Supplementary Information:

British Wind Farm Battery Attachments: Curtailment Reduction vs Price Arbitrage

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A Appendix

Additional information which may be of interest may be found herein.

A.1 Wind Farm Locations

The locations of the selected 47 wind farms, including their GPS coordinates and countries, are listed below in Table S1.

Farm Name	EIC	MW	Country	GPS (lat, lon)
Aberdeen	48WSTN0000ABRBON	96.8	Scotland	57.21666, -1.98333
Arecleoch	48WSTN0000ARCHW6	120	Scotland	55.05333, -4.88222
Baillie	48WSTN1000BABAWQ	52.5	Scotland	58.56441, -3.68027
Barrow	48WSTN0000BOWLWY	90	England	53.98333, -3.28333
Beatrice	48WSTN0000BEATOG	273	Scotland	58.30263, -2.96229
Beinneun	48WSTN0000BEINWN	108.8	Scotland	57.19552, -4.85579
Berry Burn	48WSTN0000BRYBW4	67	Scotland	57.48712, -3.54822
Bhlaraidh	48WSTN0000BHLAWZ	108	Scotland	57.22302, -4.66879
Black Law	48WSTN00000BLLAV	124.2	Scotland	55.76694, -3.73888
Black Law II	48WSTN00000BLLXM	63.43	Scotland	55.78093, -3.76413
Blackcraig	48WSTN0000BLKWWR	52.9	Scotland	55.33309, -4.14217
Braes of Doune	48WSTN0000BRDUWV	72	Scotland	56.27611, -4.0625
Burbo Extension	48WSTN0000BRBEOT	259	England	53.48333, -3.16666
Clyde (Central)	48WSTN0000CLDCWZ	195.9	Scotland	55.46722, -3.65444
Clyde (North)	48WSTN0000CLDNW2	197.7	Scotland	55.46722, -3.65444
Clyde (South)	48WSTN0000CLDSWO	128.8	Scotland	55.46722, -3.65444
Corriegarth	48WSTN0000CGTHWI	69	Scotland	57.21996, -4.4985
Crystal Rig II	48WSTN0000CRYRBT	138	Scotland	55.9, -2.55218
Dersalloch	48WSTN0000DRSLWN	69	Scotland	55.31915, -4.47189
Dudgeon 1	48WSTN0000DDGNO3	108	England	53.249, 1.38781
Dunmaglass	48WSTN0000DUNGW6	94.05	Scotland	57.27718, -4.27231
East Anglia One	48WSTN00000EAAOS	714	England	52.90778, 2.62861
Fallago Rig	48WSTN0000FALGWS	144	Scotland	55.83334, -2.74208
Galawhistle	48WSTN0000GLWSWZ	55.2	Scotland	55.53429, -3.92416
Greater Gabbard	48WSTN0000GRGBW9	504	England	51.88, 1.94
Griffin	48WSTN0000GRIFWQ	188.6	Scotland	56.61846, -3.87531
Gunfleet Sands 1 & 2	48WSTN0000GNFSWJ	172.8	England	51.73944, 1.17444
Hadyard Hill	48WSTN0000HADHW8	119.8	Scotland	55.24583, -4.72305
Harestanes	48WSTN0000HRSTWC	136	Scotland	55.21669, -3.71962
Hornsea 1	48WSTN0000HOWAOA	1218	England	51.63333, 1.48333
Humber Gateway	48WSTN0000HMGTOR	219	England	53.644, 0.293
Kilbraur	48WSTN0000KILBWA	67.5	Scotland	58.04, -4.06191
Kilgallioch	48WSTN0000KLGLWM	239	Scotland	55.05, -4.76746
Lochluichart	48WSTN0000LCLTWH	69	Scotland	57.69554, -4.79523
Mark Hill	48WSTN0000MKHLWB	56	Scotland	55.12998, -4.74805

Millennium	48WSTN0000MILWW9	65	Scotland	57.12364, -4.84852
Race Bank	48WSTN0000RCBKOV	573	England	53.276, 0.841
Rampion	48WSTN0000RMPNON	400	England	50.78424, 0.0558
Robin Rigg East	48WSTN00000RREWF	90	Scotland	54.75, -3.71885
Robin Rigg West	48WSTN00000RRWWZ	90	Scotland	54.75, -3.71885
Strathy North	48WSTN0000STRNWW	66	Scotland	58.38525, -3.89385
Stronelairg	48WSTN0000STLGW3	227.7	Scotland	57.27414, -4.64176
Walney 1 & 2	48WSTN0000WLNYWV	368	England	54.044, -3.522
Walney 3	48WSTN0000WLNY3F	330	England	54.044, -3.52418
Walney 4	48WSTN0000WLNY4D	329	England	54.044, -3.52418
Westermost Rough	48WSTN0000WTMSOT	210	England	53.805, 0.14681
Whitelee	48WSTN1000WHILWQ	322	Scotland	55.7125, -4.34111

Table S1: *Wind farm EIC, capacity (MW), and location data. Offshore wind farms are included in the nearest onshore country.*

A.2 Background Factors for Returns

The returns for the ESS attachments are shown in Figure S1.

