British Imbalance Market Paradox: Variable Renewable Energy Penetration in Energy Markets

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Abstract

The expansion of variable renewable energy (VRE) generation propagates numerous challenges for national energy systems. Despite recent years of VRE expansion and declining coal utilisation in the overall market profile, coal energy generation has maintained and grown its position as a marginal seller in the imbalance market. Coal's disproportionate resurgence as a bidder of later resort in the imbalance market also represents a shift in its bidding behaviour. A comparative breakdown of Britain's overall market with that of Germany, followed by a specific investigation of Britain's imbalance market provides insight into changing roles of VRE, fossil fuelled energy, and compensation technologies. Historically, VRE trends in the British and Ger-

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man markets have been broadly consistent. Recently, increasing distress in Britain's overall market is found to result in the increased use of high pollution technologies to meet imbalances. As a result, the composition of the overall and imbalance markets have increasingly diverged, and although the dominance of gas in the latter is expected, the resurgence of coal energy is more remarkable. Thus, while the proportion of generation by renewables has continued to increase, fossil fuelled (notably including coal) capacity, and its associated infrastructure costs and influence as the price setting marginal seller, remains dominant in the imbalance market.
Keywords: Energy, Market, VRE, Britain, Germany, Electricity

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1. Introduction

Over the past decade, the expansion of renewable energy generation has served as a core environmental strategy in Germany and the UK. In these countries, variable renewable energy (VRE) generation infrastructure such as photovoltaic (PV) solar, and primarily wind power have been expanded in an effort to displace fossil fuel energy; primarily coal, as well as gas [1]. As VRE life-cycle and electricity production emissions rates are comparably lower than fossil fuel generation, successful integration of VRE sources is crucial to the energy transition [2, 3]. Understanding the effects of this transition is of particular interest to countries such as these with high and increasing levels of VRE penetration [4–6].

The energy transition has been studied from a variety of focal viewpoints. Differing cost structures and market effects [7, 8], supply chain complexities and circular economy applications [9], construction times, geographic constraints [10–13], storage [14–16] and compensation requirements [17], micro-grid potential [18], seasonality [19, 20], and grid effects / requirements of generation types [1, 21, 22], have all served as core differences between differing power sources which must be considered along with carbon intensity. When comparing VRE sourced power [23] to fossil fuelled or battery storage [24–26], for example, the non-dispatchability of the former and dispatchability of the latter, serves as a major distinction [27]. In an American investigation, photovoltaic penetration without compensation from storage, ramping dispatchables, *etc.* was determined to face increasingly diminishing returns to expansion due to growing losses to curtailment [28]. The behavioural differences between VRE and fossil fuel energy types is therefore expected to result not only in different rates of carbon intensity, but also different characteristics in energy markets, with these markets themselves also being of key interest [29].

Numerous studies have been performed to investigate these effects in a number of countries, in the context of VRE penetration (percentage of the generation mix), price [30–32], stability [33], and volatility [33, 34]. Across these studies, VRE penetration and price are often uncorrelated or negatively correlated. A link between volatility the electricity spot price and growing VRE penetration levels is also identified. Sufficient compensation technologies are recommended to help prevent higher resulting energy prices [33].

Where VRE penetration has increased, the effects on the energy market and grid stability have been extensively investigated [35–37]. The extensiveness of German studies [38–40] in this area present an interesting basis for comparisons with other countries, such as Britain [41]. Analysis of different markets within a country, such as the overall or imbalance markets, adds further detail in understanding the sources of market stresses. It is therefore important to examine the effects of VRE deployment ongoing renewables developments, not only in the context of market-wide trends, but also in market subset data, such as marginal selling (price setting) behaviour in the imbalance market.

While decarbonisation policy has primarily focused on the key differences in emissions intensity between VRE and fossil fuel energy, the structural issue of inflexibility resulting from VRE non-dispatchability has been a topic of increasing interest [42, 43]. The issue of the emissions intensity of compensation technologies such as gas, therefore arises. A University of Victoria study, for example, found nuclear energy could be preferable source of green energy to VRE due to this dependency [44]. This phenomenon has been coined 'The Renewable Energy Policy Paradox' [45]. Analysis of the German market noted a 'German Paradox', where decreased (though still required) fossil fuel generation in the imbalance market supported the expanding contributions from non-dispatchable renewables in the overall market thanks to cross-market integration and improved forecasting [29, 46]. Consideration of the composition of the imbalance market is therefore critical in understanding both the economic and environmental challenges associated with the use of VRE generation and how they can be addressed.

The German energy imbalance market has been studied; both in its own right and by comparison (such as to the French market), with specific emphasis on the generation type of the marginal seller [47, 48]. While there exist overall market studies for Britain and Germany, study of the imbalance market allows for unique areas of investigation. Due to the disproportionate price-setting role of the imbalance market, the required readiness (e.g. spinning reserves) of its potential contributors, and its dependency on fossil fuels, a comparative analysis between the imbalance market and the overall market would provide valuable insight.

Previous investigations into the British imbalance market have been performed with a focus on compensation and pricing [49–51]. A specific analysis which studies the imbalance market with respect to fuel type and at differing VRE penetration levels, however, represent a gap in the existing literature. Investigations into these topics in the German market have been of great academic benefit in understanding the price setting role of dispatchable generation [47], and as such a similar study for Britain would be highly beneficial.

This paper solves this problem by performing an extensive investigation into the British market, including its imbalance market. Extensive analysis of the imbalance market will be facilitated by combining this generation focused study of the imbalance market, with the prices these generation technologies set. Context to existing literature is also critical. This is addressed by performing a comparative analysis of the overall British and German markets to identify individual and general behaviours in the British system.

The purpose of this paper is therefore to comparatively identify the trends of the energy transition in the British market, particularly with respect to the imbalance market. By employing a novel methodology which specifically focuses on imbalance market price setting by fuel type at different VRE penetration levels, novel insight into the market behaviours of these technologies is obtained. Coal's counter-intuitive and disproportionate resurgence as a price setter in the imbalance market is especially scrutinised.

2. Established Impacts of VRE Penetration

The effects of increasing VRE contributions to energy generation in British, German, and other markets has been of comparable academic interest. VRE and dispatchable generation technologies have significant differences in cost, dispatchability, and resulting compensation requirements. These differences are reflected in market prices, volatility of VRE volumes & prices, and the composition capabilities of the imbalance market; where VRE's non-dispatchability makes it poorly suited. These phenomena are significant not only to the study of VRE's direct impacts, but also to the ability of the grid as a whole to respond to external stresses.

The consideration of literature in these areas should therefore be expanded upon to establish a benchmark of expectations for calculations on Germany and Britain's trends, determine the gaps in this knowledge, and create a reference point for potential counter-intuitive findings in the British imbalance market. Without imbalance adjustment from generation, storage, *etc.*, curtailment poses an increased limitation [22, 28]. In Britain, for example, it is calculated that although the mean average VRE penetration level is 23.21% (median 21.32%), the mean average level during a period of curtailment is 32.78% (median 32.94%).

A general trend may be found across many developed countries, where over the past decade, coal has been replaced by gas, wind, and solar in the generation mix [52–55]. This transition has occurred in the UK and Germany, though the UK has comparatively displaced coal more thoroughly, while Germany has maintained a domestically driven dependency on lignite [53, 56, 57]. These British trends are reflected in data from the BMRS and DUKES databases (Supplementary Material's A1) [58–60].

