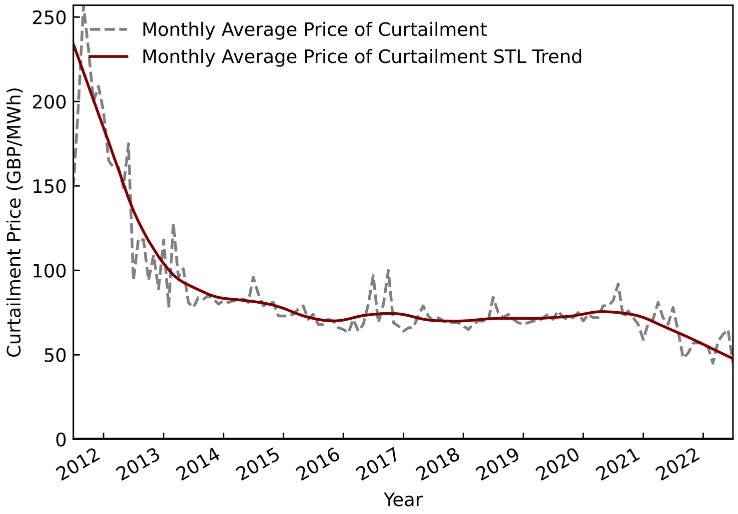


Figure 6: *Monthly average cost (GBP per MWh) for energy curtailments from British wind farms.*

Figure 6 displays the cost of curtailment per MWh. Here, the 2022 level may be seen to be at a decade low. This explains the aforementioned greater steepness in the trend of Figure 4 when compared to Figure 5. As this occurs against a backdrop of expanding wind generation, Figure 7 provides the rate of curtailment.

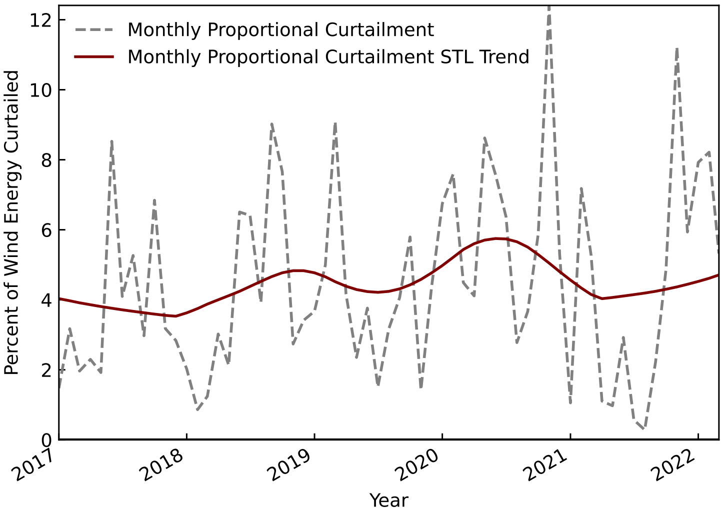


Figure 7: *Monthly percentage of wind energy curtailed (%) from British wind farms.*

Monthly national wind curtailment net volumes (Figure 4), net costs (Figure 5), and the cost per unit of energy curtailed (Figure 6) are shown (raw data and trend). The results shown by these figures bare clear relation. While a general trend of increasing (or constant) net volumes and net costs exist (Figures 4 and 5), a decreasing (or constant) trend is seen in the cost per unit of energy curtailed (Figure 6). Since 2020, while net volumes have increased, this growth is less pronounced in net costs. This corresponds to a decrease in the price per unit of energy curtailed (which in the immediate years prior to 2020 was more constant). While wind power curtailment has increased (Figure 4), so too has wind power generation. The percentage of wind power curtailed, as per Equation 1), is therefore graphed in Figure 7. A comparison between these curtailment rates, and those from previous investigations may be found in Appendix A.1.

As was established in prior literature, 2020 saw an exceptional level of curtailment [26, 71]. If this year is to be disregarded an an outlier, then the growth trend in curtailment volumes (Figure 4) remains. By extension, the (lesser) growth of total curtailment costs (Figure 5) appears more consistent. While 2020 spikes were evident in Figures 4 and 5, this is not the case when examining curtailment costs per MWh (Figure 6), with 2020 instead representing the year in which the trend changed from flat to declining (and continued to do so after 2020). Finally, as shown in Figure 7's trend, the rate of curtailment peaks in 2020, while the present state of the trend remains higher than its initial level.

4.3 Site Curtailments

To examine geospatial and comparative individual site trends, for onshore and offshore wind farms, curtailment levels are visualised in Figure 8. The most recent full year of 2021 is used.

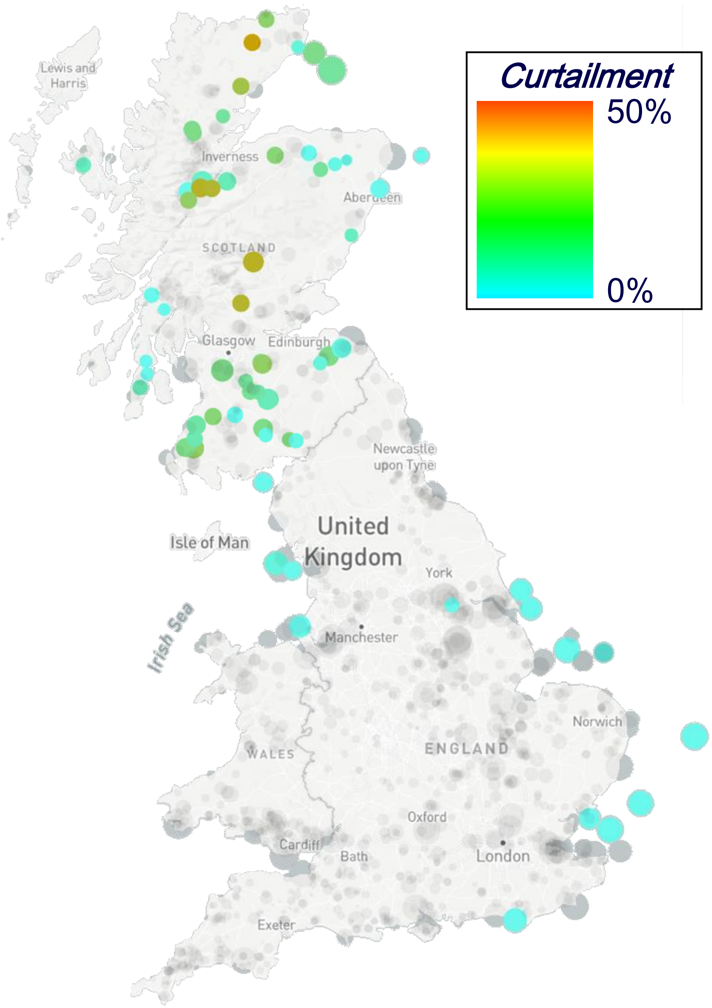


Figure 8: *Britain's 2021 wind energy curtailment for mapped BMRS reporting wind farms. Colour scale notes percentage curtailment. Circle area scaled up by capacity. Black dots represent other generators for context, including wind farms for which curtailment data was not available.*

In Figure 8 the following are observed:

- Scottish wind farms remain predominantly onshore (despite offshore expansions), while English/Welsh farms continue to be overwhelmingly offshore.
- Scottish curtailment levels are considerably greater than those of England/Wales.
- While offshore wind is curtailed at a lower rate than onshore wind, it is notable that Scottish offshore wind (in particular) is curtailed at higher rates then English/Welsh offshore wind. In previous literature there were few examples of Scottish offshore wind farms, with the 588 MW (273 MW pre-expansion) Beatrice wind farm being the only >100 MW site, and accounting for the majority of offshore Scottish wind capacity. As of 2021, however, there are two >100 MW sites, now including the 1200 MW Moray East Wind Farm which presently accounts for the majority of offshore Scottish wind capacity, though it was not fully deployed from the beginning

of 2021 and so should be considered alongside the expanded Beatrice wind farm.

To further examine these distinctions Figure 9 depicts the curtailment rates for the wind farms shown in Figure 8. Figure 8 also displays REF reported curtailment levels for a number of Scottish farms. With some exceptions these broadly align with the curtailment levels calculated from BMRS data (including the Beatrice farm, which will be of particular importance in further discussion).

