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British wind farm ESS attachments: curtailment reduction *vs.* price arbitrage†

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Energy storage systems (ESSs) are a potential solution to the rising issues of electricity price volatility and curtailment of British wind energy. This study performs an extensive and knowledge graph supported investigation into 47 potential wind farm ESS co-location sites. While all ESSs achieved payback due primarily to price arbitrage, results indicate English/Welsh sites (typically with offshore wind) had quicker payback times owing to higher capacity factors presenting more opportunistic charging times. Conversely, while batteries co-located with Scottish wind farms attained slower payback times, they accomplished greater curtailment reductions, which could be used to displace marginal selling from generally fossil fuelled sources.

Broader context

Throughout the globe energy systems and networks are undergoing a monumental transition. A vast expansion of variable renewable energy (VRE) generation from wind and photovoltaic solar lies at the centre of this change. The British grid is no exception to these trends, with vastly expanded VRE capacity (particularly from wind) there have also been increased difficulties for the transition network (despite expansions) and energy market. An increased adoption of battery energy storage systems (BESSs) is one potential solution to address these difficulties. If the integration of increased VRE generation into the grid cannot be addressed, then market challenges such as price volatility, and network challenges which may result in curtailment will hinder the uptake of VRE, and by extension require demand continue to be met by energy technologies with poorer environmental impacts. By techno-economically studying the viability of ESS attachments at British wind farms, a greater understanding of the environmental impacts of these storage systems and their role in the energy network may be achieved. This of importance to not only the academic community, but also to industry and energy policymakers who are presently investigating the role of expanded energy storage systems in many of their proposed transition pathways.

1 Introduction

To meet their climate objectives, various countries including the United Kingdom (UK) have undertaken an energy transition.[1] Historically, this has included the expansion of variable renewable energy (VRE) generation infrastructure. In the UK, onshore and offshore wind has accounted for the primary VRE source; a trend which is projected to continue.[2] To compensate for the increasing use of non-dispatchable generation, an expansion of energy storage systems (ESSs) is included in these expansion forecasts.

Throughout this expansion, transmission curtailment has grown as a source of energy loss in Britain, preventing the export of particularly Scottish wind power to the grid. Curtailment and grid stability in high VRE environments are examined across a variety of countries.[3] Mitigating these losses through interconnection, storage, or the conversion of otherwise curtailed energy into heat or hydrogen have all been suggested as potential solutions.[4] Without dispatchability or compensation, periods of high VRE penetration and lower prices (due to cannibalisation[5]) lower the financial returns of VRE sites. To later export energy which would have been curtailed or exported at a low price, numerous British wind farms expect to construct co-located ESSs.[6]

While the topic of VRE expansion has been widely investigated, the effect on prices and price volatility varies between case studies.[7–12] Based on the comparative timing of VRE penetration relative to demand peaks, for example, an

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investigation of Germany and Denmark found increased renewable penetration to have resulted in increased price volatility in the former country, but not the latter.[13] In Britain, price volatility has increased in recent years for a number of reasons, with VRE (particularly wind) penetration being greater during periods of lower energy price; which presents an opportunity for arbitrage.[14–16]

British wind energy curtailment is clearly documented, and is concentrated in Scottish wind farms; primarily due to transmission constraints.[14,17] Were this energy to be stored, it may later be exported to generate additional revenues and potentially displace emissions intensive generation.[18,19] This provides an economic and environmental incentive to potential ESS attachments in addition to the potential for arbitrage.

On a national level, such as in the UK as a whole, expansions of storage are determined to be a requirement of increased VRE penetration,[20–24] though comparative studies suggest significant national differences.[25] Large scale studies also recommend expansions of storage technology.[26–28] These may investigate shorter or longer term storage, though lithium-ion technology presently dominates over[29] competing battery chemistries.[30] This is to the extent that particular attention has been paid to the supply chain, and economy of scale recycling of lithium-ion batteries.[31–33] Other technologies of note in these studies include hydro, hydrogen/ammonia, geothermal, biomass, and compressed air.[28,29,34,35] Further demand scheduling and related approaches include electric vehicle (EV) charging, smart industry, household applications, and renewable fuel production.[36–40]

As ESSs are often planned, and have their energy returns on investment calculated on a site by site basis, studies are also performed on an individual farm basis; including in Britain.[6,41] Current literature examines curtailment mitigation for Scottish wind farms (Whiteley and Gordonbush).[41] By only investigating a limited number of sites, the investigation of broader trends remains an open question. Large scale investigations into ESS model input factors such as price volatility and geospatial curtailment, however, identify trends of their own.[42]

A larger scale analysis which considered a variety of wind farms would be required for such an inquiry. This scale would extend to the number of farms, their placement onshore or offshore, their locations in Britain given regional influence on transmission constraints which cause curtailment,[42] and the flexibility of their modelling such that both price arbitrage and curtailment mitigation are permitted. The investigation of ESS attachments throughout Britain would therefore be of great interest to examine the potential for storage solutions.

This paper performs a study of this scale. Using a knowledge graph framework, this investigation accordingly expands upon existing literature by considering 47 wind farms throughout Britain for comparison. A linear optimisation model for battery attachments, a common approach in power modelling,[43] is used to determine the economic returns of co-located storage units. Using a flexible methodology which permits both price arbitrage and curtailment mitigation, this study provides an integrated investigation into ESS behaviour. These results are used to determine the economic viability of wind farm co-located ESSs.