2.1. Price

The relationship between VRE penetration and energy prices has been extensively discussed over numerous timescales, with this paper comparing hourly/half-hourly penetration in specific due to its emphasis on imbalance compensation. The expansion of VRE generation and its effect on energy prices has been studied in numerous countries, with differing results. In the US a weak effect in lowering retail prices is identified [34]. In Japan, wind was found to have no significant effect in lowering prices, while solar did in some years [32]. A merit order effect motivated decrease in the spot price was identified in Colombia; demonstrating the ability of increased VRE generation levels to lower the electricity spot price, with a dependency on other technologies to meet imbalance / be the marginal seller [30]. In Germany prices have been noted to lower, but with a dependency on VRE output forecasting [38, 61, 62]. Some of these investigations, however, only note VRE expansion to be a minor influence on price reduction [63]. An investigation of the German market further concludes imbalances caused by wind and solar forecasting errors result in increased prices [35]. The effects of other sources are also considered, such as gas, coal, and nuclear; the phasing out of which in Germany was noted to have had an upwards effect on prices [48].

The impact of VRE penetration on price can thereby be seen to vary based on the country, timescale (especially long term effects), and generation type investigated. As this study will focus more on short-term impacts from factional penetration to the generation mix by VRE, and compensation from the imbalance market (for short-term requirements), a breakdown for Britain will therefore be performed using a half-hourly timescale. Due to competition, high VRE levels will be expected to coincide with lower energy prices while they occur. The longer term impacts of VRE dependency by the grid fall outside the scope of this investigation, with this study instead investigating trends such as the generation type of marginal seller (and its average price) in the British market at different levels of VRE penetration. This approach builds upon similar methods to those previously used for the German market [47]. British VRE and market trends are also analysed with respect to comparable markets, such as that of Germany [41].

Methodologies for analysis in this area often include regression, and moving average approaches (of raw data and correlations) [64–66]. More specific approaches have also been developed in related forecasting studies [66–68]. Seasonal-Trend decomposition using Locally Estimated Scatterplot Smoothing (LOESS), also known as STL, is employed in this study to identify seasonal trends [69, 70]. This local regression method will have its seasonality calibrated to an annual timescale.

While VRE minimally participates in the imbalance market, incentivising balancing is still important to facilitate VRE integration [49]. Despite this significance, "balancing settlement prices are comparatively under-researched" in the British market [50]. As a result imbalance markets, such as that of

Germany or Britain, are prone to counter-intuitive [29] and non-linear behaviour [50].

While VRE generation is rarely the marginal seller, particularly during high price periods, its penetration at differing price levels allows for a better understanding of its integration. One such study, with respect to marginal seller fuel types, was performed for the German balancing market [47, 48]. Although analysis of the British imbalance market has been performed with respect to policy, pricing, and congestion [49–51], a breakdown using a similar methodology focused on the marginal seller fuel type is presently lacking in the academic literature. Furthermore, when considering the underlying causes of imbalance market changes through analysis of the overall market, a comparative analysis of wholesale market trends could also provide a significant point of reference.

2.2. Volatility

The potential relationship between price volatility and VRE penetration has been extensively investigated [71, 72]. This volatility may be measured in terms of greater extremes, standard deviation, variance, *etc.*. These results are also investigated across differing countries and timescales. Higher volatility from VRE penetration was identified in Australia, the US (New England), and Europe (Spain, Germany, and broader markets) [33, 73–77].

Denmark, which like the UK has favourable conditions for offshore wind, was found to be a notable exception, where unlike in Germany the hourly price profile was flattened by the inclusion of wind power [11, 77]. "Access to flexible generation capacity" and "wind power generation patterns" were noted to contribute to this difference [77]. The weekly volatility of electricity prices, however, was found to increase in both Denmark and Germany, due to the intermittency of VRE generation. Across the studied markets, therefore, increased use of VRE was often associated with higher volatility of electricity prices, though with notable exceptions such as in Denmark on an hourly timescale.

2.3. Hydro / Storage

Storage technologies such as hydro, batteries, hydrogen, ammonia, compressed air, *etc.*, have also been considered in conjunction with VRE sources such as wind, in the contexts of markets and variability compensation [78–80]. Of these, hydropower is heavily discussed, owing to its present scale of deployment; e.g. in Sweden, Germany, Turkey, and the Pacific Northwest [48, 81, 82]. These studies find hydro to assist in the integration of wind, though often as only a partial mitigation in its current scale. In a British estimation, if storage is to be responsible for meeting imbalances, then exponentially more will be required to compensate for the expansion of VRE infrastructure [14, 15].

2.4. Imbalance Market

The imbalance market is where supply-demand fluctuations from expectations/forecasts are resolved to ensure grid stability [29, 55]). Imbalances can result from generation scarcity or unexpected volatility. The bidding from this process, though subject to broader competition, ultimately determines the spot price of energy. Particularly where there are differences between the composition of the overall market and imbalance market, the disproportionate role of the imbalance market should be considered to ensure an understanding of price discovery [45, 47]. As they are non-dispatchable, VRE sources are particularly inadequate at fulfilling the needs of the imbalance market and are thus underrepresented. This lack of direct VRE feasibility in resolving supply-demand mismatches also makes the imbalance market of particular interest in the context of the energy transition [83].

Along with the earlier discussed solutions of hydro and other storage technologies (Section 2.3), gas generators, especially combined cycles gas turbines (CCGTs), are also noted to perform a complementary role to intermittent renewables, and typically dominate the imbalance market, as may be expected [84]. The idea of 'The Renewable Energy Policy Paradox' was dubbed in an economic analysis of the role of (dispatchable) fossil fuel generation in compensating for the inflexibility of VRE [45].

As such, expansion of the imbalance market to compensate for VRE sources may be generally expected, though this is not always the case. A 'German Paradox' was noted, for example, where increased efficiencies, and a more integrated imbalance market with the rest of Europe, led to Germany's imbalance market appearing to not require equivalent growth locally [29, 46, 85]). During year of 2020, for example, this dependency (particularly in France) was noted to be particularly acute [86].

Counter-intuitive and anomalous results such as Denmark's lacking VRE effect on volatility (earlier discussed in Section 2.2), the 'German Paradox', and the increased performance of renewables during 2020 are of critical importance to ensure a thorough understanding of real-world phenomenon

[29, 77, 86]. The 'paradoxically' expanding requirements for dispatchable capacity to offset the effects of the expansion of VRE has been documented both economically, and extensively in the German market [45, 47]. This paper will hence use the German market for comparison while performing a similar analysis focused on the British market. In these papers, fossil fuel energy is noted to be of increasing significance as the marginal (price-setting) seller of last resort [29, 44, 45]. In Germany, marginal selling from gas and hard-coal during periods of unmet residential loads increased, while low-marginal-cost / low-ramp-rate lignite and nuclear power were otherwise more common [47]. This is to be expected as generators with higher ramp rates will be able to more rapidly increase their output to compensate for increased energy demand. Where these generators are the marginal sellers, i.e. the current sellers of last resort, their transaction will set the price for the market.