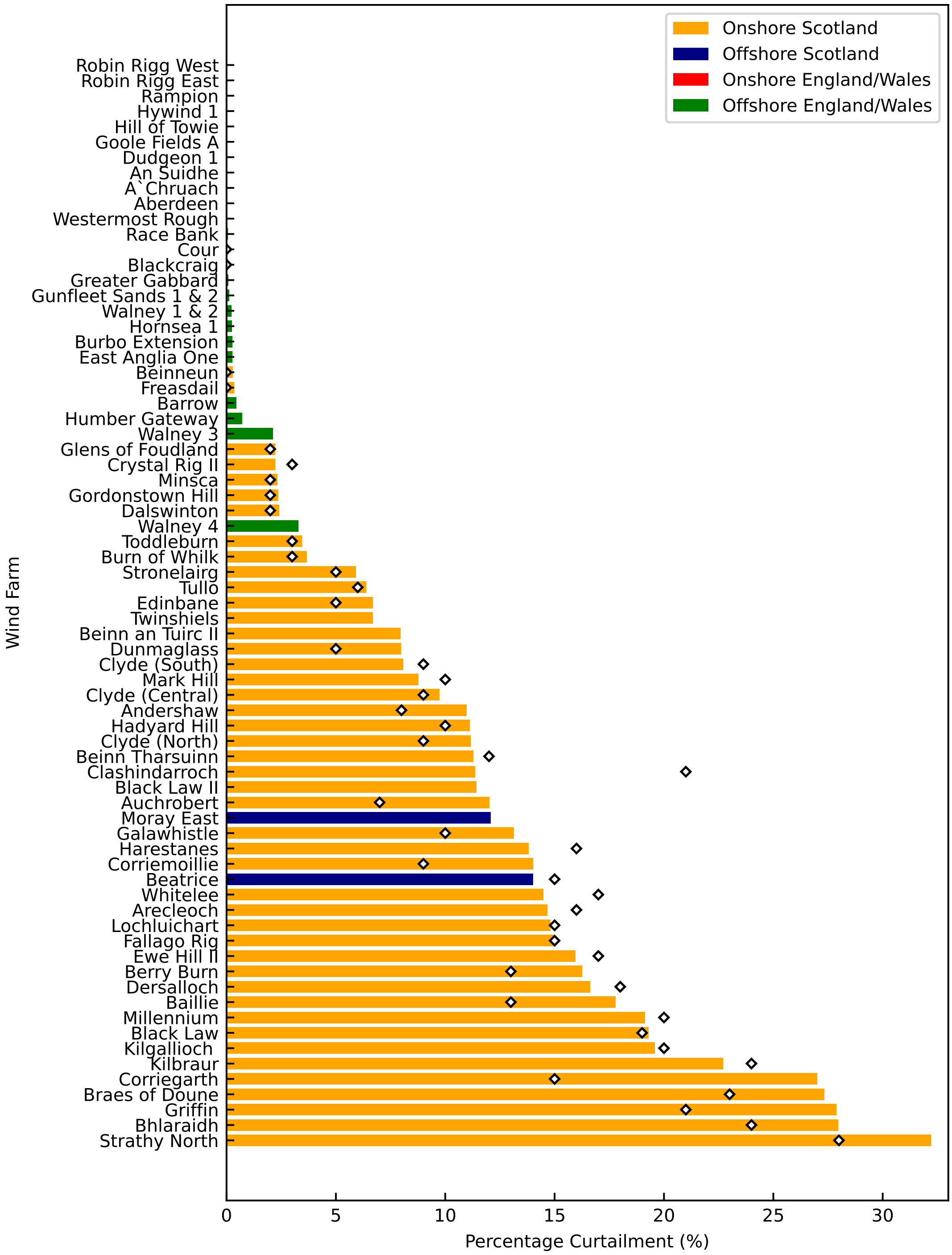


Figure 9: *Bars represent: Curtailment percentage (%) of British Wind Farms in 2021 [6–11]. Bar colours represent: Farm type / location. Diamonds represent: REF values (only available for some farms) [58–60].*

In Figure 9 a comparison of BMRS derived, and (for a subset of these) REF site curtailment values are shown. These curtailment levels (between BMRS and REF sources) are broadly aligned (particularly for larger farms, for which there is more regular data), with an average difference in the % curtailment rate of 2.1% (2.4% for <100 MW farms, and 1.6% for >100 MW farms).

Although the map in Figure 8 may provide a clearer overall perspective of the geospatial divisions in curtailment, Figure 9 allows for more specific points to be made clear. These are as follows:

- The Robin Rigg West, Robin Rigg East, Rampion, Hywind 1, Hill of Towie, Goole Fields A, Dudgeon 1, An Suidhe, A'Chruach, Aberdeen all recorded curtailment rates of 0% for 2021. To make types (as per the key) more clear, a modified figure may be found in Appendix A.4.
- While Scottish wind is generally onshore, and English/Welsh wind offshore, the deployment of the Moray East wind farm and Beatrice expansion, allows for a unique quantity of data to now be analysed with respect to offshore Scottish wind energy.
- Conversely, with respect to onshore English/Welsh wind, only one site was mapped (the 33 MW Goole Fields A farm). Given that there is only one site, and that this site is of a very low capacity, the quantity of data available (no curtailment instances for 2021) is insufficient for direct discussion on English/Welsh onshore wind curtailment.

Thus, when wind farm quantities and, especially, sizes, are considered, there remains substantial data on onshore English/Welsh wind and offshore Scottish wind. Recent expansions presents a unique opportunity to gain insight into offshore Scottish wind. Finally, the small Goole Fields A, with no recorded curtailment instances (in the BMRS data) in the examined time period (not only 2021, but 2017 to early 2022) provides insufficient information to serve as a direct basis discussion on onshore English/Welsh wind.

4.4 Site Exports

To provide a more comprehensive understanding of wind farm performance, a capacity adjusted discussion is also of interest (i.e. hourly exports, curtailment, and generation / capacity). Rather than providing a comparative metric between exports and curtailment, these metrics will instead provide a comparative metric with respect to the underlying infrastructure of sites themselves. So too may some energy be deemed more valuable by the market price than exports during different time periods. As such the average spot price [6, 7] of exported power will also be calculated. From an economic perspective, these the output of wind farms would be better considered within onshore or offshore wind farm datasets, rather than between them (due to significantly differing construction costs per MW of capacity). Finally, as the Moray East wind farm was incrementally deployed in 2021, it will be excluded from this part of the analysis due to its deployed capacity at each period of time not being provided.

