Supplementary Material

to

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

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A1. UK Generation Mix Proportions

The proportional mix of the UK's energy generation is of interest, particularly with respect to noting the decline in coal (in the general market, which as the paper discusses, is interestingly not reflected in the imbalance market), and the growth of VRE. Two databases were used for this, DUKES (for which there are more years), and BMRS (the main source of data in this paper, and which at the time of writing has data published to a more recent date) [1, 2, 3].

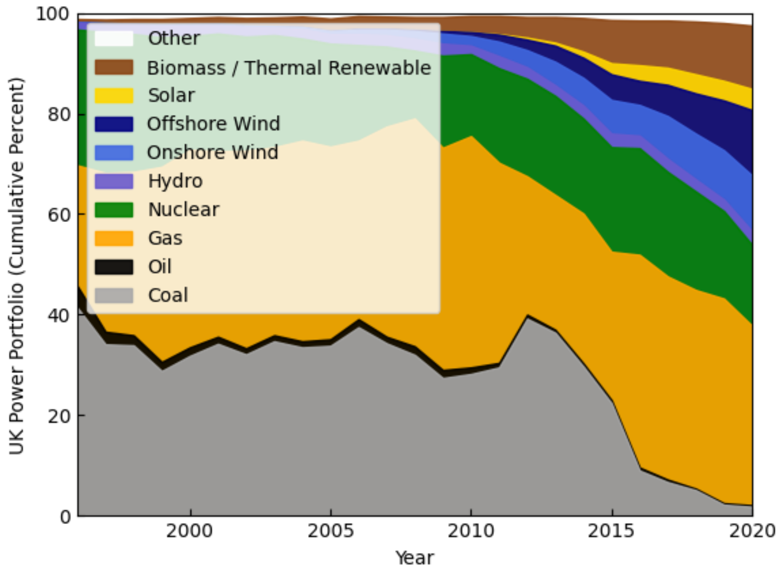

Figure A1: DUKES: Proportional generation type of energy (electricity), in the UK.

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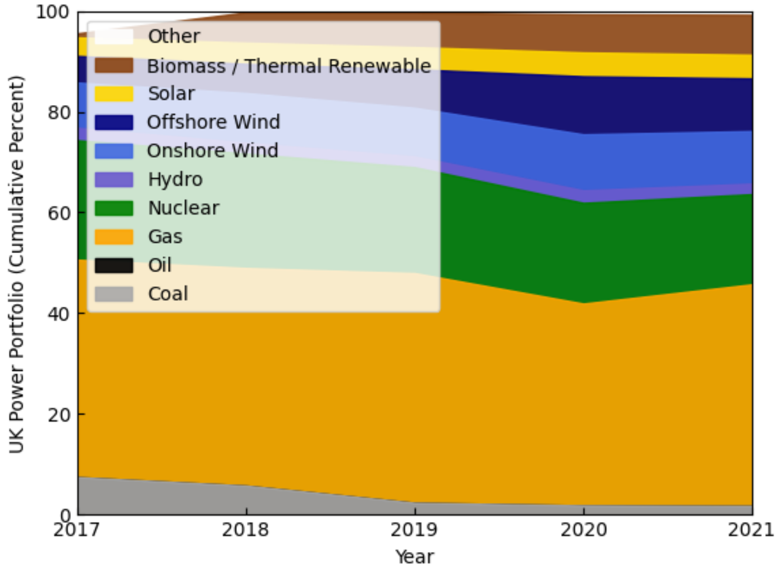

Figure A2: BMRS: Proportional generation type of energy (electricity), in the UK.

Note that in both these figures there is a clear trend of coal power decline and VRE growth, as advised to continue [4]. This is in contrast to imbalance market trends discussed through the paper.

Numerous sources also exist for Germany (and other countries), which may be of interest for future investigations into related topics [5, 6, 7, 8, 9].

A2. STL Decompositions

Seasonal and trend decomposition using LOESS (STL) was performed to identify trends in various datasets analysed in this paper. This was performed for German and British data, which both considered multi-year periods. These were generated using the 'Statsmodels' Library for Python [10].

A2.0.1. Decompositions for Introductory VRE Penetration

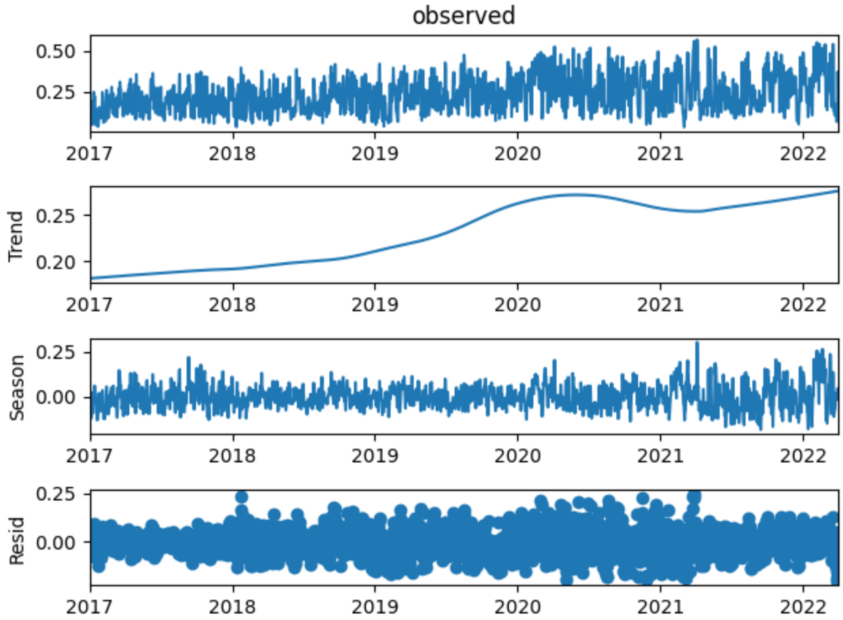

Figure A3: STL decomposition of Britain's fractional variable VRE penetration.