2.5. British & German VRE Penetration

While extensive literature makes German data promising for comparison, the British market will be of primary interest. VRE expansion has been a policy focus in both countries, which may be verified with respect to available data. Due to the overlap between VRE penetration levels, compensation by marginal sellers, and the 'paradoxical' results therein, the British imbalance market will be of significant interest.

This paper will consider two years of German data [87, 88], and five years of British data [59, 60, 89, 90]. These periods include significant VRE penetration levels in the overall markets of these countries. Figures 1 and 2 display the fractional VRE generation penetration in Britain and Germany along with the seasonal trend generated via STL with an annual seasonality. The STL method will be discussed later, and will be used throughout this paper.

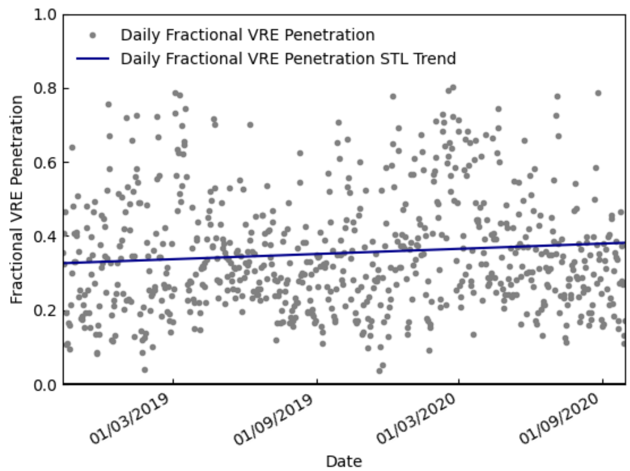

Figure 1: Germany's fractional variable renewable energy (VRE) penetration (i.e. fractional generation) and seasonal trend of VRE penetration from 2019 to 2020. Points display the daily values, while the line shows the trend.

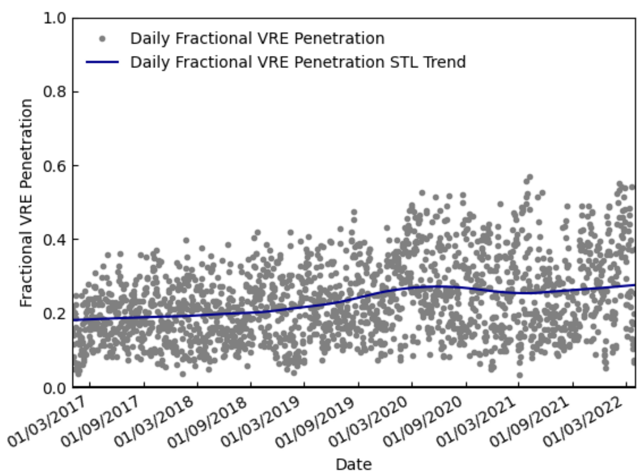

Figure 2: Britain's fractional variable VRE penetration and seasonal trend of VRE penetration from 2017 to 2022. Points display the daily values, while the line shows the trend.

The fractional VRE penetration in Figures 1 and 2 are both significant, and steadily growing. While there are similar objectives in the overall British and German renewable zeitgeists, significant differences between these systems may be observed, even at this level. For example, Germany saw higher levels of penetration, but lower levels of growth when compared to Britain, including within just the timescale of the German data.

German and British data are therefore of both individual and comparative interest. As VRE continues to be expanded in Britain it will be important to determine the challenges faced by the electricity market. Increased market distress or diminishing environmental returns, deriving from a reliance on or inability to displace dispatchable fossil fuel generation using intermittent generation, should be investigated thereafter by comparing the British overall and imbalance markets, expanding upon related methods employed in other countries.

3. Data & Methodology

This paper analyses the following data from the perspective of price, generation, and technology type:

- Overall German market.
- Overall British market.
- British imbalance market.

Note that fractional or percentage penetration of generation will be discussed throughout this paper. This specifically refers to the contribution of VRE to the generation mix at each specific time on a half-hourly, hourly, or daily window, as opposed to penetration over a longer timescale or some other metric such as installed capacity. Data relating to other markets was unfortunately unavailable, however, this paper presents a methodology which would be applicable for the use of such data in future studies for policy makers in other countries.

3.1. Overall German Market

Open Power System provides data on a number of countries [87]. Of these, Germany's data was most suitable for comparison to Britain. Open Power System collects this data from the European Network of Transmission System Operators for Electricity [88]. Generation (day-ahead) price, and VRE generation technology was available for Germany on an hourly timescale, from October 2018 to September 2020.

3.2. Overall British Market

By comparison, British data was on a half-hourly timescale for spot price and generation technology type. These types are divided into VRE which consists of offshore wind, onshore wind, and solar generation technologies, and non-VRE which consists of coal, gas, nuclear, biomass, hydro, and other generation technologies. This information was taken from January 2017 to March 2022. The Balancing Mechanism Reporting Service (BMRS) was used as the primary source of information [59, 60, 89–91].

3.3. British Imbalance Market

BMRS data was also used as the main source of information on the imbalance market. Here, individual generation units are noted in the ‘detailed system data’, which can be mapped to a generation type either directly, or indirectly via an associated power-plant [60, 90, 91]. As types are not always provided, however, mapping to types listed the Digest of UK Energy Statistics (DUKES) was also performed using Energy Identification Codes (EICs) and other details provided [58, 92, 93].

3.4. Data Decomposition

Various analyses on these datasets are performed (Section 4). For many of these analyses, results contain both trend components, along with significant seasonality. Observing the trend by removing seasonality is particularly significant given the high resolution of the data. This paper uses the STL method to identify trends by removing noise and seasonality from an observed dataset. STL applies a standard stastisticap approach for trend identification, de-noising, and prediction [94, 95]). Graphed trends throughout this paper were thereby determined using the STL method.

Using the 'Statsmodels' Library in Python, STL decompositions were therefore performed due to the suitability of this methodology to analyse datasets with these characteristics [69, 70]. While the aforementioned high resolution of the data can make the visual identification of seasonality difficult, it is often significant enough to even be visible in the raw data. Regardless, while trends are generally discussed in the main paper, decomposition outputs can also be found in the Supplementary Material's A2.

4. Results and Analysis

Numerous examinations of German and British data are performed with respect to the trends of renewables in the energy markets. Given that more detailed data is available for Britain, more detail may be placed into its examination. Comparing both countries, however, is still of interest, with Germany serving as a benchmark while Britain is the primary focus.

4.1. Germany's (DE) Energy Mix & Overall Market

German (DE) energy data was obtained for the time-span of October 2018 to September 2020, on an hourly timescale. This data notes energy (day-ahead) price, energy demand, along with the output from solar, and wind. Compared to the data available for Britain (Section 4.2), this data, though not as comprehensive in completeness, timescale, duration, and granularity, still allows for a number of comparable analyses to be performed; such as in Figures 1 and 2.

4.1.1. DE: Energy (Electricity) Demand

Firstly, to establish a background for the energy demand in Germany, the load is graphed in Figure 3.