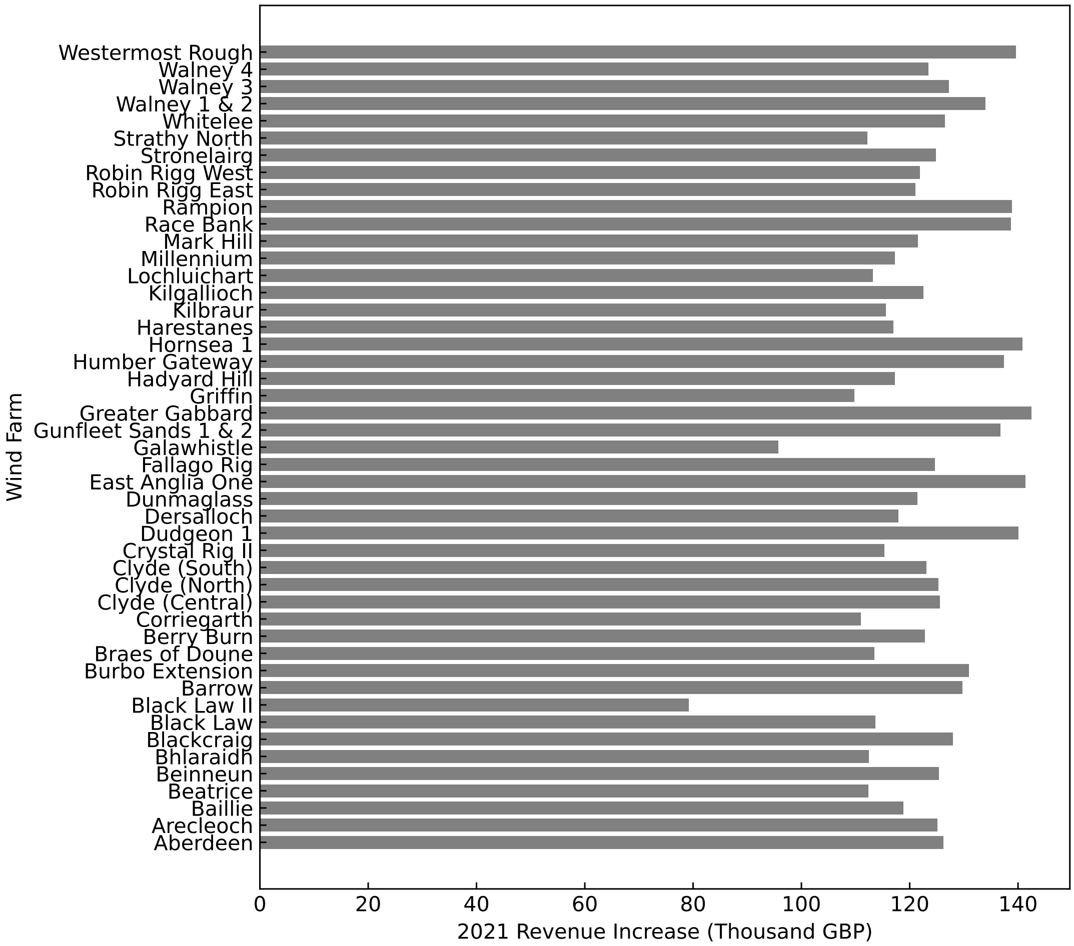

Figure S1: *2021 revenue increases modelled for an ESS attachment at various wind farm sites.*

Type, and geospatial factors may also be considered alongside these paybacks. With respect to curtailment, onshore vs offshore, and Scottish vs English/Welsh comparisons are identified [1]. These are also interrelated, with Scotland having more onshore capacity, and England/Wales having more offshore capacity.

With respect to outputs themselves, onshore vs offshore distinctions are also significant, with offshore wind experiencing more consistent wind conditions and having a higher average capacity factor. Using 2019 BEIS (UK) data, a University of Oxford study notes offshore wind farms as having an average capacity factor of 39.6%, compared to 26.2% for onshore sites [2]. 2021 capacity factors are listed for specific farms in Figure S2. Here, higher capacity factors are broadly seen for English/Welsh offshore wind farms in particular.