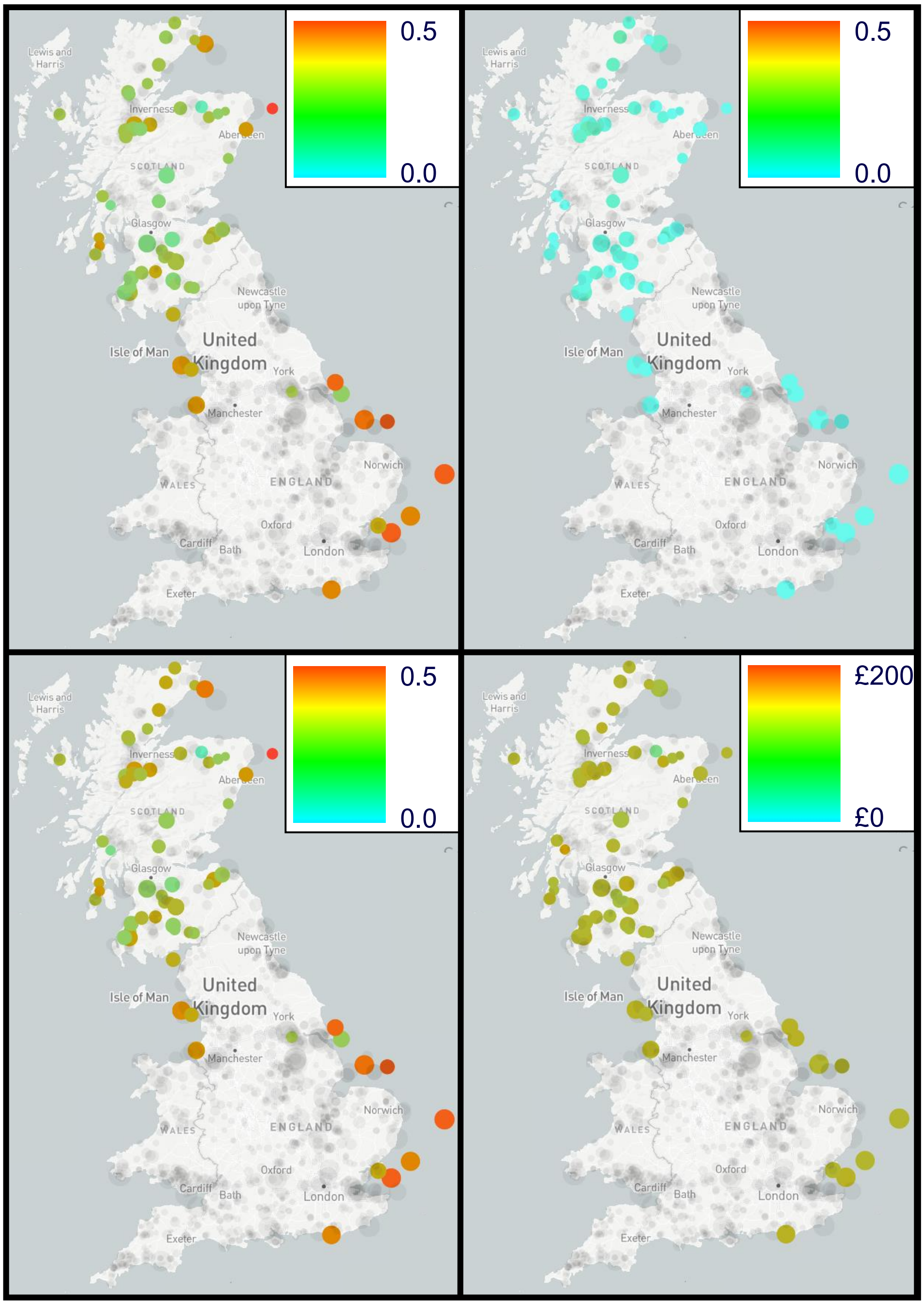


Figure 10: *Top Left: Export Factor (hourly energy exported / capacity).*
Top Right: Curtailment Factor (hourly energy curtailed / capacity).
Bottom Left: Generation Factor (hourly energy generated / capacity, i.e. The summed Export Factor and Curtailment Factor).
Bottom Right: Average spot price of energy exported (GBP / MWh).
Black dots represent other generators for context, including wind farms for which curtailment data was not available.

Figure 10 displays these metrics, which will be further visualised below. Generation, export and curtailment factors are also represented in Figure 11, while the average spot price per exported MWh is shown in Figure 12. For consistency these show wind farms in the same order as Figure 9.

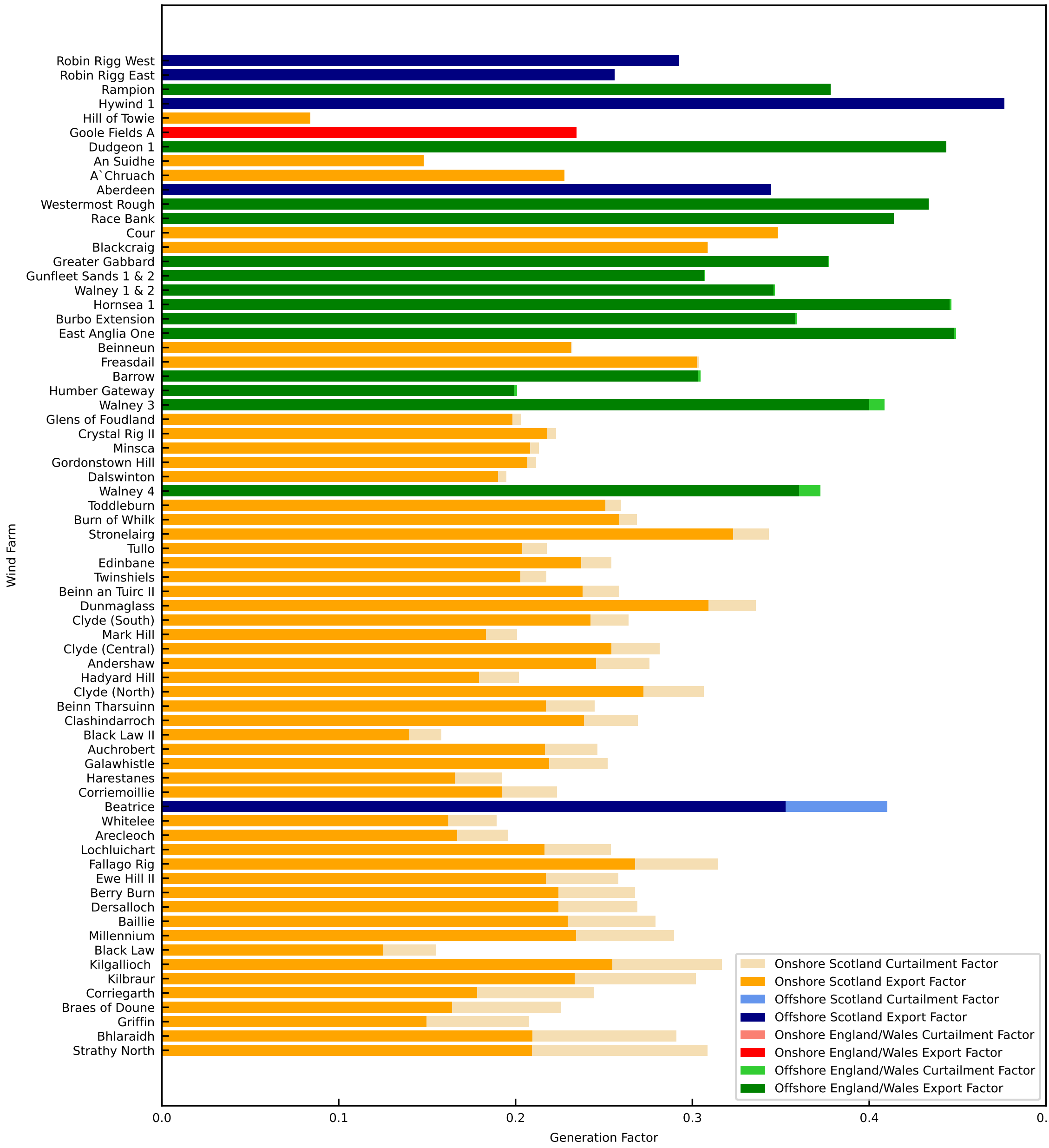


Figure 11: *Generation factor decomposed into export and capacity factor by wind farm, as per equation 2 (colours representing location and type).*

In the overall generation factors of Figure 11, more similarity is seen for farms of a particular type, rather than location (unlike with curtailments in Figure 9); as can be seen when examining the broadly higher generation factors of offshore wind farms compared to onshore wind farms. This reflects the higher capacity factor of offshore wind.