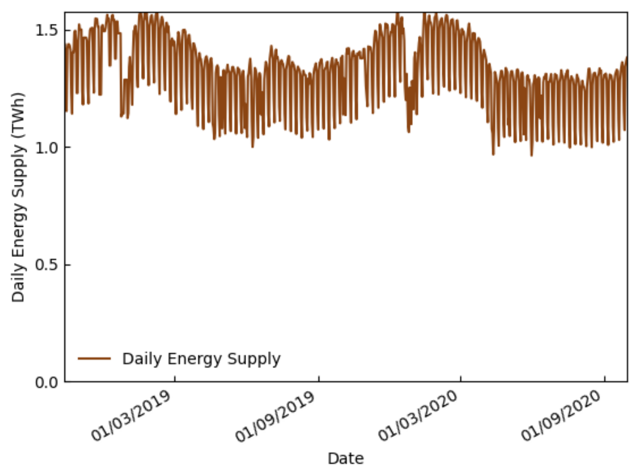

Figure 3: Germany's daily electrical energy load (TWh).

The observable seasonality in this data is to be expected given increased winter demand in December, January, and February. Furthermore, the load drop at the end of December during this otherwise period of higher demand is due to the holiday break. This annual seasonality should be kept in mind when considering further trends. Lesser weekly fluctuations also exist.

4.1.2. DE: Energy Prices and VRE Penetration

Previous studies generally find VRE penetration to be either uncorrelated, or negatively correlated with energy prices. How does Germany compare?

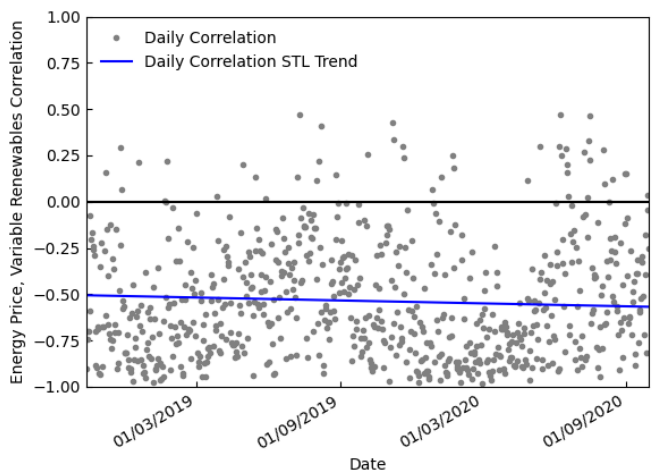

Figure 4: Germany's energy price (EUR/MWh) to fractional variable renewable energy penetration correlation, and trend. This trend is persistently negative.

As can be observed in Figure 4, a negative correlation coefficient trend exists between VRE penetration and energy prices. Seasonality is also observable in the raw data, with the higher-demand winter seeing the strongest negative correlation, though the trends are of primary interest in this analysis.

4.1.3. DE: VRE Penetration, and Energy Price Standard Deviation

Due to inflexibility from non-dispatchability, an increase in the standard deviation of VRE penetration is expected to occur alongside an expansion of penetration. Figure 5 notes this trend a daily basis.

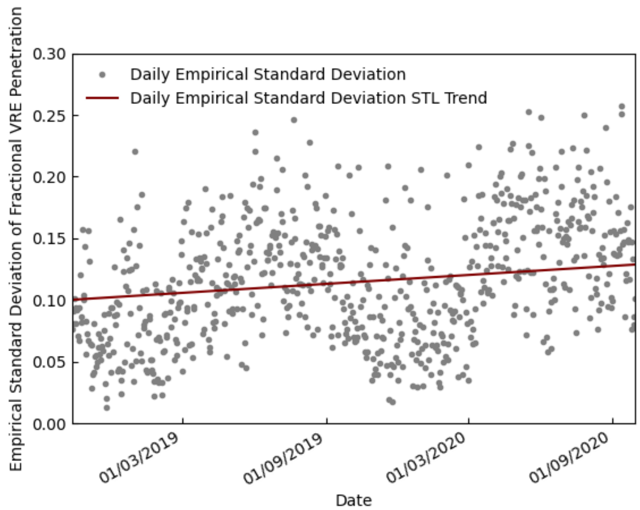

Figure 5: Germany's standard deviation of fractional variable renewable energy penetration, and trend.

Observable in Figure 5 is an increase in VRE penetration's standard deviation over time (as expected), though with significant seasonality. A more interesting trend exists in Figure 6, where the volatility of price does not show an equivalent increase.

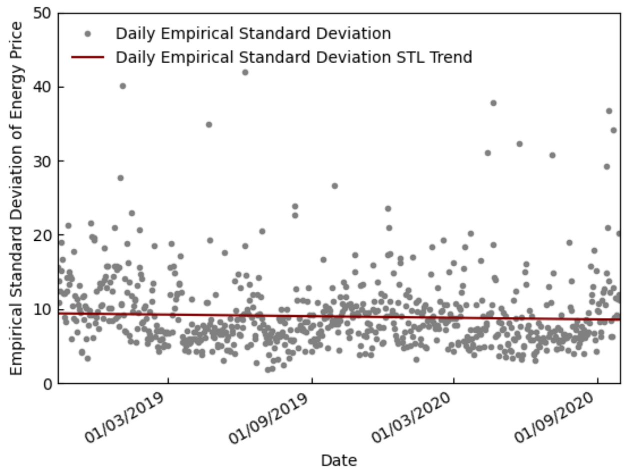

Figure 6: Germany's standard deviation of energy price, and trend.

4.1.4. DE: Energy Prices and Individual VRE Type Penetrations

The correlation between VRE penetration and price may also be broken down further into wind and solar separately, as seen in Figure 7.

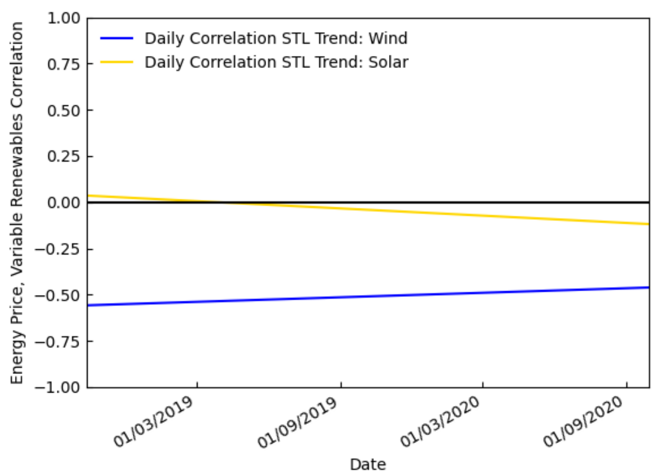

Figure 7: Seasonal trends of Germany's energy price (EUR/MWh) to fractional wind, and solar (PV) penetration correlation.

The negative correlation between VRE penetration and price is clearly driven by wind, with wind having a generally negative correlation while solar's correlation trends are closer to zero. With approximately three times higher the average wind penetration compared to solar, this results in the overall trend observed in Figure 4. Note that penetration is in terms of fractional generation, not capacity. This is important, given solar's "dismal" [96, 97] capacity factor compared to wind in Germany.

4.2. Britain's (BR) Energy Mix & Overall Market

Data for Britain (BR) was comparatively more detailed than that obtained for Germany. For Germany data is provided for total generation from all sources, and individually for the VRE renewables types of solar and wind. The British data differentiates by source, with seperate figures for gas, oil, coal, onshore wind, offshore wind, solar, biomass, other, *etc.*. Furthermore, British data is on a half-hourly timescale, over a longer timescale, and provides a spot price via its imbalance market (discussed later in more detail in Section 4.3). This allows for additional detail and figures to be provided to expand upon equivalent trends to those examined for Germany.