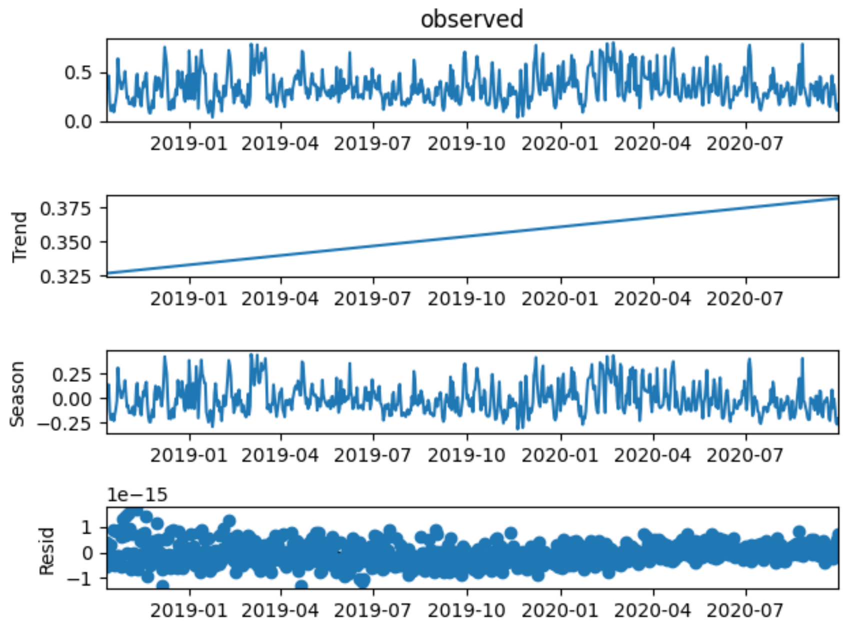

Figure A4: STL decomposition of Germany's fractional variable renewable energy penetration.

A2.0.2. Decompositions for Energy Prices and VRE Penetration

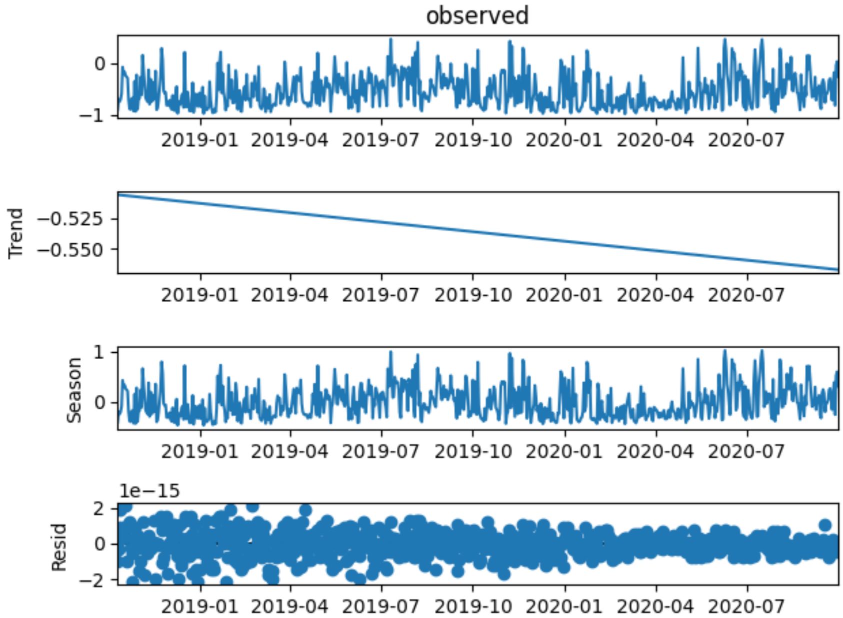

Figure A5: STL decomposition of Germany's energy price (EUR/MWh) to fractional variable renewable energy penetration correlation.