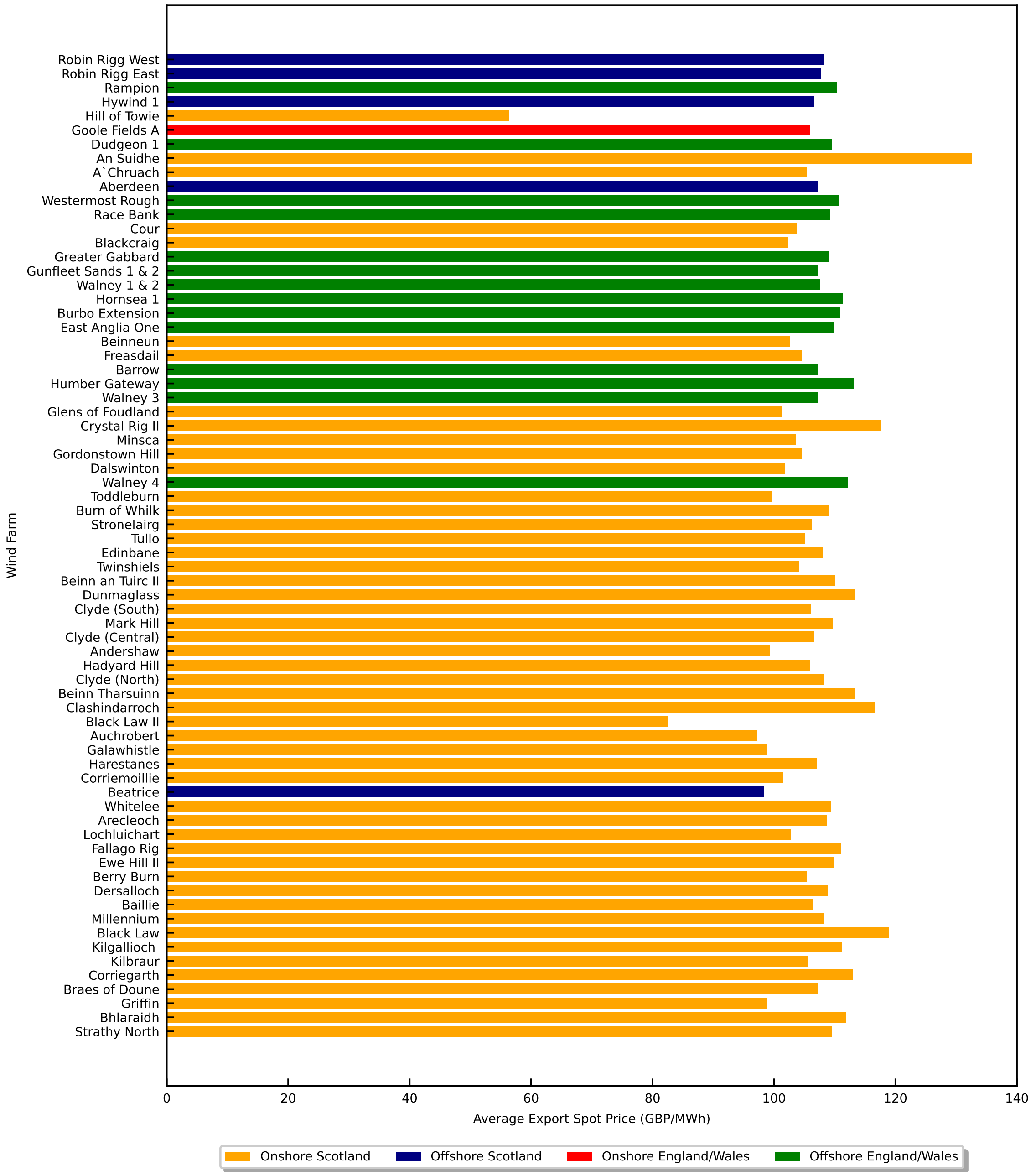


Figure 12: *Average spot price at point of export per MWh of exported energy.*

Finally, Figure 12 displays relatively more consistency between farm types and locations, as opposed to the aforementioned geospatial divide in Figure 9, and the type division in Figure 11. Further investigation is also conducted in Appendix A.5.

4.5 National Growth Profile

Given the significance of the Scottish vs English/Welsh divide identified in the site analysis, national profile trends are returned to, with respect to this distinction. Given the dominance of Scottish curtailment (in volumes, and percentage terms), these results will be presented in tabular form.

Table 2: *Site aggregated curtailment data for Scotland and England/Wales.*

Year	2017	2018	2019	2020	2021
Curtailment (GWh): Scotland	1256	1385	1631	2959	1840
Curtailment (GWh): England/Wales	17	22	34	104	91
Exports (GWh): Scotland	6098	7316	12223	12394	11763
Exports (GWh): England/Wales	6865	12115	16189	22322	20254
Percentage Curtailment: Scotland	17.07	15.92	11.77	19.27	13.53
Percentage Curtailment: England/Wales	0.24	0.18	0.21	0.47	0.45
Percentage of Curtailments from Scotland	98.68	98.45	97.96	96.59	95.30

Table 2 displays the divide between Scottish and English/Welsh curtailment levels by aggregating the data from specific mapped sites from BMRS (as opposed to other aggregate sources as was used for Figure 7). The disproportionate expansion of offshore wind in England/Wales is especially evident.

5 Discussion

So far this investigation has considered the curtailment of British wind energy on an aggregate and site specific basis. These findings have already been compared extensively with the findings of existing literature. Given the rapid expansion of wind generation, however, analysis is also warranted with respect to the current state of wind energy curtailment in the British energy sector.

The results obtained by this paper were found using a knowledge graph assisted approach to facilitate mapping for a multi-source investigation. This is of particular importance given the differences between sources, as discussed in Subsection 2.1 and Appendix A.1. Consistency amongst sources will therefore be of interest throughout this discussion.

With respect to existing literature (Section 2), the following points should be recalled:

- Offshore wind energy has been curtailed at a lower rate than onshore wind energy.
- Scottish wind energy has been curtailed at a higher rate than English/Welsh wind energy.
- The two main causes of this distinction are: (1) Differences in curtailment costs (between onshore and offshore wind), and (2) Greater grid constraints on Scottish energy (due to the Southern concentration of demand and associated increased transmission requirements).
- Both generation and transmission infrastructure have been expanding rapidly and are expected to result in major changes in curtailment volumes and costs (eg. new wind farms, Western HVDC Link).

- The year 2020 saw anomalously high wind curtailment along with a high load factor (due to demand-side behaviour).

These points will be further discussed in this section.

5.1 Onshore and Offshore Wind Curtailment

As can be seen in Figures 8 and 9, onshore wind continues to be curtailed at a much higher rate than offshore wind. On an aggregate basis (Figure 4) wind curtailment therefore continues to be dominated by curtailment from onshore wind farms. Furthermore, (given the rising costs of offshore curtailment and falling costs of onshore curtailment) it can also be seen that onshore wind costs dominate per MWh curtailment costs (Figure 6), resulting in a lower growth in total curtailment costs (Figure 5) compared to total energy curtailments.

On an individual basis, however, Figure 9 clearly shows that (particularly on a volume adjusted basis) offshore wind farms off the Scottish coast are curtailed a much higher rates than those in the south. Offshore Scottish wind energy rates of curtailment are more comparable with curtailment rates of onshore Scottish wind.

5.2 Curtailment Costs and Transmission Constraints

While the curtailment rates of onshore and offshore wind farms clearly differ, there are multiple factors which may underpin this distinction. While many explanations are possible, the leading distinctions (as discussed above, and in associated literature) are transmission constraints (linked to geospatial conditions / location), and differing curtailment cost structures (linked to technology types). To distinguish between these causes, the geospatial vs generation type influences on curtailment rates may be examined. If cost factors dominate, then more consistency would be expected amongst onshore / offshore farms (regardless of whether or not they are in Scotland). If transmission factors dominate, then more consistency would be expected amongst wind farms in Scotland or England/Wales (regardless of whether or not they are onshore or offshore).

A key issue in making this distinction, however, is the lack of farms which may enable this comparison. For example, insufficient data exists on onshore wind farms in England/Wales. By extension, a limited capacity was mapped for offshore wind farms in Scotland. This issue is compounded by the significant range of curtailment rates between farms. In past literature, however, only the (pre-expansion) Beatrice Offshore Wind Farm (and various smaller installations) provided curtailment reporting, while data is now available from the recently installed, and much larger, Moray East Offshore Wind Farm.

While future investigations would be recommended to continue examining role of curtailment with respect to these (and future) facilities, this paper's results indicate that offshore Scottish wind farm curtailment is more in line with onshore Scottish wind farm curtailment than with offshore English/Welsh wind farm curtailment. This behaviour indicates that of the subsidy cost and transmission constraint causes for curtailment, that the latter appears to dominate. This has occurred despite both a drop in the cost of onshore wind curtailment, and increase in the subsidy cost in offshore wind energy curtailment.

5.3 Changing Onshore/Offshore Costs and Transmission Expectations

Past literature notes that policy differences such as the allocation of Renewables Obligation Certificates (with more being given to offshore wind), has resulted in different subsidy costs for offshore wind compared to onshore wind (and thus relatively incentivised the curtailment of onshore wind). It has already been discussed above how transmission constraints appear to dominate over subsidy cost factors, but even if curtailment costs have a lesser effect on curtailment volumes, they remain of interest as both a secondary influence on curtailment differences, and critically due to their impact on cost of curtailment itself.

The changes on offshore and onshore curtailment costs therefore warrant discussion. From 2004 to 2020, offshore curtailment costs have been increasing [61]. As of 2012 the cost of offshore curtailment was lower than that of onshore wind curtailment. In the next two years, however, as offshore wind curtailment costs continued to steadily grow, onshore wind costs fell dramatically. Until 2020 the curtailment cost of offshore wind continued its increase, while the decline in onshore wind curtailment costs slowed (resulting in a period of stable onshore wind curtailment costs. In recent years, however (starting in 2020, but continuing thereafter), this paper observes onshore wind curtailment costs to have begun to decline once again. This is reflected in the (aforementioned onshore wind dominated) trend in Figure 6, which may be contrasted with the results published by the Renewable Energy Foundation for offshore wind curtailment costs [61].

Curtailment costs, however, do not exist independently of transmission constraints (and their impact on costs). Imperial London College's investigation of British curtailment and balancing, for example, noted "expansions in grid infrastructure have been expected to lower associated constraint costs" [40]. Given the significance of the Western HVDC Link increasing Scotland to England/Wales transmission capacity by approximately 25% (by comparison to a grid model representation of the former British transmission system [73]), how has this prediction fared?