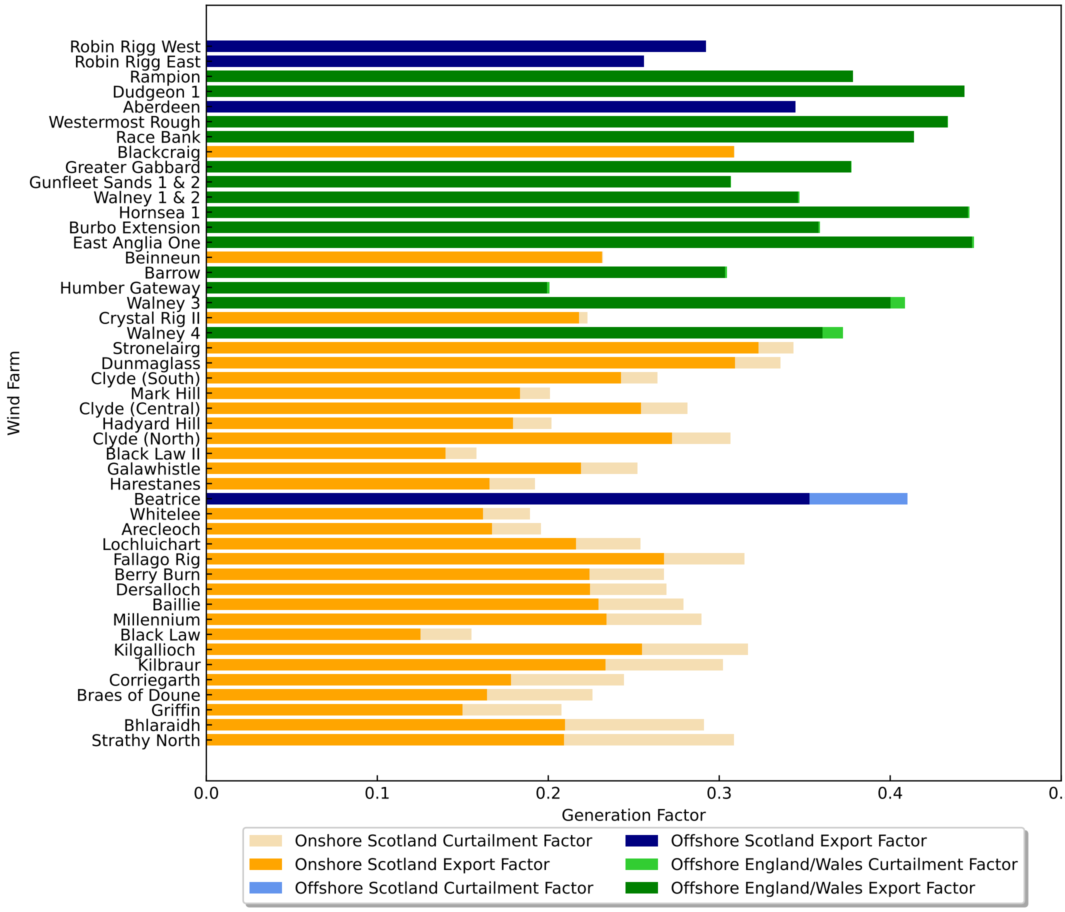

Figure S2: *UK wind farm capacity factors (with and without curtailed energy, such that: $EnergyGenerated = EnergyExported + EnergyCurtailed$). No Onshore England/Wales wind farms are considered in this paper.*

These factors will therefore be included in the main document's analysis.

A.3 Emissions Intensity by Site

The main document determines the emissions intensity of the imbalance market (which an ESS attachment would likely export into and where the energy spot price is determined for the grid). To estimate the emissions offset from reduced curtailment by an ESS attachment an estimate of the emissions intensity of the market is useful. More detail, however, may be provided by determining an emissions intensity on a site by site basis.

The mix of marginal generation technologies is used to determine the emissions intensity of marginal generation for each site individually. Table S2 displays these figures.