4.2.1. BR: Energy (Electricity) Demand

UK energy supply has been trending downwards, at least until 2020, for the past decade, with clear seasonality, e.g. higher demand in the British winter from December to February. This demand is graphed in Figure 8.

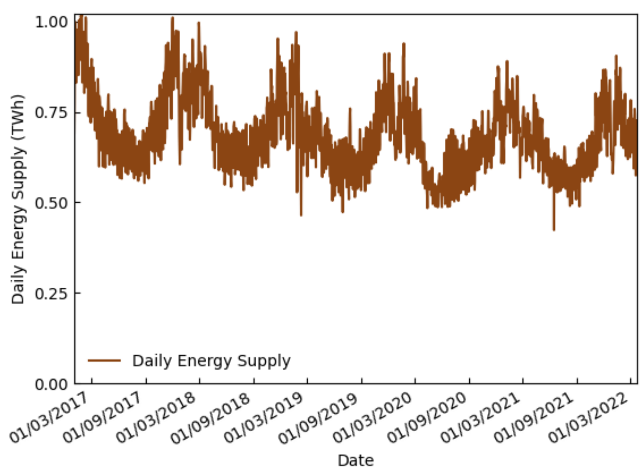

Figure 8: Britain's daily energy (electricity) load (TWh).

In Figure 8 this annual seasonality may be seen. Both in Britain and Germany, therefore, demand is seasonal. This seasonality peaks in the winter and dips in the summer, though there is a brief drop during the winter holiday period.

4.2.2. BR: Energy Prices and VRE Penetration

The correlation coefficient between the spot price and the summed generation of VRE sources is graphed in Figure 9.

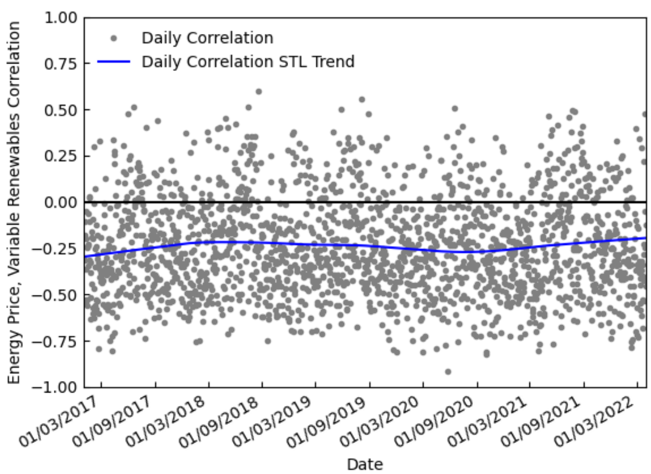

Figure 9: Britain's energy price (GBP/MWh) to fractional variable renewable energy penetration correlation coefficient. The trend is persistently negative.

Figure 9 displays a generally weak, negative correlation between energy price and the proportion of energy contributed by VRE sources, though of a lower magnitude than in Germany.

Coal and gas are summed to find the correlation between fossil fuel generation penetration and energy price, as is shown in Figure 10.

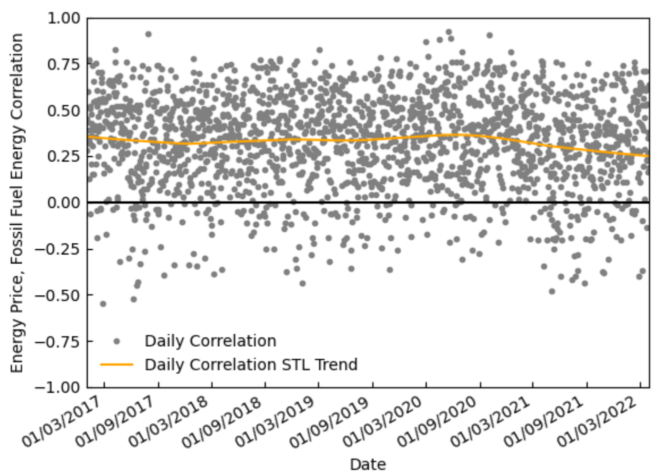

Figure 10: Britain's energy price (GBP/MWh) to fractional fossil fuel energy penetration correlation.

In Figure 10, it can be seen that fossil fuels exhibit a generally weak, positive correlation with the spot price. This is in clear contrast to the VRE trend, which was negative. As these figures refer to the generation penetration rates at each time interval, these prices reflect a marginal cost based merit order dispatch.

4.2.3. BR: VRE Penetration, and Energy Price Standard Deviation

As with the German data, the standard deviation of fractional VRE penetration is calculated, along with an associated trend.

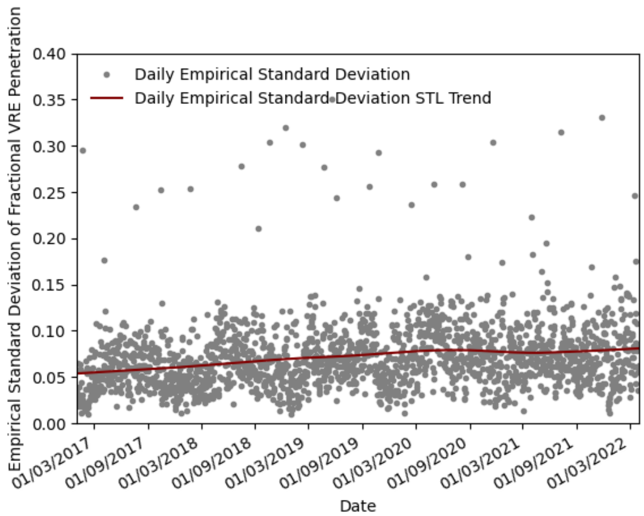

Figure 11: Britain's standard deviation of fractional variable renewable energy penetration. Daily and trend.

In Figure 11, the standard deviation can be seen to have increased steadily as expected. This corroborates the trends expected from an increasing VRE environment. In particular where storage, despite some growth, has not kept pace in resolving the variation of non-dispatchability; which is of relevance to the later discussed (Section 4.3) imbalance market.

The standard deviation, and trend, is also found for the energy price (GBP rather than EUR).

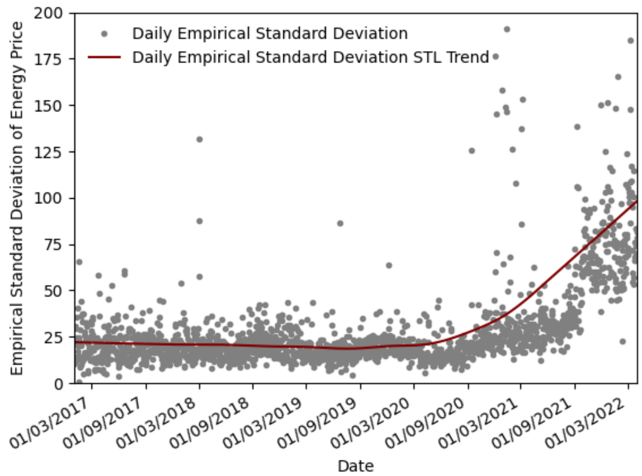

Figure 12: Britain's standard deviation of the spot energy price and associated trend. Due to several outlier prices, this image is cropped for readability, with the full version shown in Figure A17 of the supplementary Material.