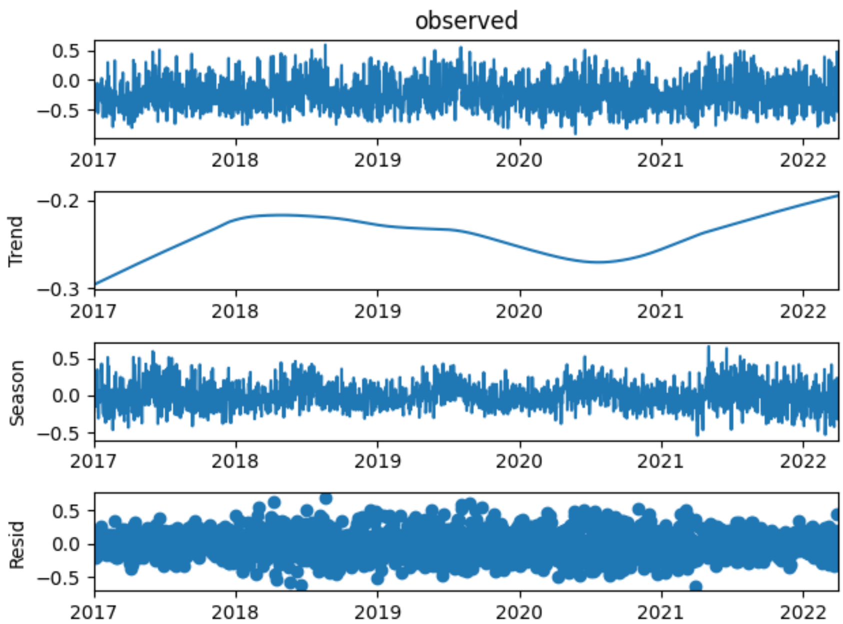

Figure A6: STL decomposition of Britain's energy price (GBP/MWh) to fractional variable renewable energy penetration correlation.

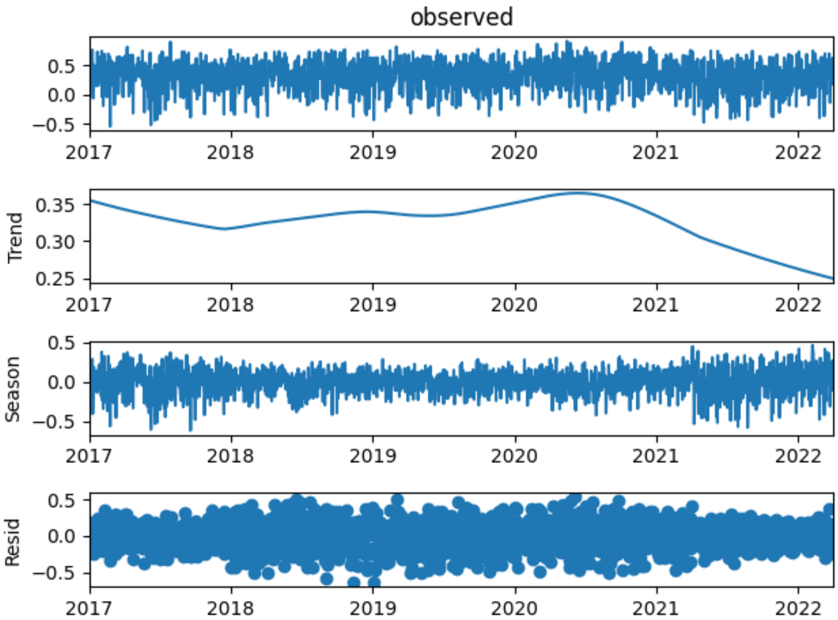

Figure A7: STL decomposition of Britain's energy price (GBP/MWh) to fractional fossil fuel energy penetration correlation.

A2.1. Decompositions for VRE Penetration, and Energy Price Standard Deviation

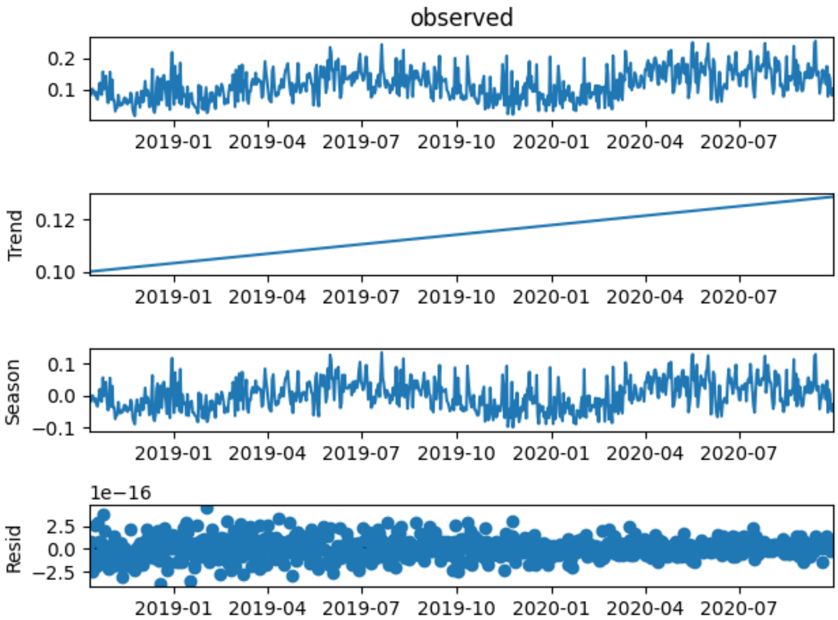

Figure A8: STL decomposition of Germany's standard deviation of fractional variable renewable energy penetration.