Table S2: *Marginal seller type during wind farm (with ESS attachment) export to grid (percentage), and associated emissions intensity $kgCO_2/MWh$.*

Farm Name	Gas %	Coal %	Hydro %	Wind %	Emissions $kgCO_2/MWh$
Aberdeen	83.57	4.41	11.47	0.54	370.64
Arecleoch	83.13	4.55	11.92	0.4	370.16
Baillie	84.14	4.35	11.14	0.37	372.27
Beatrice	83.31	4.68	11.59	0.42	372.09
Beinneun	83	4.61	11.87	0.52	370.2
Bhlaraidh	82.87	5.01	11.92	0.2	373.44
Blackcraig	83.83	4.18	11.45	0.53	369.49
Black Law	82.23	5.22	12.2	0.35	372.88
Black Law II	83.09	4.99	11.53	0.4	374.08
Barrow	83.79	3.97	11.75	0.49	367.35
Burbo Extension	83.29	4.49	11.7	0.52	370.21
Braes of Doune	83.26	4.98	11.42	0.34	374.72
Berry Burn	83.61	4.6	11.47	0.32	372.55
Corriegarth	82.99	4.82	11.85	0.34	372.15
Clyde (Central)	83.63	4.56	11.45	0.36	372.21
Clyde (North)	83.4	4.56	11.76	0.27	371.35
Clyde (South)	83.68	4.42	11.5	0.4	371.11
Crystal Rig II	84.23	3.91	11.44	0.42	368.48
Dudgeon 1	83.91	4.35	11.26	0.48	371.36
Dersalloch	82.69	4.92	12.07	0.32	371.92
Dunmaglass	83.93	4.25	11.39	0.43	370.51
East Anglia One	83.72	4.42	11.42	0.45	371.26
Fallago Rig	83.78	4.55	11.37	0.3	372.7
Galawhistle	83.29	4.72	11.63	0.36	372.42
Gunfleet Sands 1 & 2	83.63	4.28	11.59	0.51	369.56
Greater Gabbard	83.6	4.52	11.41	0.47	371.74
Griffin	83.01	4.6	12.08	0.31	370.18
Hadyard Hill	83.58	4.43	11.7	0.29	370.79
Humber Gateway	83.98	4.4	11.12	0.5	372.15
Hornsea 1	83.75	4.55	11.28	0.43	372.59
Harestanes	83.22	4.29	12.03	0.46	368.04
Kilbraur	83.14	4.69	11.72	0.45	371.56
Kilgallioch	83.58	4.61	11.63	0.19	372.47
Lochluichart	83.72	4.37	11.58	0.33	370.78
Millennium	83.39	4.67	11.52	0.42	372.33
Mark Hill	83.27	4.34	11.87	0.51	368.78
Race Bank	84.08	4.25	11.17	0.49	371.13
Rampion	83.37	4.42	11.72	0.49	369.86
Robin Rigg East	83.1	3.98	12.35	0.57	364.7
Robin Rigg West	83.3	3.93	12.2	0.57	365.04
Stronelairg	83.68	4.46	11.5	0.36	371.49

Strathy North	83.05	4.6	12.12	0.23	370.28
Whitelee	83.19	4.67	11.77	0.37	371.54
Walney 1 & 2	83.87	3.97	11.66	0.5	367.65
Walney 3	83.85	4.11	11.57	0.46	368.88
Walney 4	84.09	4.09	11.33	0.49	369.65
Westermost Rough	84.13	4.4	10.99	0.49	372.69

Table S2 notes the marginal seller type during periods of site export due to the ESS attachment (i.e. periods where the ESS exports energy into the grid). While the main document also (used for later analysis) notes this breakdown, the figures themselves are provided here for further detail.

Finally, while this paper considers generation side emissions, upstream emissions may also be of interest. Numerous studies investigate the topic of fugitive (carbon dioxide and methane) upstream emissions for coal and gas [3–5]. As upstream adjustment factors vary, some example adjustments of 20%, 30%, and 40% are shown in Table S3.

Table S3: *Emissions factors of wind farms (kgCO_2/MWh). Scaled for increased upstream emissions.*

Farm Name	Base	+20%	+30%	+40%
Aberdeen	370.64	444.77	481.83	518.9
Arecleoch	370.16	444.19	481.21	518.22
Baillie	372.27	446.72	483.95	521.18
Beatrice	372.09	446.51	483.72	520.93
Beinneun	370.2	444.24	481.26	518.28
Bhlaraidh	373.44	448.13	485.47	522.82
Blackcraig	369.49	443.39	480.34	517.29
Black Law	372.88	447.46	484.74	522.03
Black Law II	374.08	448.9	486.3	523.71
Barrow	367.35	440.82	477.56	514.29
Burbo Extension	370.21	444.25	481.27	518.29
Braes of Doune	374.72	449.66	487.14	524.61
Berry Burn	372.55	447.06	484.32	521.57
Corriegarth	372.15	446.58	483.8	521.01
Clyde (Central)	372.21	446.65	483.87	521.09
Clyde (North)	371.35	445.62	482.76	519.89
Clyde (South)	371.11	445.33	482.44	519.55
Crystal Rig II	368.48	442.18	479.02	515.87
Dudgeon 1	371.36	445.63	482.77	519.9
Dersalloch	371.92	446.3	483.5	520.69
Dunmaglass	370.51	444.61	481.66	518.71
East Anglia One	371.26	445.51	482.64	519.76
Fallago Rig	372.7	447.24	484.51	521.78