Due to the aforementioned multi-year roll-out of the Western HVDC Link, followed by the outlier year of 2020, there is some difficulty in analysing this prediction, but an overview may still be discussed. Following the roll-out of the Western HVDC Link, curtailment costs fell on a per MWh basis, but not decisively on an aggregate basis (due to the increased curtailment volume). For completeness it should be mentioned that these trends persist whether in both national, and Scottish specific figures (which should benefit the most from this expansion), though, as previously discussed, these are extremely similar due to the significantly higher rate of Scottish curtailment (with Scottish curtailment consistently declining from >98% of curtailment in 2017 to 95% in 2021).

While Scottish wind curtailment still remains the vast majority of British wind curtailment, this decline reflects another trend; the greater rate of growth of wind generation infrastructure outside of Scotland.

5.4 Wind Generation Growth and Changing Curtailment Rates

Compared to the upwards trend in Figure 4 (and even Figure 5), when examining the trend in % wind energy curtailed seen in Figure 7, a much lower rate of growth is seen. A key factor here has been the locations of new wind installations. While transmission infrastructure and curtailment subsidy policies may be modified to accommodate wind farm installations, the placement of new wind farms in more advantageous locations (in this case, at locations with lower rates of curtailment), has directly impacted the results of Figures 4 and 7.

Using DUKES and BMRS data respectively, Figure 1 and Table 2 denote the rate of wind energy growth, which shows a higher rate of offshore wind generation growth relative to its onshore equivalent. From 2017 to 2021 onshore wind generation grew by 16%, while offshore wind generation grew by 98%. While Scotland is not without offshore wind, this expansion has disproportionately been off the English/Welsh coast.

From 2017 to 2021, therefore, the following changes occurred (using BMRS data):

- Scottish curtailment grew by 47%, while English/Welsh curtailment grew by 542% (note that Scottish curtailment still accounts for 95% of all curtailment).
- By comparison Scottish wind generation exports grew by almost a factor of 2 compared to almost 3 in England/Wales.
- In percentage terms Scottish curtailment fell by 20%, from over 17% to under 14%. Comparatively, English/Welsh wind energy curtailment (in percentage terms) grew by 83% from 0.24% to 0.44%. As such, while the percentage growth of English/Welsh curtailment may seem extreme, it is still curtailed at significantly lower rates than Scottish wind energy.

By focusing on installations closer to (Southern concentrated) demand centres, these new wind farms have placed less strain on the transmission system and as a result, have been less curtailed. While some diminishing returns are arguably observed, curtailment rates between England/Wales (offshore wind) and Scottish wind generation still remain far from parity.

5.5 Future Investigations

The disproportionate rate of southern, offshore wind generation expansion is set to continue, and should be a focal topic of new wind energy literature. Technoeconomic investigations, for example, may be wary of the higher construction costs and curtailment subsidy costs of offshore wind (but also higher generation capacity factors), even if its placements in Britain tend to incur lower rates of curtailment. Conversely, the extent to which these higher costs can be justified may be determined with respect to the benefits of higher export capacity factors, which this paper's findings suggest are superior for southern offshore wind sites. Due to the rapid growth expected to continue in British wind generation, the topics of investigation discussed in this paper will be of continued interest in future studies as the transmission / generation arms race continues.

If future scenarios with increased transmission capacity were to be considered, curtailment resulting from national surplus generation (due to there being a non-zero 'optimal' level of curtailment, transmission constraints presently appear more significant), and price cannibalisation (which is already of note), would also be topics of heightened importance. The correlation between offshore wind generation and Scottish onshore wind generation would also be of interest with respect to supply-demand mismatches, as well as transmission limitations for Scottish offshore wind in particular. By extension, the role of pumped hydro (also disproportionately in Scotland and thus subject to fewer transmission constraints with respect to charging from otherwise curtailed Scottish wind energy) and distribution limitations may also be worthwhile expansions.

Investigations into the mitigation of curtailment through storage (batteries in electric vehicles, re-pumped hydro, fixed storage, new storage technologies, *etc.*) should consider the placement of such that charging is not constrained by the same transmission limitations which cause the curtailment they seek to mitigate. Analyses of the correlation between wind conditions (and farm outputs) will be of increasing relevancy as VRE is increasingly used. This will be of particular relevancy for transmission curtailment studies.

6 Conclusion

Given the rapid expansion in the UK's generated wind energy, the study of curtailment is of increasing importance. Using a knowledge graph approach this paper performs a multi-source analysis using BMRS, REF, DUKES, and internal data to analyse the current status of wind energy curtailment in the UK.

For the past few years, the following key trends were identified:

- As generation volumes have increased, so too have curtailment volumes and net costs continue to grow. Comparatively, when considering these developments in per MWh terms, onshore wind curtailment costs have recently begun to decline (following the expansion of transmission infrastructure), offshore wind curtailment costs have continued to rise, and fractional curtailment has risen at a relatively lesser rate.
- Curtailment continues to occur overwhelmingly in Scotland, which although dominated by onshore wind farms, has comparable curtailment levels at its offshore wind sites. This confirms transmission constraints to be the primary cause of curtailment, rather than generation type and associated differences in subsidy cost structures.
- The relatively low rate of % curtailment growth in recent years is primarily the result of new wind installations disproportionately being southern wind farms (i.e. there is disproportionately more growth in English/Welsh offshore wind farms, as opposed to new capacity in Scotland). While some diminishing returns are evident, curtailment rates of (less transmission system constrained) southern wind farms remains significantly lower than the curtailment rates in Scotland.

The growth of British wind is set to continue, along with significant expansions to its transmission network. Future curtailment studies should make particular note of new and continuing trends identified by this paper, along with this study's methodology and discussion of curtailment level estimations found in existing literature. At present, however, transmission constraints remain the primary determinant of British curtailment, and are a consideration of increasing influence in the construction of new wind farm infrastructure. While offshore wind farms were found to have higher capacity factors compared to onshore sites, and English/Welsh offshore wind farms in particular were found to have significantly lower rates of curtailment, future investigations should still be wary of the substantially higher capital and operational costs of offshore wind generation.

Research Data

Raw data, such as that obtained from BMRS can be obtained using the references made within this paper. Code associated with this project may be found under version control at: https://github.com/cambridge-cares/TheWorldAvatar. A summary of the DUKES / BMRS mapping (used in conjunction with BMRS data) may be found in the following repository: doi:10.17863/CAM.92517.

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A Appendix

Here may be found additional information which is unnecessary for inclusion in the main paper, but may be of interest for additional detail.

A.1 Wind Curtailment and Generation Comparison

Some differences exist between wind curtailment levels reported in previous investigations, and those calculated in this investigation. For reasons such as differences in reported generation levels used by each study, calculations of curtailment can vary, though some similarities between studies may also be observed. These curtailment values are displayed in Table 3.

Table 3: *British Annual Wind Energy Curtailment (% of total wind energy generated). As per Imperial College London (ICL) [40], Wind Europe [74], Kyoto University [79], the University of Strathclyde [28], and by this paper in Figure 7 [8, 58, 59]. Note that data is not provided or obtained for all years from all sources/papers. This table expands upon Table 1 from Section 2.1, by including in this investigation's rates of curtailment.*

Year	ICL	Wind Europe	Kyoto	Strathclyde	Figure 7
2012	0.44	0.4			
2013	2.39	2			
2014	3.58	3.1	2	2.8	
2015	5.68		0.7	4.2	
2016	5.64		2.9	4	
2017			2.9	4	3.79
2018			2.6	3.9	3.98
2019			3		4.28
2020			4.2		6.45
2021					4.46

With regards to wind energy generation, as curtailment information is typically obtained through market data, it may not necessarily include results from all wind farms [8, 25, 40, 74]. A dilemma therefore arises between calculating percentage curtailment using market data directly, or using a potentially more extensive data-source for wind generation which lacks equally extensive curtailment data (or curtailment data at all, such as DUKES). In Table 4 the wind generation figures are shown from a variety of sources.