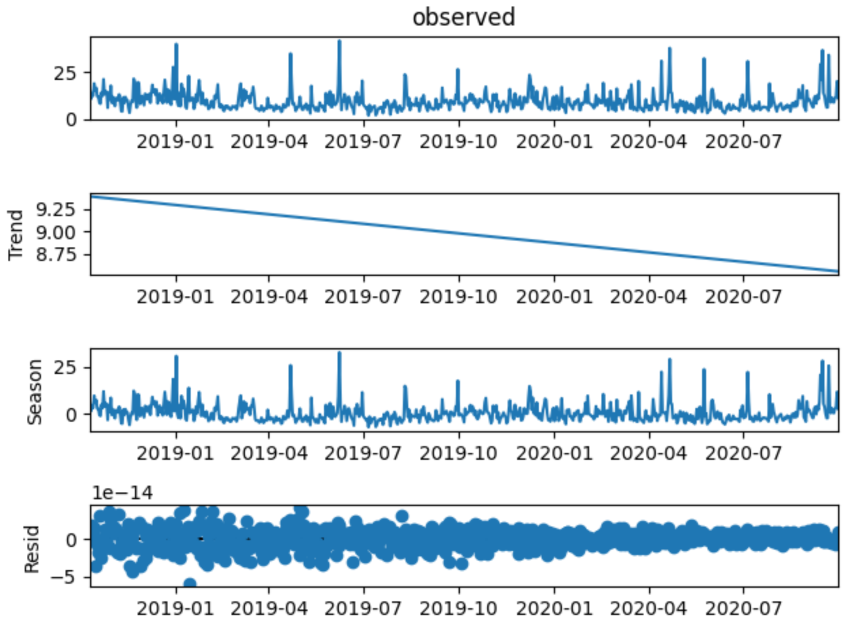

Figure A9: STL decomposition of Germany's standard deviation of energy price.

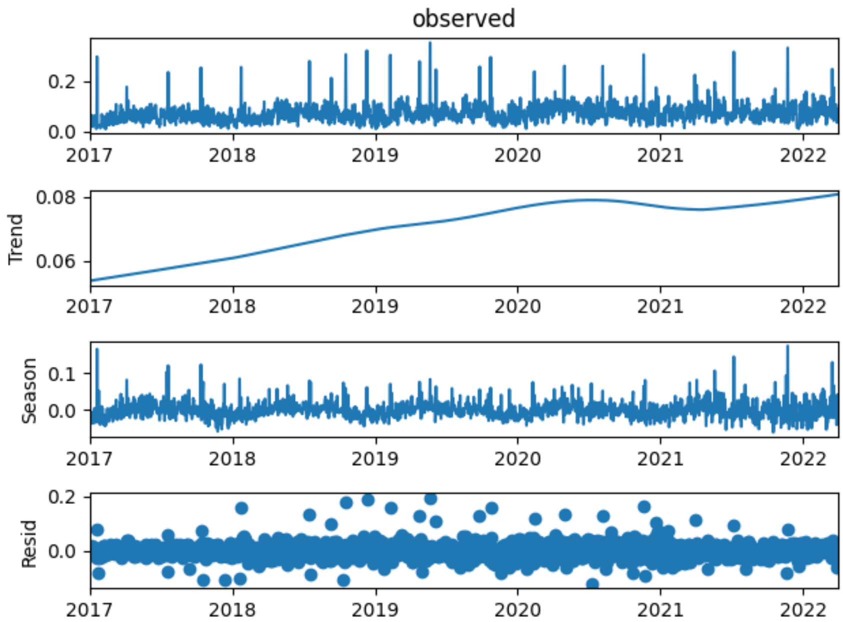

Figure A10: STL decomposition of Britain's standard deviation of fractional variable renewable energy penetration.

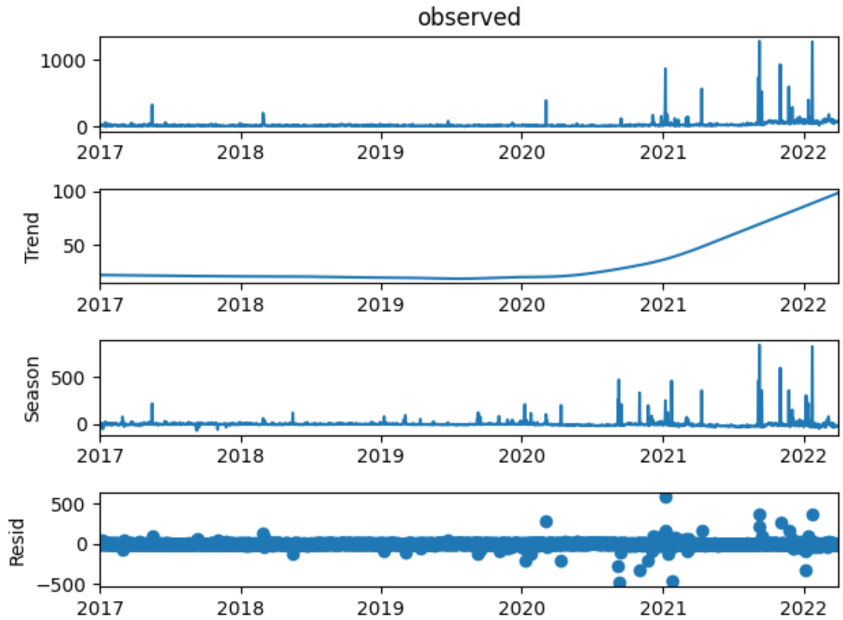

Figure A11: STL decomposition of Britain's standard deviation of the spot energy price. Corresponds to Figure A17.