Figure 12 portrays the standard deviation of the spot energy price. A dramatic increase of the spot energy price can be seen in recent years, before which it was constant. Thus, before 2020, British and German trends appear much more similar with a significant difference in their price standard deviation trends since. Finally, while price volatility has increased since early 2020, the (slower) growth in VRE penetration volatility stalled in late 2020, though it remains historically high.

4.2.4. BR: Energy Prices and Individual VRE Type Penetrations

The comparison between energy prices and VRE penetration in Britain (Section 4.2.2) is decomposed by type. Here, the same analysis is performed, but individually considering onshore wind, offshore wind, and (photovoltaic) solar. To avoid clutter, only the trends are graphed in Figure 13.

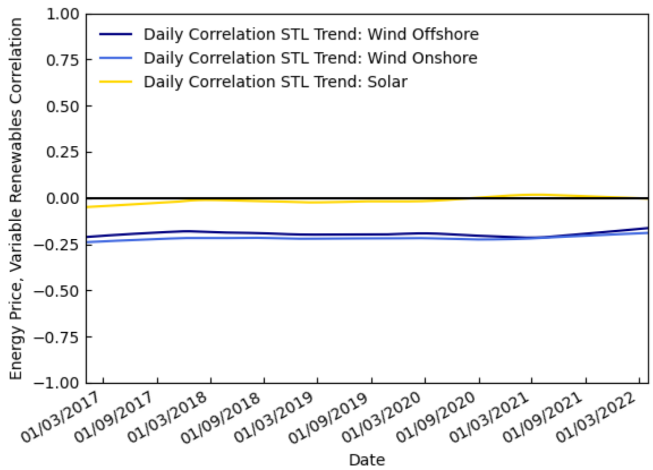

Figure 13: Seasonal trends of Britain's energy price (GBP/MWh) to fractional offshore wind, onshore wind, and solar (PV) penetration correlation.

A few key observations from Figure 13 may be noted. Firstly, both wind sources are clearly far more aligned with one another, than with solar. Secondly, wind power is also closely aligned with the overall VRE trend (Section 4.2.2) seen in Figure 9, which is unsurprising given their far greater contributions to the network. Thirdly, while wind has a persistently weak, negative correlation, the correlation of solar is near zero.

4.3. Britain's Marginal Seller in the Imbalance Market

While the above cases focused primarily on the market's overall energy proportions, the marginal interactions on the imbalance market are of particular importance in influencing the spot price, and the overall market as a whole by extension. Dispatchables were predictably responsible for over 99% of marginal sales, i.e. how often they were the marginal seller, as per data from the imbalance market. Using data from the energy market the generation type of the marginal seller was determined for the majority of time instances. Of the known marginal sellers, four types were identified during the examined time period: gas at 89.66%, hydro (generally, or specifically re-pumped hydro) at 5.64%, coal at 4.18%, and wind at 0.53% (more detail in Supplementary Material's A4). Hydro/storage is not only dispatchable, but also chargeable. If storage/hydro is excluded, then the imbalance market would have its marginal seller be gas overwhelmingly (95.02% of the time).

The marginal seller type over time is shown in Figure 14.

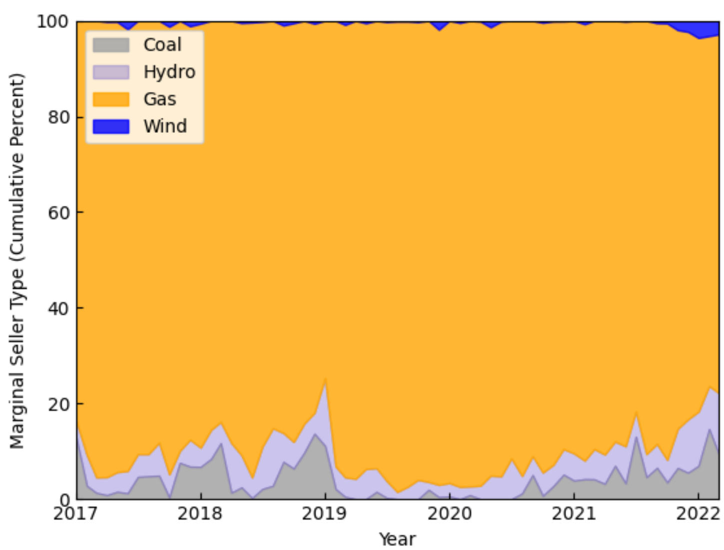

Figure 14: Monthly Marginal Seller Type in the British Energy Imbalance Market (2017-2022). Ordered by average energy price (GBP/MWh) when each type is the marginal seller).

In Figure 14 coal can be seen to decline as a marginal seller from 2019 to 2020, only to resurge in 2021 and 2022. This is despite a resurgance of equivilent scale not occurring in the overall generation mix. Historically, coal has been more consistently utilised as a baseload energy source, with gas being later dispatched more opportunistically.

Table 1: Average price set (GBP/MWh) when fuel type is the marginal seller from 2017 to 2022.

Wind	Gas	Hydro	Coal
-38.89	67.42	99.81	102.02

Table 1 notes the average price set by each technology type when they are the marginal seller. These prices are also indicative of dispatch order. Were gas to be dispatched after coal, then a higher average price set by gas would be expected. The data, however, instead indicates that coal is a bidder of later resort as it typically sets a higher price. The prices shown in Table 1 may be further analysed in combination with the results shown in Figure 14.

By doing so, the presence of wind (as negligible as it is), may be further broken down. Despite less than 2% (1.65%) of time periods having a $\leq$0 GBP/MWh energy price, the majority (87.85%) of the instances where wind is the marginal seller, occur when this is the case. Specifically, the average spot price when wind was the marginal seller was -38.89 GBP/MWh, as opposed to 67.42 GBP/MWh for gas, 99.81 GBP/MWh for hydro, and 102.02 GBP/MWh for coal. Wind power outside of the imbalance market, may still affect prices via competition, but its direct influence on the marginal side of the market, is certainly weaker. By extension, the displacement of gas (or even coal) by VRE, under existing trends, will be of increasing difficulty as dispatchability becomes increasingly important for remaining fossil fuel operators.

The most counter-intuitive finding, is the re-emergence of coal as a marginal seller in the energy (imbalance) market. While a broad range of factors may contribute to this paradoxical result, it should be further noted that this re-entrenchment has not been seen in the overall proportional generation rates in the energy market (Supplementary Material's A1).

The re-entrenchment of coal from 2020 onward aligns with the price volatility increase in Figure 12, unlike 2017-2019, which may also be of interest in future investigations of possible reversals. To further investigate this, a breakdown considering VRE penetration levels is performed. Figure 15 shows the marginal seller type (in percentage terms) at different VRE penetration levels, along with also breaking down the percentage rate of each VRE penetration level, which for context, has a mean level of 23.09% and a median level of 21.30% for time periods with determined marginal seller types.