Galawhistle	372.42	446.9	484.15	521.39
Gunfleet Sands 1 & 2	369.56	443.47	480.43	517.38
Greater Gabbard	371.74	446.09	483.26	520.44
Griffin	370.18	444.22	481.23	518.25
Hadyard Hill	370.79	444.95	482.03	519.11
Humber Gateway	372.15	446.58	483.8	521.01
Hornsea 1	372.59	447.11	484.37	521.63
Harestanes	368.04	441.65	478.45	515.26
Kilbraur	371.56	445.87	483.03	520.18
Kilgallioch	372.47	446.96	484.21	521.46
Lochluichart	370.78	444.94	482.01	519.09
Millennium	372.33	446.8	484.03	521.26
Mark Hill	368.78	442.54	479.41	516.29
Race Bank	371.13	445.36	482.47	519.58
Rampion	369.86	443.83	480.82	517.8
Robin Rigg East	364.7	437.64	474.11	510.58
Robin Rigg West	365.04	438.05	474.55	511.06
Stronelairg	371.49	445.79	482.94	520.09
Strathy North	370.28	444.34	481.36	518.39
Whitelee	371.54	445.85	483	520.16
Walney 1 & 2	367.65	441.18	477.95	514.71
Walney 3	368.88	442.66	479.54	516.43
Walney 4	369.65	443.58	480.55	517.51
Westermost Rough	372.69	447.23	484.5	521.77

A.4 Example Run

This paper models the performance of multiple ESSs over a full year with a half-hourly time resolution. To further understand the operation of this algorithm in practice an example run is herein provided. To further demonstrate the functionality of the model, some features are deliberately exaggerated to make these points more apparent.

Firstly, a 90% loss is used for charging as well as discharging (each), so more clearly show how the model accounts for inefficiency. In practice, a loss of this magnitude would not be consistent with the efficiency provided in the literature, but by doing so in the example run, losses from inefficiency are made more apparent for the reader.

Secondly, a low level of wind output is selected. This is to show how the ESS is constrained to charged from the output of the wind farm as the inflow can be seen to never exceed the wind generation level.

Thirdly, a rating of 1 C is used to create more times in which this constraint is invoked and therefore can be seen.

Finally, a minimum and maximum state of charge of 0% and 100% are defined to simplify the output results.

The prices throughout the sample day are as follows:

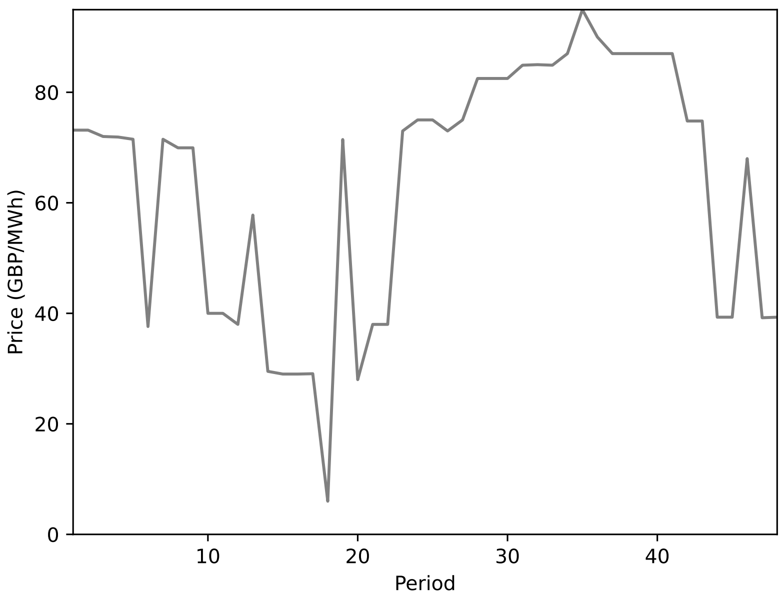

Figure S3: *Energy prices throughout the example run day.*

The energy generation from the wind farm, and inflows to the ESS are as follows:

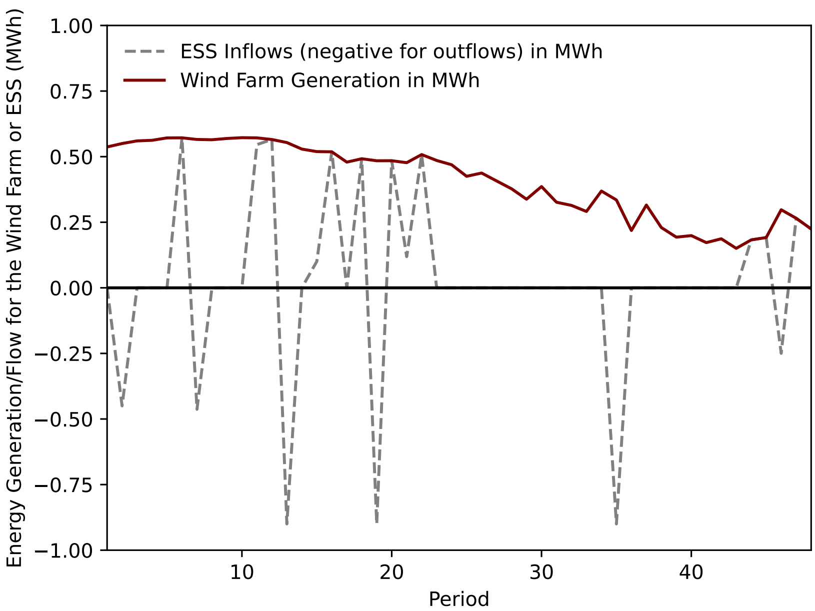

Figure S4: *Energy flows throughout the example run day.*

Finally, the state of charge of the battery was as follows:

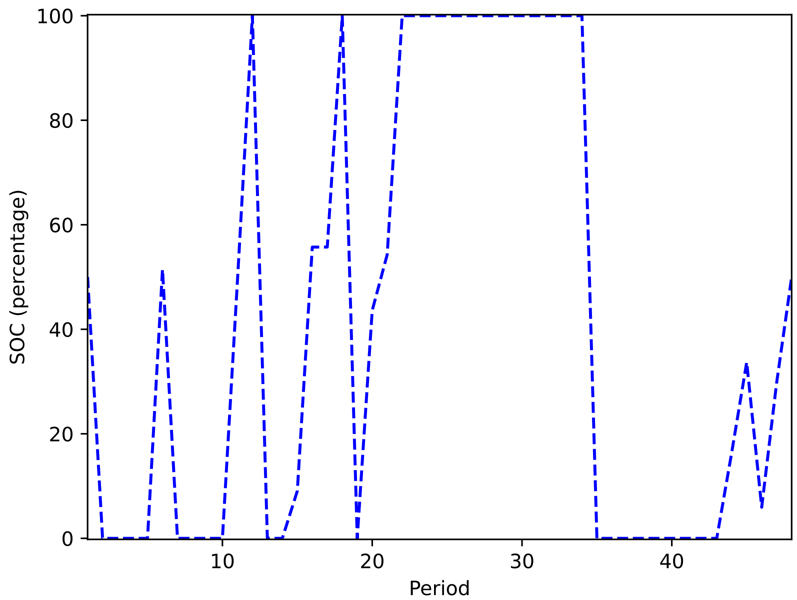

Figure S5: *ESS SOC throughout the example run day.*

In Figure S3 it can be seen how the energy price fluctuates throughout the day (which as per BMRS convention is divided into 48 half-hourly periods). Here the price can be seen to fluctuate significantly, with a dip in the early morning (where there is low demand), and peak in the evening (coinciding with peak demand).

Figure S4 notes the generation of the wind farm, and the inflows into the ESS. Inflows are taken to be positive such that it may be observed that inflows never exceed wind farm generation, as the co-located ESS can only charge using energy generated by the wind farm. Due to this constraint the ESS never charges at its full rate, but it can be seen to discharge as such (subject to inefficiency losses).

The may be seen to operating consistently during the period of morning volatility to capitalise on the numerous charging and discharging opportunities. In the evening, however, where such opportunities do not present themselves, the ESS may be seen waiting for the price maximum in the 36th period where it exports. Figure S5 also displays this behaviour, but with respect to the state of charge rather than energy flows.

A.5 Further Curtailment Details

While curtailment is already discussed in the main paper, and in Appendix A.2, given its significance in contributing to ESS emissions reductions, further details are included here. This curtailment serves as a direct source of ESS emissions reductions and therefore warrants further examination.