A2.2. Decompositions for Energy Prices and Individual VRE Type Penetrations

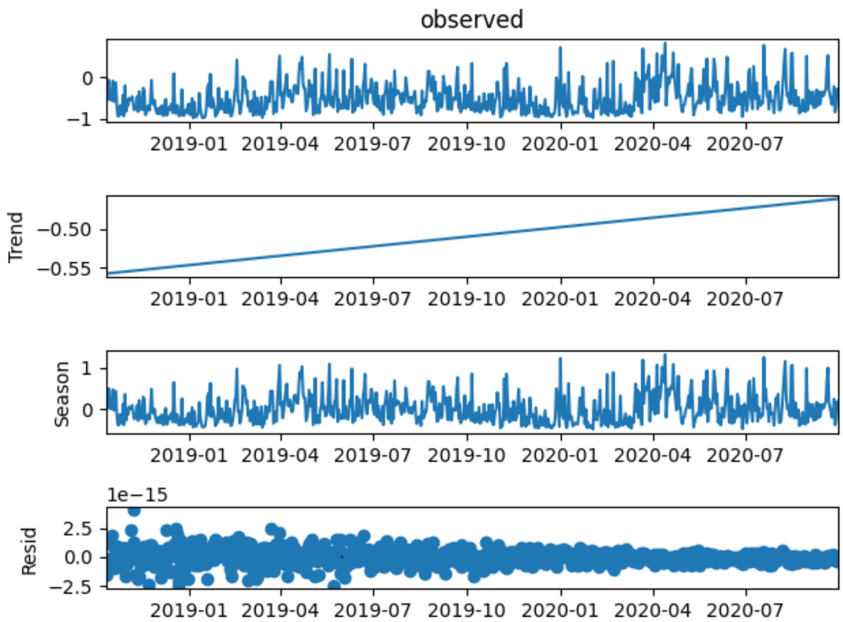

Figure A12: STL decomposition of Germany's energy price (EUR/MWh) to fractional wind penetration correlation.

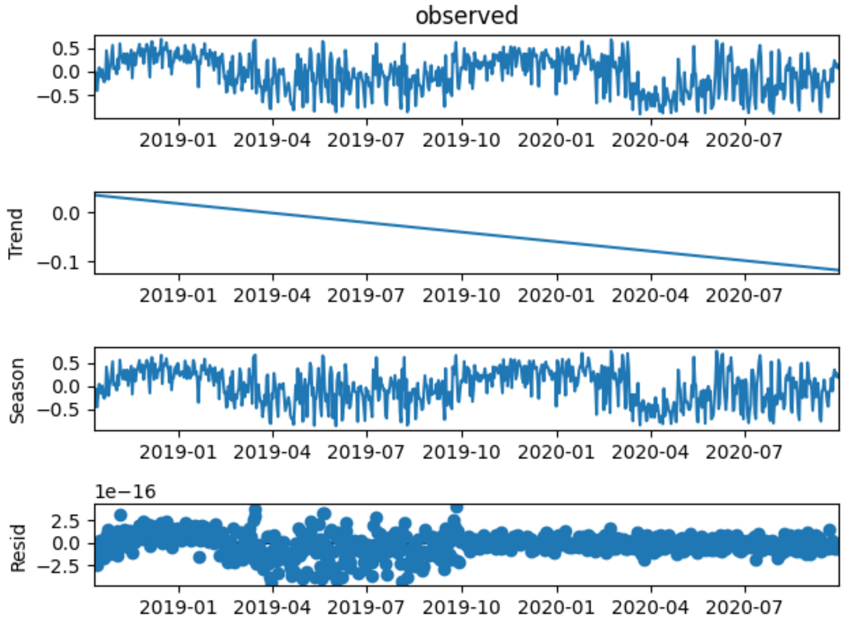

Figure A13: STL decomposition of Germany's energy price (EUR/MWh) to fractional solar (PV) penetration correlation.

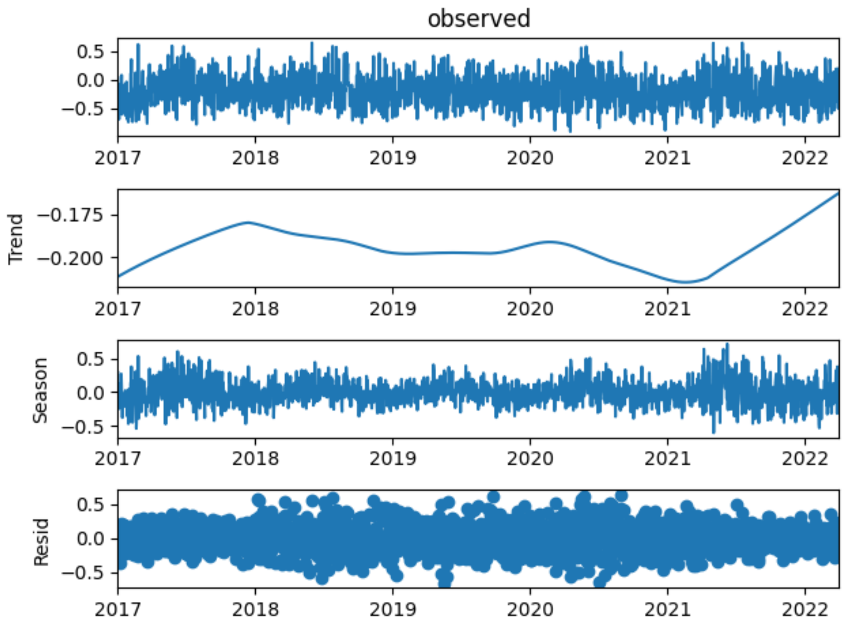

Figure A14: STL decomposition of Britain's energy price (GBP/MWh) to fractional offshore wind penetration correlation.