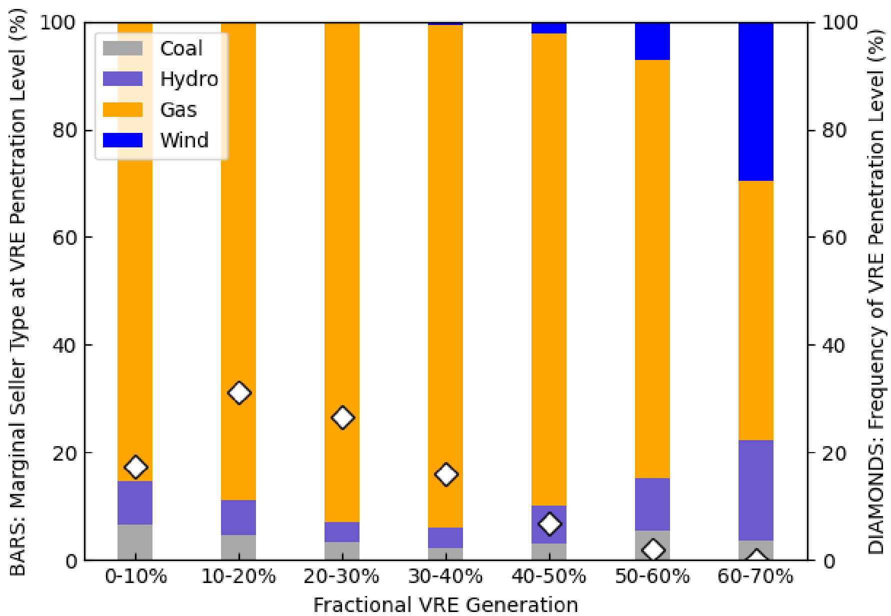

Figure 15: Bars display the marginal seller generation type (as a percentage) during differing levels of VRE penetration. Diamond markers display the percentage of time periods during which this level of VRE penetration occurred. For example, while wind was the marginal seller 29.63% of the time when overall VRE penetration was at 60-70%, VRE penetration rarely reached this level of contribution.

In both Figure 14 and 15, gas clearly dominates. Furthermore, coal and hydro can be seen to be more responsible for grid compensation during periods of below average VRE penetration. As VRE penetration was negatively correlated with prices (Figure 9), this corroborates the higher average spot prices charged during periods of hydro and coal marginal selling. This is particularly evident for coal in Figure 15, as well as hydro when the frequencies of different VRE penetration levels are considered. The ‘British Paradox’, therefore appears to be most effectively explained by an increasing need for compensation, as indicated by volatility.

5. Discussion

Thus far this paper has reviewed the expected trends and counter-intuitive results in energy markets with respect to VRE penetration. Many of these trends were recreated and compared in Germany and Britain, the former being more extensively studied in past literature, and thus serving as an effective benchmark, though with recent developments of interest. In particular, a 'British Paradox' of coal reemergence in the imbalance market, coinciding with increasing volatility, was found.

Gas domination of the imbalance market is not unexpected. This aligns with past literature exploring, with notable exceptions, the paradoxically complementary nature of dispatchable fossil fuel generation in the imbalance market, and VRE expansion to replace fossil fuels in the general market. In Britain's case, however, what was counter-intuitive was the resurgence of previously declining coal energy as the marginal seller in the imbalance market.

5.1. Underlying Trends in Britain and Germany

Firstly, the general trends can be summarised:

- In both Germany and Britain, periods of higher VRE penetration were correlated with lower energy prices. These correlations tended to be persistent, but weak, especially in Britain. This is calculated on an hourly/half-hourly time frequency and bares relevancy to cost-optimisation modelling, rather than long term price effects.

- These trends have resulted from the contributions from wind energy, rather than solar.
- In both Germany and Britain the volatility (standard deviation) of VRE penetration has steadily increased.
- The volatility (standard deviation) of energy prices, however, has remained constant in Germany and Britain until early 2020, after which in Britain, a clear upwards trend is observed and continues into 2022.

Annual seasonality was decomposed to more thoroughly investigate these trends.

It is not surprising that some anomalous results would be found in 2020, or since in areas such as price volatility, however these changes are not uniform across markets. The paradoxical behaviour in the British imbalance market has not been matched by general generation trends; i.e. overall UK generation mix proportions do not reflect a resurgence in coal energy generation.

5.2. Effects in the British Imbalance Market: Coal Re-Entrenchment, Volatility

Coal re-entrenchment is observed in the imbalance market, but not in the overall market. So while the overall market's coal penetration has declined, and policy guidance scenarios typically project a shift away from coal (capacity and generation), the use of coal as a marginal seller has increased. Based on these overall goals, coal contributions in the imbalance market may have been expected to be replaced by marginal sales from other sources such as gas or hydro, however, coal has instead re-emerged. Speculation as to the explanation of this 'British Paradox' should be careful to explain not only this phenomenon, but also its particular scope.

The imbalance market continues to be dominated by gas generation. Coal, by comparison, has a higher average spot price when it is the marginal seller, as seen in Table 1. An alignment therefore exists between increasing price volatility (Figure 12) and increasing coal marginal selling (Figure 14), with coal and hydro serving as marginal sellers of last resort compared to gas (Figure 15). The imbalance market, therefore, seems to generally prefer gas to coal, with hydro (storage) interestingly serving a very similar function to coal and having a similar average marginal selling price, as being more of an opportunist in the imbalance market.

The behaviour of the imbalance market is not necessarily in conflict with decarbonisation objectives, as can be seen in the changes in the overall generation mix, which the imbalance market compensates for. These results, however, do indicate that there is a significant difference between lowering energy generation from fossil fuels, and fossil fuel energy capacity. Under current imbalance market circumstances, fossil fuel (increasingly coal) capacity is used to compensate for the extremes in the overall market even as its decarbonisation is pursued. This, however, is not exclusively the case for fossil fuels, as hydro and potentially other storage by extension, appear to be capable of fulfilling a comparable role to coal as marginal sellers, and are thus capable of competing with it.

Presently, however, the role of fossil fuels in the imbalance market remains persistently stubborn. Findings related to gas dominance in the imbalance market despite a general emphasis on VRE expansion, therefore, are consistent with renewable energy policy and market paradoxes previously investigated [45, 47]. Coal re-entrenchment, however, is of particular note given the extent to which the trend of its contribution in the imbalance market has reversed while its decline remains clear in the overall market. The role of hydro (storage), while less counter-intuitive, was also shown to be of interest due to the similarity in pricing and VRE penetration compensation of its behaviour to coal.

5.3. Macro Events

Energy markets experienced significant shocks from major global and domestic events between 2019 and 2022. These events have a noticeable effect on energy demand, prices, and price volatility. Thus, while the influences of the energy transition are ongoing, the impacts of these macro events should be discussed.

The first of these events may be seen in 2020, where reduced demand is observed in Figures 3 and 8. This reduction is clearly related to Covid-related lock-downs implemented in both the UK and Germany. While reduced demand may impose a short-term downwards pressure on energy prices, subsequent production and supply chain disorder during re-openings have the opposite effect. Due to the global scale of similar policies, these trends are reflected in global energy prices.

The second major event was the conflict between Russia and Ukraine, and its subsequent effect on energy prices. While increased price volatility proceeds this event, as is seen in Figure 12, the subsequent increase in energy prices is still significant. In 2022 energy prices spiked much higher than in their prior 2021 peak. Globally, the price of natural gas increased substantially, while the price of coal increased even more so [98, 99]. European markets saw disproportionately higher prices still. As a caveat it should also be noted that gas makes up a greater proportion of generation costs for gas turbines, compared to the proportional cost of coal in coal power plants, which have higher maintenance costs [100].