A.5.1 Geographic Breakdown

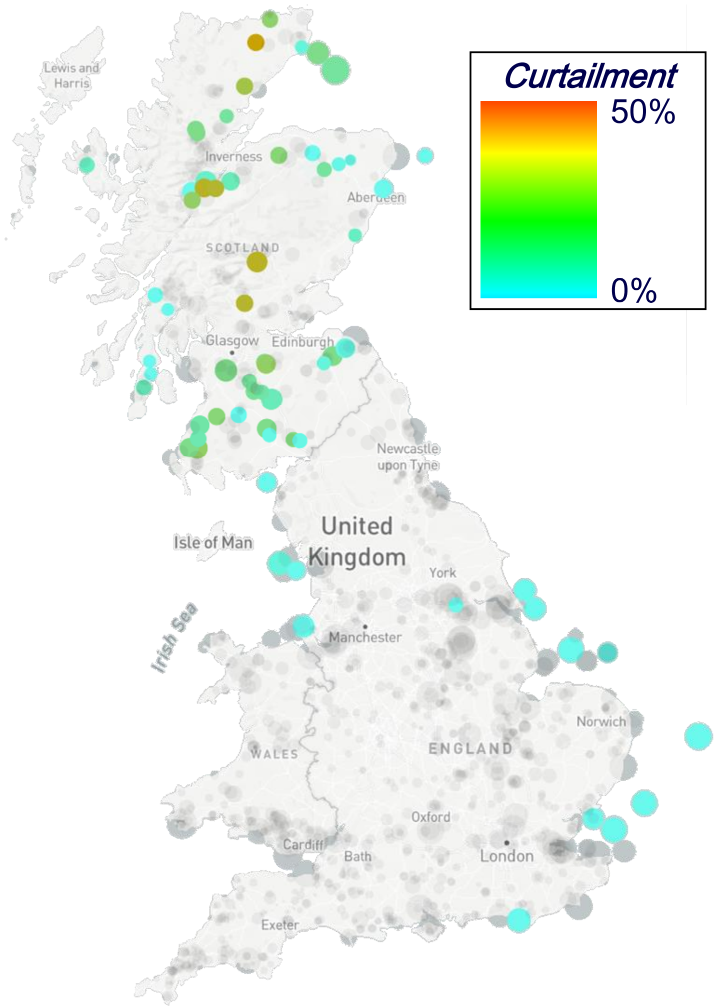

Figure S6: *Britain's 2021 wind energy curtailment for mapped BMRS reporting wind farms. Colour scale notes percentage curtailment. Circle area scaled up by capacity. Black dots represent other generators for context, including wind farms for which curtailment data was not available.*

These curtailment rates may be observed geo-spatially for each site, as can be seen in Figure S6. The curtailment volumes have been increasing alongside the expansion of VRE in the grid, while remaining persistent even in proportional terms. Figure S7 displays a further breakdown of generated, exported, and curtailed energy by site, as well as noting the typical export price for each wind farm. These results further emphasise the greater rate of Scottish wind farm curtailment, and higher capacity factors (including more persistent rates of generation) of predominantly offshore English/Welsh farms.