Table 4: *British Annual Wind Energy Generation (TWh). As per Imperial College London (ICL, estimated from provided data) [40], Wind Europe [74], Kyoto University [79], the University of Strathclyde [28], BMRS [8], and DUKES [25]. Note that data is not provided or obtained for all years from all sources/papers.*

Year	ICL	Wind Europe	Kyoto	Strathclyde	BMRS	DUKES
2012	11.36	12.61				19.85
2013	15.9	18.62				28.4
2014	18.44	21.15	30.62	21.1		31.96
2015	21.83		38.62	29.4		40.27
2016	19.86		35.87	27.3		37.16
2017			47.57	36.8	39.11	49.64
2018			54.73	39.2	41.6	56.91
2019			61.87		43.35	63.83
2020			73.15		53.6	75.61
2021					50.3	64.66

As can be seen in Table 4, DUKES data (which measures wind generation across more wind farms, by including those for which curtailment data is not available) consistently reports higher wind generation figures than the other sources (all of which report or provide curtailment data as per Table 1). With the exception of Kyoto University's figures (which is comparably only slightly lower than DUKES), reported wind generation data is considerably lower across all sources compared to DUKES (though these too vary amongst themselves). As mentioned above, this is because these sources attempt compare wind curtailments with wind generation from similar selections of wind farms (thereby excluding generation data from wind farms for which curtailment data is not provided).

There are therefore cases of both methodologies (curtailment vs generation from the same farms, vs curtailment vs generation from a more extensive range of farms). The former, more common approach, will be used for the purposes of this paper and its estimation of curtailment (as a percentage of wind generation) in Table 1 and Figure 7. i.e. BMRS generation data will be used (which is also available with a much higher time resolution) rather than DUKES.

A.2 29 Bus Network Locations

Locations were estimated for bus locations from the network model available from the University of Edinburgh [73]. This model has been used in a number of publications from Imperial London [1, 13]. These locations were estimated based on substation locations (with the exception of London for which there were multiple), with resulting bus locations being extremely similar to those used in past literature. As per either estimation it is clear that the branches connecting buses 6 and 9, as well as 7 and 8 jointly Scotland and England. For reference, these estimated locations may be seen in Table 5.

Table 5: *29 Bus Model Locations [73].*

Bus	Name	Lat	Lon
1	Beauly	57.4698798	-4.4906735
2	Peterhead	57.4745293	-1.7998211
3	Errochty	56.7070037	-4.0107947
4	Denny/Bonnybridge	56.0386335	-3.8890767
5	Neilston	55.8095298	-4.4768292
6	Strathaven	55.7509421	-4.0805189
7	Torness	55.966361	-2.4082467
8	Eccles	55.6684972	-2.3299805
9	Harker	54.9419311	-2.9618091
10	Stella West	54.9744212	-1.7329921
11	Penwortham	53.7443568	-2.7549931
12	Deeside	53.2292472	-3.0317476
13	Daines	53.4269672	-2.3787821
14	Th. Marsh/Stocksbridge	53.4877894	-1.6016288
15	Thornton/Drax/Eggborough	53.9002325	-0.8235841
16	Keadby	53.5973069	-0.755805
17	Ratcliffe	52.862919	-1.257635
18	Feckenham	52.2512438	-1.9735155
19	Walpole	52.7269277	0.1981251
20	Bramford	52.0716528	1.0631638
21	Pelham	51.9351319	0.1167908
22	Sundon/East Claydon	51.9270632	-0.9099366
23	Melksham	51.3749726	-2.1441581
24	Bramley	51.3358918	-1.0775578
25	London	51.5077431	-0.1271547
26	Kemsley	51.3684603	0.7414151
27	Sellindge	51.1050295	0.9761146
28	Lovedean	50.9163709	-1.0383188
29	S.W.Penisula	50.7674626	-3.4061633

A.3 National Monthly Decompositions

STL decompositions were performed on the monthly data of Figures 4, 5, and 6. Below these can be seen.

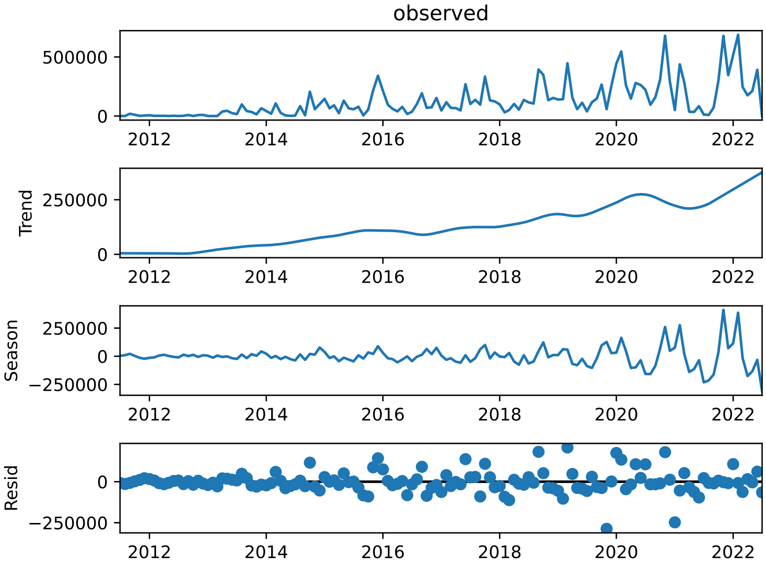

Figure 13: *STL decomposition of: Monthly energy curtailments from British wind farms. Corresponds to Figure 4.*

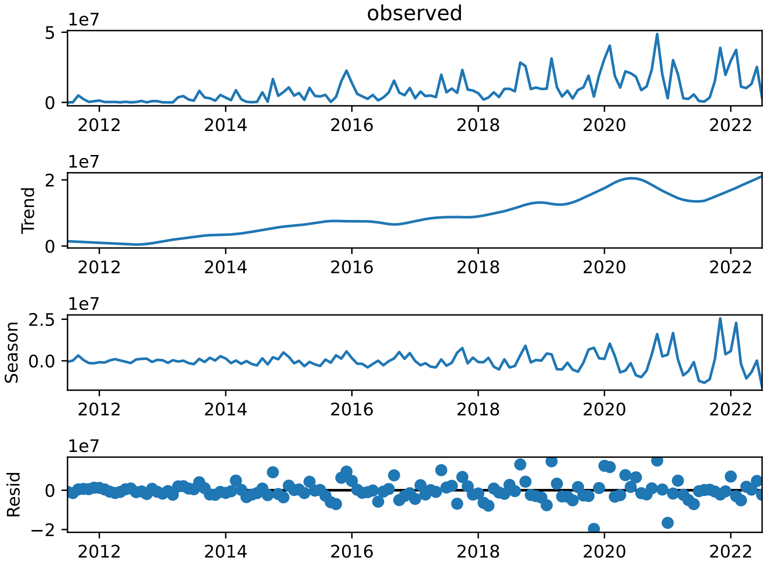

Figure 14: *STL decomposition of: Monthly constraint payments for energy curtailments from British wind farms. Corresponds to Figure 5.*

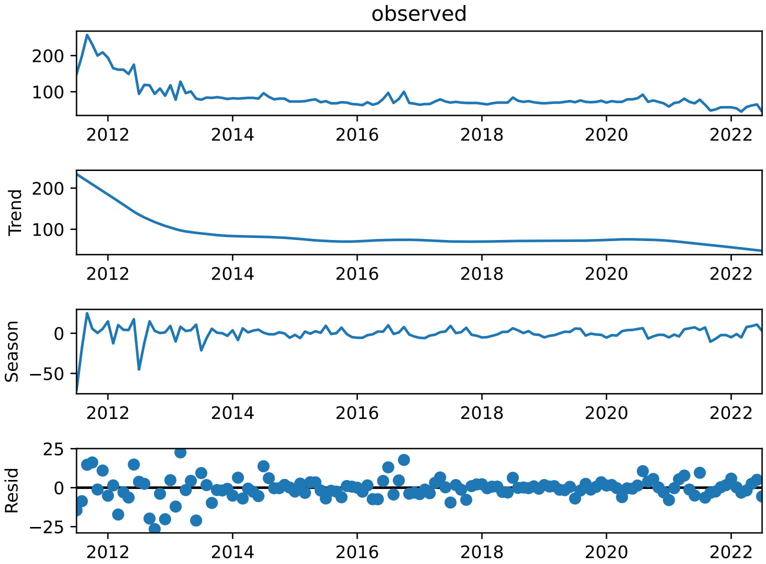

Figure 15: *STL decomposition of: Monthly average cost (per unit of energy) for energy curtailments from British wind farms. Corresponds to Figure 6.*