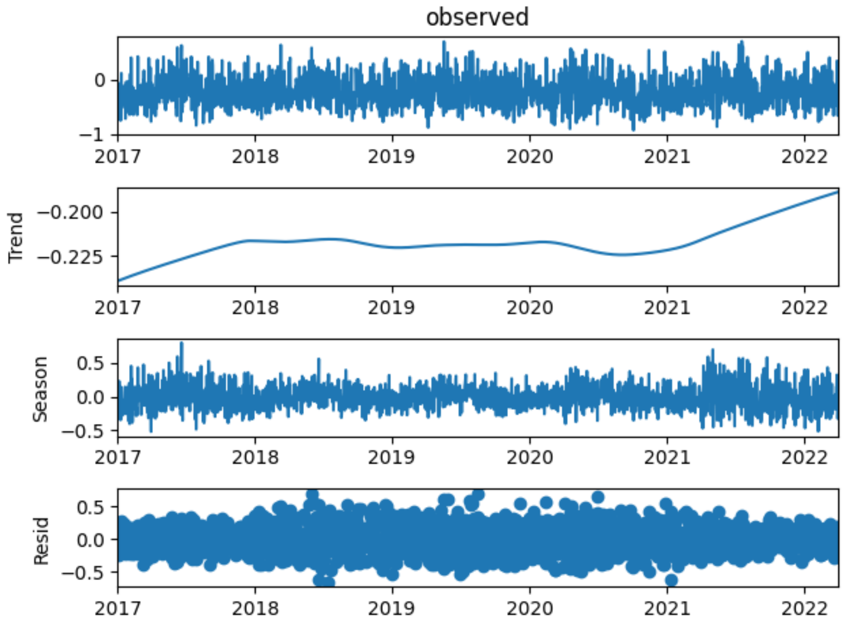

Figure A15: STL decomposition of Britain's energy price (GBP/MWh) to fractional onshore wind penetration correlation.

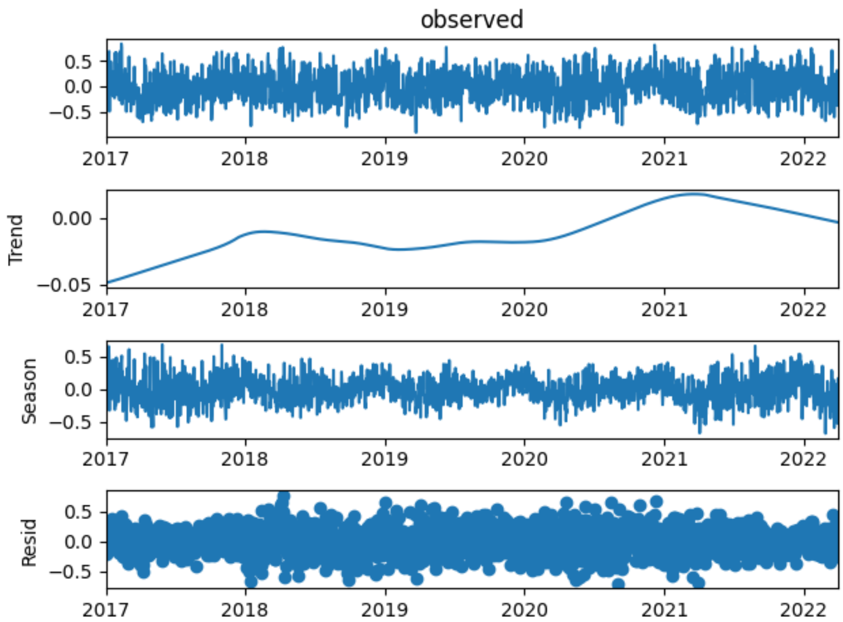

Figure A16: STL decomposition of Britain's energy price (GBP/MWh) to fractional solar (PV) penetration correlation.

A3. Full British Energy Price Standard Deviation

Due to outlier points, the paper's Figure 12 is cropped for readability in the main document. Figure A17 shows the full version for completeness.

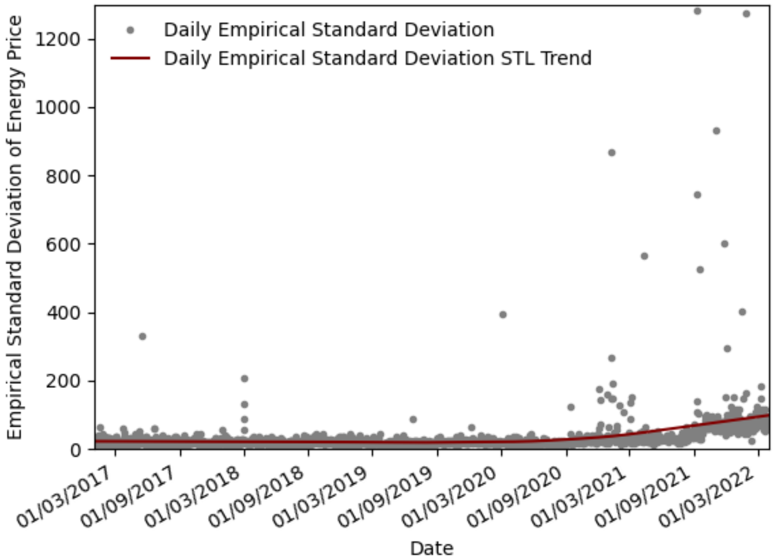

Figure A17: Britain's standard deviation of the spot energy price, and STL trend. Due to a number of outlier prices, this image is cropped for readability, with the full version being shown here.