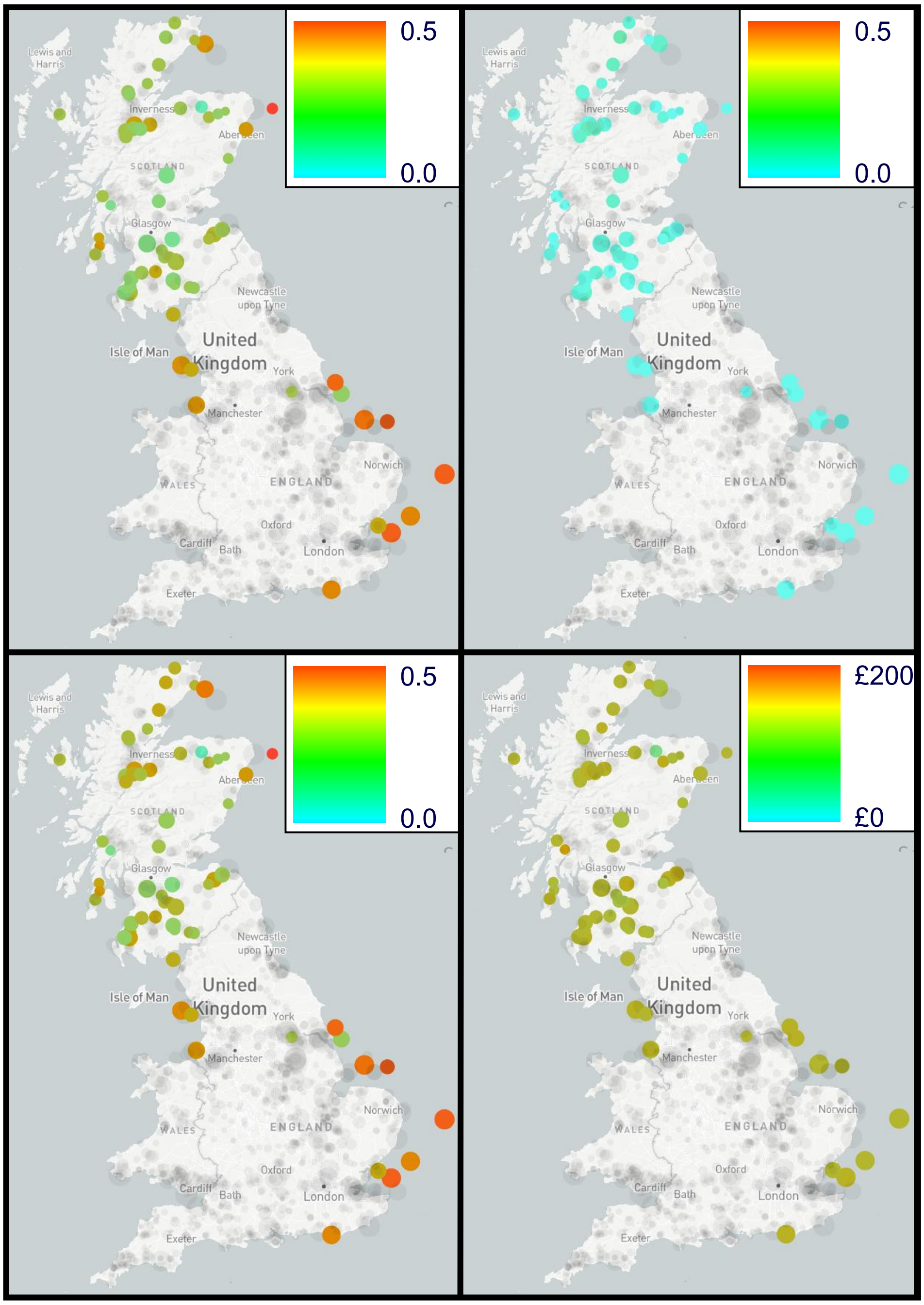

Figure S7: *Top Left: Export Factor (hourly energy exported / capacity).*
Top Right: Curtailment Factor (hourly energy curtailed / capacity).
Bottom Left: Generation Factor (hourly energy generated / capacity, i.e. The summed Export Factor and Curtailment Factor).
Bottom Right: Average spot price of energy exported (GBP / MWh).
Black dots represent other generators for context, including wind farms for which curtailment data was not available.

A.5.2 Curtailment Methodology

Different sources have used differing methods to estimate curtailment rates of British wind farms. As curtailment rates may not be known or reported for all wind farms, some studies will calculate the curtailment rate using individual sites for which this information is known. Other studies instead compare national curtailment and wind generation figures to obtain a curtailment measure, which includes generation from all wind farms - though this includes generation from farms without reported rates of curtailment. The figures used from BMRS fall within range of the curtailment rates reported by other studies.

Table S4: *British Annual Wind Energy Curtailment (% of total wind energy generated). As per Imperial College London (ICL) [1], Wind Europe [6], Kyoto University [7], the University of Strathclyde [8], and by this paper's results [9–11]. Note that data is not provided or obtained for all years from all sources/papers. This table expands upon the literature overview's source comparison, by including in this investigation's rates of curtailment.*

Year	ICL	Wind Europe	Kyoto	Strathclyde	BMRS
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

A.5.3 Annual Curtailment Changes

Finally, these results may also be aggregated for Scotland and England/Wales for each year.

Table S5: *Site aggregated curtailment data for Scotland and England/Wales.*

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

Table S5 displays the divide between Scottish and English/Welsh curtailment levels by aggregating the data from specific mapped sites from BMRS. More broadly, the disproportionate expansion of offshore wind in England/Wales is especially evident; motivated by trends such as those above.

Future investigations should be keenly aware of changes in these curtailment rates by region, as they strongly effect the performance of ESS attachments and potential emissions reductions through the export of otherwise curtailed energy.

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