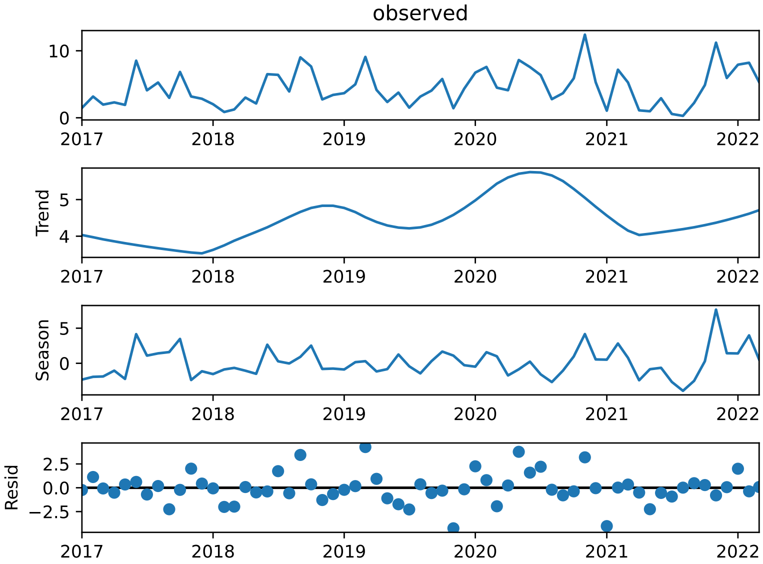

Figure 16: *STL decomposition of: Monthly percentage of wind energy curtailed (%). Corresponds to Figure 7.*

A.4 Individual Site Types Graph

Thin coloured lines are added in Figure 17 for more specific clarity compared to Figure 9.

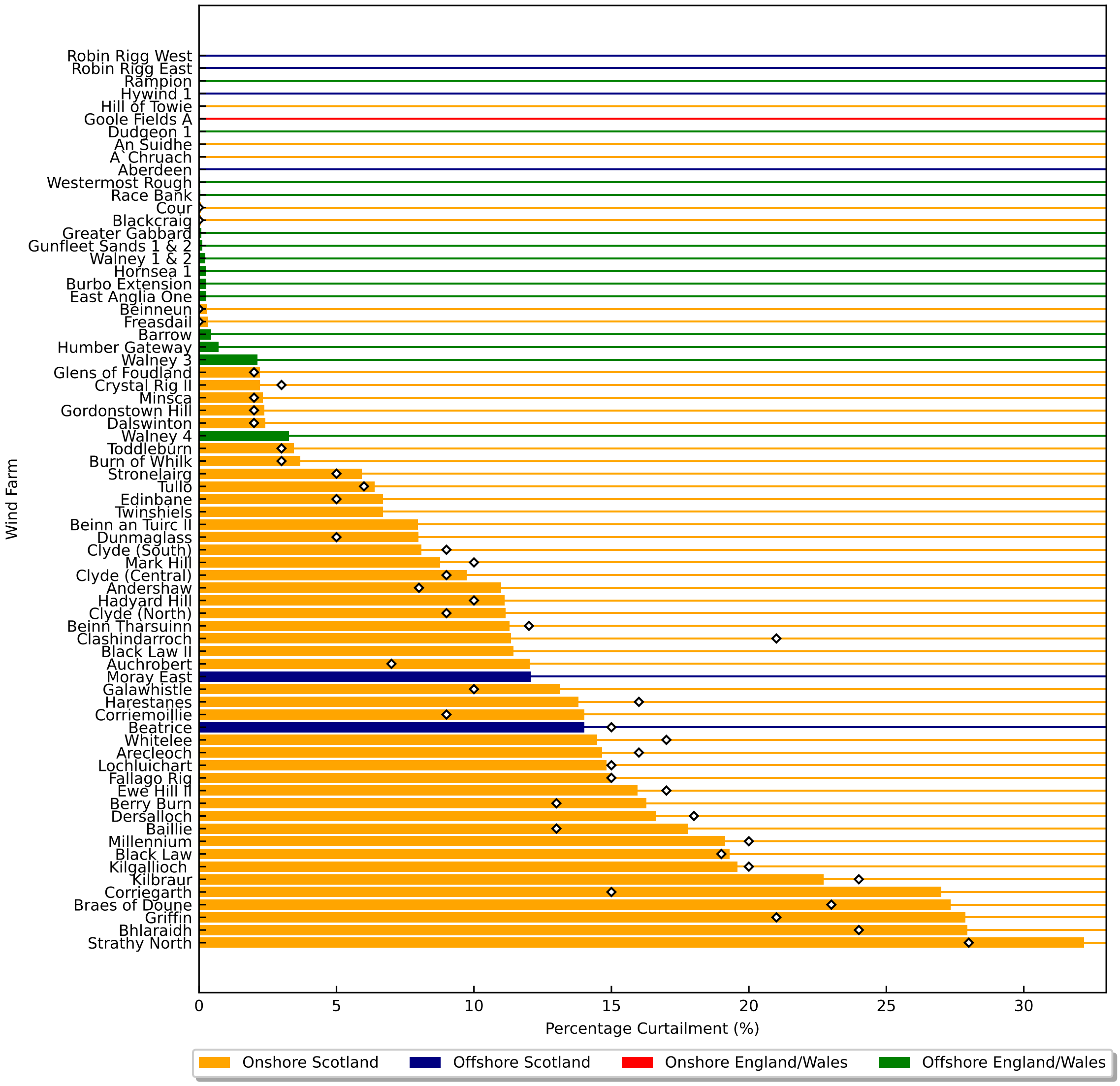

Figure 17: *Bars represent: Curtailment percentage (%) of British Wind Farms in 2021 [6–11]. Bar colours represent: Farm type / location. Diamonds represent: REF values (only available for some farms) [58–60]. Thin coloured lines exist to make the farm type more clear for low curtailment bars and reflect only the type as per the key (not any quantity).*

A.5 Further Site Generation Analysis

Further investigation will be conducted on the generation (as per equations 1 and 2) of wind farms investigated in Site Exports (4.4). These sites are shown in Figure 18. For the remainder of this section, the order of sites will be as per these capacities.