A4. Further Imbalance Market Details

The overall marginal seller type is overwhelmingly (overwhelmingly CCGT) gas (89.66%), but also contains hydro/storage (5.64%), coal (4.18%), and wind (0.52%).

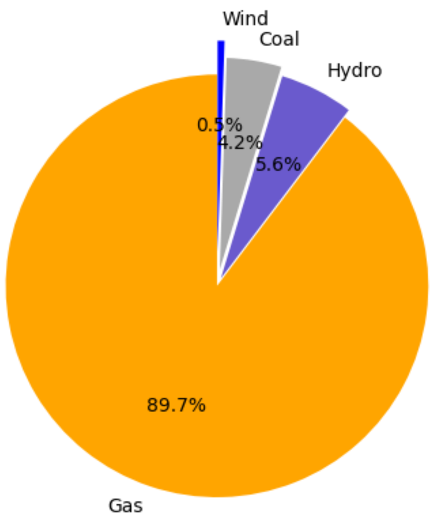

Figure A18: Marginal Seller Type in the British Energy Imbalance Market (2017-2022).

Figure A18 displays this breakdown. As might be expected under typical market operations, the vast majority of the time this role is fulfilled by gas (generally CCGT). Following this is hydro, which is either exclusively re-pumped, or with this capability; thus effectively serving a storage (or similar) role. Third is coal, which is similar to gas in being a dispatchable power source which may be used to meet imbalances. Finally, there is wind in a small fraction of cases. These wind cases are the most negligible, and are typically a reflection of ≤0 prices.

Returning to the more significant marginal seller types (gas, hydro, and coal), these sources fall clearly into the categories of typical dispatchables (gas and coal), and (also dispatchable) storage (hydro with re-pumping capability, or exclusively re-pumped). Thus, storage and fossil fuel dispatchables are the key competition on the marginal market, with these types' over-representation coming at the expense of VRE types compared to the overall market penetration of these types.

In the context of VRE, storage (such as re-pumped hydro) can play a uniquely complementary role, as it is not only dispatchable, but can further be charged using surplus renewable energy. If storage/hydro is excluded, gas to be the marginal seller type in 95.02% of mapped cases, as shown in Figure A19.

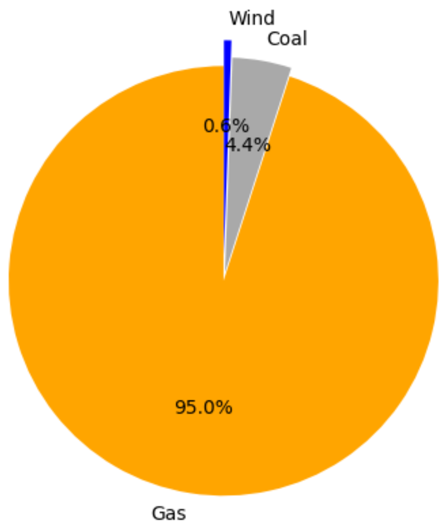

Figure A19: Marginal Seller Type in the British Energy Imbalance Market, excluding storage/hydro (2017-2022).

Due to the non-dispatchable nature of VREs, the marginal market is predictably still disproportionately dominated (compared to overall market penetration by type), by gas (and other dispatchables). While renewables penetration has grown, storage has been necessary to facilitate competition with fossil fuels on the imbalance market for the position of marginal seller. Given the significance of the marginal seller in the energy market (by having its sale determine the spot price), pure investigations of renewable expectations (particularly those considering marginal cost and associated price expectations independently of the bidding market) should be cognisant of this trend. Rather, by considering the disproportionate influence of the marginal component of the market (or by examining other methodologies (e.g. lifetime costs), more reasonable price expectations may be achieved.

This breakdown may also be considered on an annual basis (thus avoiding pervasive seasonal fluctuations determined earlier):

Table A1: Marginal seller of energy on the imbalance market in Britain from 2017-2021.

Year	Gas (%)	Coal (%)	Hydro (%)	Wind (%)
2017	90.94	4.15	4.54	0.37
2018	87.02	6.03	6.63	0.32
2019	93.34	1.61	4.71	0.34
2020	94.14	1.41	4.22	0.23
2021	87.85	5.37	6.23	0.55

Table A1 displays this breakdown. Due to the aforementioned seasonality, however, 2022 was not included (though out of interest it has currently has a breakdown of gas: 76%, coal: 10%, hydro: 11%, wind: 3%, but this would be better left to the monthly results in the paper's Figure 14). For the years where the full dataset exists, however, the most notable observation is the lack of a changing trend. While renewables have (particularly wind for the UK) grown in capacity and penetration terms, the direct effect in the price-setting margin appears to be non-existent. While the lack of a direct effect from wind is unsurprising, even if wind were to have an impact indirectly via storage, a clear trend in hydro is also not observed (though storage is a far more significant marginal seller than wind is directly). Seasonal and/or wind production forces may have been able to displace gas in the overall market (in penetration terms), but by comparison, the marginal market has not only been more stubborn, but exceptionally so.

Finally, some more details on pricing can be noted. This is performed to determine the average energy cost (GBP) by generation type (mean and median) in Table A2.

Table A2: Average spot price of energy (GBP) for each marginal seller type.