Simultaneously increased VRE penetration persists, resulting in a lower proportion of non-variable generation capacity that is able to be dispatched to compensate for shocks. This trend in particular, is expected to continue. So while a reduction in coal use and market volatility may still be expected were macro conditions to improve, the long-term increase in VRE use will still result in an increased requirement for compensation technologies. Alternative dispatchable generation sources, load-shifting batteries, improved transmission and system integrity services, superior predictive capabilities, and demand schedulability will therefore all remain topics of long term interest due to their relevance to VRE integration. As fossil fuel technologies such as coal and gas are increasingly displaced from the overall generation mix, their displacement from balancing services will explicitly require the consideration of these options due to the low prevalence of VRE price setting in the imbalance market.

In the short term, with respect to demand, Britain's ESO (electricity system operator) has already suggested a continuation of the Demand Flexibility

Service for the coming winter [101]. This scheme incentivises consumers to reschedule their energy use outside of peak demand periods. On the topic of coal resurgence to meet imbalances the ESO also stated, that they are discussing the availability of two Drax coal units for contingency contracts, while currently only one unit is in use [101]. Coal's return in the short-term, however, is thus clearly ongoing. Though the current resurgence of coal represents a divergence from prior forecasts, a longer term decline in coal use is still expected [102]. With non-dispatchables like VRE being poorly suited for addressing contingencies, dispatchable capacity from other generators, hydro, batteries, *etc.* would be required to displace the presently expanding balancing operations performed by coal. Even if market shocks were to subside, therefore, market resilience will require these technologies in order to be resilient to unexpected future events, particularly as the existing coal fleet retires entirely.

A key point of this 'British Paradox' is, therefore, not only that coal generation has resurged in recent years, but that it has disproportionately resurged as an opportunistic bidder to meet imbalances. Historically coal was cheaper and less capable of ramping than gas power plants, and was thus dispatched prior to gas. The data suggest these roles are now reversed. While an increased use of coal may be explained by an increase in a disproportionate price of gas generation relative to coal, though this is uncertain, it would not explain this change in coal's bidding behaviour as a seller of later resort.

In Figure 14 the return of coal as a marginal seller is evident. While overall generation has also increased, this has not been to the same extent. Furthermore, as can be seen in Table 1, the average price set by coal is higher than gas, as is typical of a seller of later resort. Finally, as was shown in Figure 15, during periods of lower VRE penetration, where generation is more scarce, coal is more likely to be the marginal seller. The 'British Paradox' of increased coal generation as a marginal seller, therefore, is also indicative of the need for balancing services, which will be an issue of ongoing interest due to increasing VRE generation, even if short term conditions improve.

5.4. Future Role of Storage and the Imbalance Market

Most projected plans from the UK government anticipate a phasing out of coal, while a continued role for gas remains present in some trajectories [103–107]. The resurgence of coal in the imbalance market, therefore, appears to be a matter of desperation. It may even be the case that there are observable limits in some 'efficiency vs stability' trade-off with respect to surplus capacity at the imbalance market's disposal.

Compared to these projections, the role of storage to assist in compensating for increased VRE deployment, may have been underestimated [25, 26]. If coal replacement was pursued, then more gas or storage may be required. New advancements in other compensatory technologies, such as rapidly ramping small-modular nuclear reactors, could also be beneficial. Finally, though electricity consumption is projected to increase due to electrification, this includes an expansion of more easily scheduled demand from electric vehicles and heaters. Presently, however, storage may further assist the needs of the imbalance market. This may serve a specialised role in replacing coal, but with respect to future investigations more broadly, may also displace some marginal sales from gas generators.

Further investigations of market prices should also make particular note of the marginal seller's role in determining the spot price of energy. Future studies seeking to assess the decarbonisation role of storage operations, may seek to approximate this effect by examining the marginal seller type at that time, as opposed to the overall generation mix; which would overwhelmingly be gas. If storage were further sought as a marginal seller to displace coal (these being similarly priced) or gas, the negative VRE penetration to price correlation indicates that a profit-motivated cost optimisation storage approach would be incentivised to compensate for VRE generation and displace fossil fuels in the imbalance market. This could complement VRE in the overall market, given that VRE generators lack the flexibility desirable in the imbalance market. The imbalance market is therefore of particular interest when investigating not only the spot price of energy, but also the environmental impacts of future expansions (such as in storage) given the first generation type to be economically displaced would be the former marginal seller.

5.5. Recommendations Summary

Under these conditions, there is a disconnect between decreasing fossil fuel generation and capacity, with the latter being disproportionately difficult to displace due to its variable use in the imbalance market, even if this behaviour increasingly compensates for VRE volatility. While this is consistent with past literature with respect to gas, coal's reemergence suggests a desperation in meeting the needs of the imbalance market compared to national policy expectations. The market behaviour of hydro suggests storage can (where cost-viable) serve as an alternative marginal seller to coal in particular, and gas more generally. While VRE has had success in displacing fossil fuelled electricity in the overall generation mix, this success does not extend to the imbalance market. Findings regarding VRE and market price trends suggest cost-optimising storage or demand scheduling would complement VRE in the grid. Given the imbalance market composition and pricing, however, competition with existing hydro storage may occur. Furthermore, estimations of storage decarbonisation may make use of the marginal seller's displacement to contextualise their environmental impact.

6. Conclusion

This study comprised of two main components. Firstly, it confirmed many general energy market trends relating to VRE penetration, price, and volatility in Britain against the benchmark of Germany. Secondly, it further analysed these trends in the context of the British imbalance market, where extensive analysis of VRE penetration levels, price setting generation types, and the prices they set was performed, resulting in the uncovering of counter-intuitive coal behaviour compared to its historic norm.

- In Germany and, to a lesser extent, Britain, periods of high VRE penetration have a negative correlation with price. These trends:
  - Occur in a framework with annual seasonality;
  - Are specifically the result of wind energy contributions, and,
  - Are accompanied with higher VRE penetration volatility, and recently, considerably higher energy price volatility in Britain.
- The marginal seller in the British imbalance market is generally gas,

though hydro and coal have regained their former (minority) proportions.

- The trend of coal re-entrenchment is counter to that of the overall market. Coal is not simply returning to the market to perform its conventional role, but instead as a seller of later resort. This 'British Paradox' aligns with the aforementioned increases in market volatility, such that there now exist scenarios where coal regains cost viability similar to hydro/storage. It is not simply higher energy prices, but increase energy price volatility, that incentivises coal's new bidding behaviour and its similarly to storage technologies which generate revenues from price spreads.

As such, while higher VRE penetration is linked to lower energy prices (when it occurs), during periods of higher price and generally lower VRE penetration where compensation is required, higher volatility appears to facilitate a cost structure allowing the re-entrenchment of marginal sellers which typically sell at a higher cost, such as hydro and coal, though gas remains dominant. While this resurgence of coal as a price setter may reverse, the fundamental requirement for dispatchable capacity for market balancing operations for VRE integration, remains as a key challenge as VRE capacity is expanded. The expansion of hydro, battery, or other dispatchable generation capacity may be pursued as alternatives. Direct VRE penetration conclusions should therefore be tempered by these broader market effects, particularly with respect to this paper's recommendations.

Research Data

Raw data, such as that obtained from BMRS (for Britain) and Open Power System (for Germany) 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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