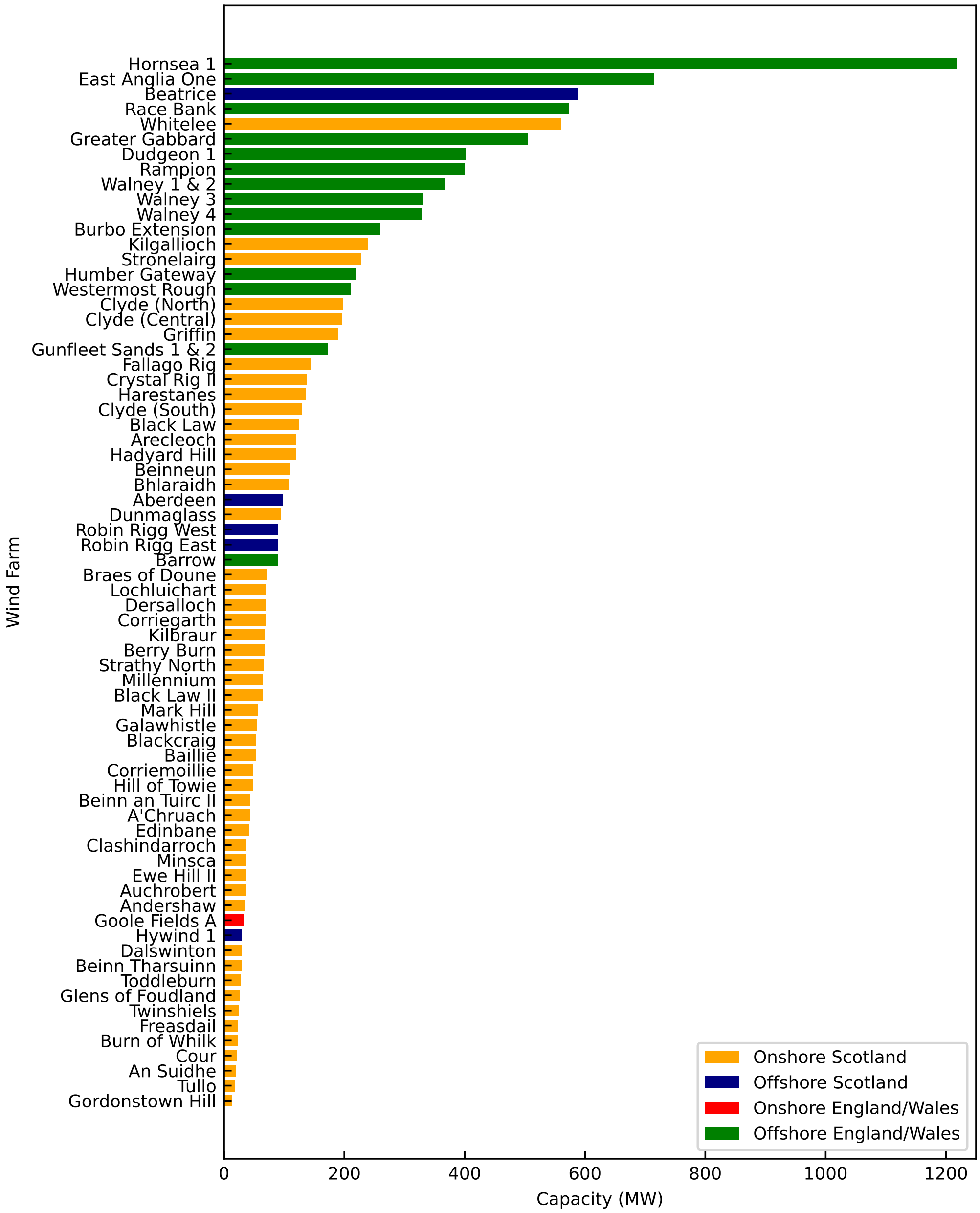

Figure 18: *Capacities (MW) of British wind farms analysed in this section.*

The volatility of wind farm generation may also be of interest for investigation. Were generation parameters in Scotland to differ from those in England/Wales (e.g. due to differing wind conditions), then this may pose an alternate explanation to the Scottish vs English/Welsh wind farm divide from Figure 9 than that concluded by this investigation.

For completeness, therefore, generation volatility will also be considered. This will only be a rough check, however, with this paper focusing on major curtailment causes suggested in existing literature. Further investigation would be recommended for a more in-depth analysis of this topic, such as studying higher frequency data or using differing metrics to account for sometimes higher offshore wind capacity factors.

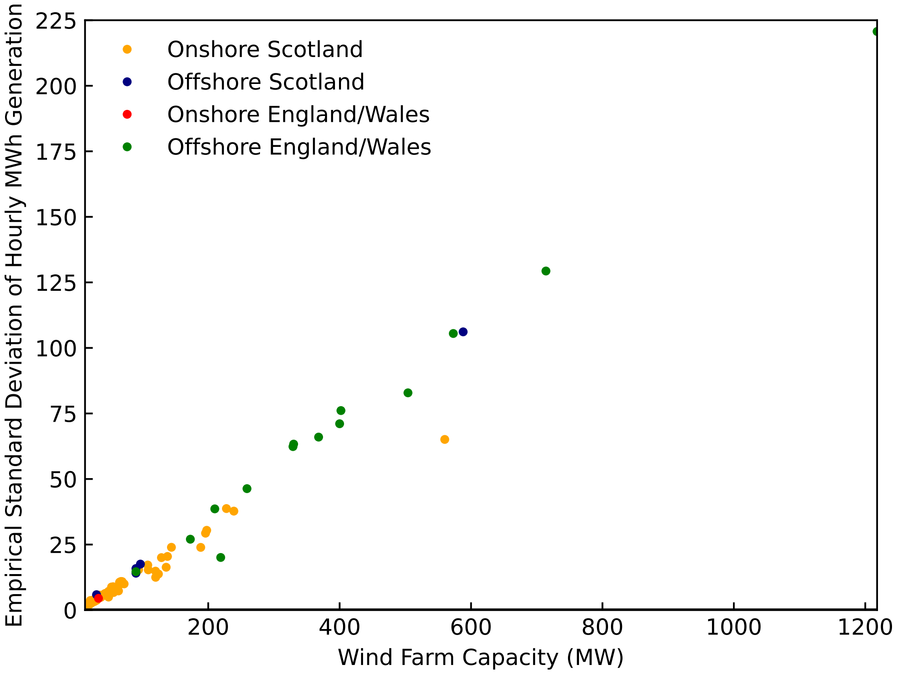

Figure 19: *Generation standard deviation (MWh) of British wind farms.*

Figure 19 depicts this volatility for sites of differing type (onshore vs offshore) and region (Scotland vs England/Wales). A relationship between capacity and generation (MWh) volatility clearly exists. By considering the volatility of percentage generation (wind farm generation (MWh) as a percentage of capacity), Figure 20 is therefore plotted.

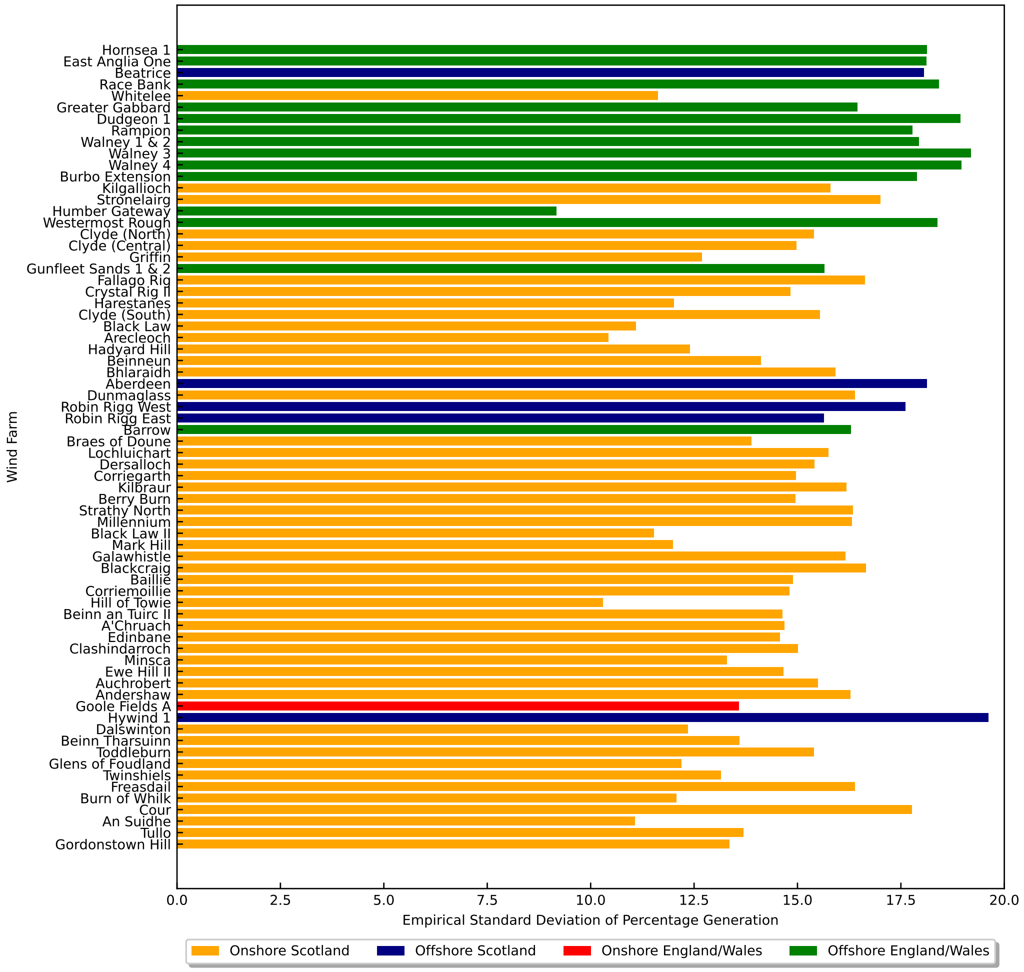

Figure 20: *Percentage generation (of capacity) standard deviation of British wind farms.*

Were curtailment a response to site output volatility rather than subsidy cost or transmission constraint factors, Figures 19 or 20 would be expected to display greater volatility results for Scottish wind farms, but this is not the case.

Table 6: *Average (mean) capacity, generation (MWh) volatility (standard deviation), and generation (% capacity) volatility (standard deviation).*

	Scottish Onshore	Scottish Offshore	English/Welsh Onshore	English/Welsh Offshore
Capacity	86.30	178.96	33.00	413.49
MWh Volatility	12.23	31.89	4.48	73.14
Percentage Volatility	14.33	17.80	13.58	17.23

Table 6 summarises these results. Here, onshore wind has lower average volatility than offshore volatility, with comparable means within each type. As per the findings of previous British literature, transmission constraints (as opposed to local connection /

distribution constraints - as these results do not reflect) and imbalance/subsidy costs are more likely explanations of British wind energy curtailment. These causes remain in focus for discussion in section 5, which will conclude the dominance of Scottish to English transmission constraints as cause of British wind curtailment.

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