Average	Gas (GBP)	Coal (GBP)	Hydro (GBP)	Wind (GBP)
Mean	67.42	102.02	99.81	-38.89
Median	49.00	63.83	90.00	-63.72

The trends of higher coal and hydro prices, along with negative wind prices are consistent in both metrics of Table A2. The mean results are sufficient in discussing this trend in the main paper. Next, the average (mean) energy cost (GBP) at different levels of VRE penetration are shown in Table A3. Time periods where <30 instances occur (eg. if there are 0 instances) are listed as 'NA' (not applicable) due to statistical insignificance.

Table A3: Average spot price of energy (GBP) at different VRE penetration levels, by year.

Year	0-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%
2017	52.10	47.02	40.19	32.09	24.09	*NA*	*NA*
2018	58.61	60.46	58.50	51.09	39.33	*NA*	*NA*
2019	51.34	45.14	41.09	35.95	27.98	12.01	*NA*
2020	49.98	41.4	35.25	33.43	24.47	17.23	*NA*
2021	134.26	125.33	109.56	106.45	94.93	68.56	*NA*
2022	312.81	235.32	211.30	196.72	159.85	126.91	54.00

The paper's results are sufficient in discussing pricing trends at different VRE penetration levels (and the fractional frequency of those VRE penetration levels). A clear trend exists where lower penetration levels result in higher prices. Notably, with respect to discussions of volatility, this trend persists when the VRE penetration level is below average (<20%), which has provided an opportunity for the re-entrenchment of coal in the imbalance market to compensate for low VRE penetration levels (when they occur).

While this imbalance market and its distressed use of coal has been primarily discussed with respect to price (Tables A2 and A3), the average proportional generation in the overall market may also be noted for each marginal seller type. The aggregate types in the overall market (as per the BMRS data [2, 11]) will be broken into Biomass, Hydro Pumped Storage, Hydro Run-of-River (ROR) and Poundage, Fossil Hard Coal, Fossil Gas, Fossil Oil, Nuclear, Other, Wind Onshore, Wind Offshore, and Solar. The marginal seller types, as elsewhere in this paper, are Gas, Coal, Hydro, and Wind.

Table A4: Average percentage (%) composition of the general market for different marginal seller types (Gas, Coal, Hydro, Wind).

	Gas	Coal	Hydro	Wind
Biomass (%)	5.94	5.58	5.75	5.90
Hydro Pumped Storage (%)	0.75	0.96	1.43	0.37
Hydro ROR and Poundage (%)	1.42	1.44	1.55	1.49
Fossil Hard Coal (%)	3.20	7.14	3.91	1.26
Fossil Gas (%)	43.24	46.11	45.07	20.27
Fossil Oil (%)	0.00	0.00	0.00	0.00
Nuclear (%)	21.77	18.55	20.28	25.76
Other (%)	1.34	1.11	1.15	0.85
Wind Onshore (%)	10.08	9.00	9.26	20.66
Wind Offshore (%)	8.03	6.74	7.84	18.06
Solar (%)	4.23	3.38	3.77	5.38

Table A4 makes this breakdown. While the imbalance market is significant in setting the market price, and has broader infrastructure cost implications (even if that infrastructure is often left in reserve), it is considerably smaller than the overall market in terms of energy volumes. Only minor differences in the overall market composition, therefore, may be expected between marginal seller types. Finally, while there are a variety of generation types shown, 'Fossil Gas (%)' will be primary focus when discussing the differences marginal seller types.

As was discussed earlier, wind tends to be the marginal seller during exceptional VRE output peaks. Rather than being deployed to account for unexpected demand, wind is often the marginal seller when excess generation drives down the market price, and thus other generators from the market. This is reflected in Table A4 by significantly lower gas output.

The higher 'Nuclear (%)' when wind is the marginal seller also implies these periods have relatively lower demand (as nuclear presently tends to produce a consistent power output, as opposed to gas, which is more commonly and easily ramped up/down). The reverse trend may also be seen for when hydro, and especially coal, are the marginal sellers. Table A5 verifies this by displaying the aggregated energy outputs themselves, including total generation (for mapped half-hourly periods).

Table A5: Average aggregate generation (MWh) by type, of the general market, for different marginal seller types (Gas, Coal, Hydro, Wind).

	Gas	Coal	Hydro	Wind
Biomass (MWh)	833.34	896.01	874.70	737.32
Hydro Pumped Storage (MWh)	121.48	174.84	241.72	54.66
Hydro ROR and Poundage (MWh)	210.70	244.94	244.66	186.40
Fossil Hard Coal (MWh)	543.23	1322.99	722.87	167.02
Fossil Gas (MWh)	6423.48	7929.54	7383.85	2673.70
Fossil Oil (MWh)	0.00	0.00	0.00	0.00
Nuclear (MWh)	3061.12	3022.96	3058.72	3140.83
Other (MWh)	198.19	190.11	183.47	107.32
Wind Onshore (MWh)	1456.10	1443.20	1345.18	2575.55
Wind Offshore (MWh)	1141.04	1057.31	1108.98	2226.94
Solar (MWh)	649.52	548.25	594.54	749.18
Total (MWh)	14638.19	16830.16	15758.68	12618.92

The paper's Figure 15 noted higher coal and hydro levels during particularly low VRE levels. If gas were used as a replacement in the overall market during these periods, and was thus less available to meet further imbalances, then a higher 'Fossil Gas (%)' may be expected when coal or hydro is the marginal seller in comparison to when gas is the marginal seller. This may be seen, though these differences are smaller than those observed when wind is the marginal seller. These results also align with the implications of the marginal sale price from Table A2. As such, these results appear consistent with earlier market analysis.

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