By specifically considering the replacement of marginal generator emissions from the imbalance market, this paper develops and utilises a decarbonisation estimation method suitable to the investigation of individual site ESS attachments; where existing literature may instead make assessments on an aggregate or bus network basis, but is comparably lacking in site specific analyses.[44,45] This method is calculated on a site specific basis, and applied to curtailment reductions. The purpose of this study is therefore to determine the economic and decarbonisation performance (*via* curtailment reduction) of ESS attachments throughout Britain. From these results, broader trends are investigated and limitations are discussed. Leading wind farm co-location sites are identified with respect to payback time and decarbonisation (*via* curtailment reduction).

2 Literature review

A variety of storage technologies exist to compensate for VRE non-dispatchability by meeting imbalances, arbitraging price, and lowering curtailment. Depending on the specific application desired, different ESS types may be more suitable. For example, the viability of different storage methods may depend on the storage timescale (short term *vs.* long term); from an energy return on investment perspective.[46,47]

2.1 Storage data in Britain

In Britain national assessments consider different storage durations,[22,48–50] while site specific analysis focuses on short-term storage.[41] Curtailment, price, and export data is provided by the Balancing Mechanism Reporting Service (BMRS) on a site specific basis, with a half-hourly time resolution.[14–16,51,52] A knowledge graph framework will be used to facilitate BMRS data and ESS modelling.

2.2 Storage technologies and British installations

While electro-chemical ESS types, such as lithium ion batteries, will likely be well suited to this application, a review of other storage technologies will be performed for completeness and to define a clear scope for this investigation. These will be discussed in the context of short (daily) and long (seasonal) term storage solutions. Parameters of the selected technology types will be used as inputs by this paper's ESS model.

For rapid response times, capacitor, superconducting magnetic, and flywheel energy storage systems exist,[29,53] though electro-chemical batteries are more common. The chemistry of these include lead acid, lithium ion, sodium (*e.g.* NaS, NaNiCl), and redox flow (*e.g.* V-Redox, ZnBr, Zn–air) types.[29]

Lithium ion batteries are the most commonly deployed design in the context of VRE co-located storage. The UK Government's Renewable Energy Planning Database includes entries for co-located battery units.[6] Here, lithium ion batteries are extensively used as the ESS technology type of choice.[54–56]

The capacities of these batteries vary from 0.1 to 40 MWh, with a size of 1 MWh being the most common.

Other solutions exist to fulfil longer term (larger scale) storage requirements. In Britain re-pumped hydro is the most widely used.[52] Further technologies include compressed air, hydrogen (made from water or natural gas, using electrolysis, thermolysis, *etc.*), and synthetic natural gas energy storage.[29,57] Ammonia conversion may also be used to expand the applications of hydrogen storage (including with VRE co-location);[58–62] though this is more applicable to seasonal storage or long distance fuel transport *via* shipping.[63,64]

In addition to the aforementioned planned lithium ion attachments, large volumes of hydro storage also exist in Britain.[52] Their placement, however, is more geographically restricted, and thus these reserves are more suitable to long term, rather than the short term co-location applications this paper will focus on. Co-location not only particularly suitable to addressing curtailment (especially curtailment resulting from grid constraints),[41] but is also recommended by a Monte Carlo simulation by the University of Exeter, which concluded co-location to result in more uniform storage device operation.[65] British Wind Farm and ESS studies may be conducted on a site specific basis,[41,42] or with a simulated grid.[66] Various curtailment and frequency control studies focus specifically on site specific investigations.[41,67,68] Furthermore, the dispatch of wind farm co-located ESSs, such as into the balancing market, is also studied on a site specific basis.[69]

Research from ETH Zurich, using IEA data, confirms the dominance of lithium ion and pumped hydro outside of the UK as well. By comparison far more negligible shares were found for vanadium redox flow, lead–acid, and sodium–sulfur batteries, as well as compressed-air and other storage types.[30] This was projected to continue (with increasing lithium ion investment in net and proportional terms) through to 2030.[30] Specifications of these storage technologies were also provided, and are broadly consistent with previous literature such as that summarised by Cardiff University in a review of their own.[29] Capital expenditure figures therein also fall within the price ranges of cost specific projections by MIT and the National Renewable Energy Laboratory.[70,71]

2.3 Storage specifications

Given the literature's indication of the clear suitability of lithium ion to wind farm co-located storage applications in Britain, the specifications of these co-attachments should be determined. Numerous sources exist which provide ESS specifications.[29,30,72,73] Those from the aforementioned ETH Zurich study shall be primarily used.[30] The optimal depth of discharge (DOD) and charge/discharge rate are obtained from a recent Nanyang Technological University publication (Table 2.1.1 therein).[72] While the battery size is configurable, the earlier discussed most common size of 1 MWh shall be used.[6] Specifications are as follows:

• Size: 1 MWh.[6]
• Charge/discharge rate: 0.5C (*i.e.* 2 hours for full charge/discharge).[72]
• Efficiency: 95%.[30]
• Lifespan: 12 years, and 4996 cycles (at optimal DOD).[30]
• Optimal DOD: 80%.[72]
• Cost: 316 000 USD per MWh.[30] Using the 2021 USD/GBP exchange rate of 1.162995,[74] this is 271 712 GBP per MWh.

The above efficiency will consider round-trip and inverter losses, but not transmission or distribution losses. As ESS attachments will be co-located, it is assumed that all transmission and distribution losses will only occur after energy is exported from a site, as would be the case if it were simply exported from a wind farm directly.

For the purposes of economic modelling, a discount rate of 10% will be used, as is consistent with existing literature.[75] Future investigations should also be aware of the potential for falling costs,[76] though this paper will use the above existing battery specifications from recent literature. Changes in the market prices of future years would also impact these results as this modelling assumes market exposure to live prices.

3 Methodology

Individual, market exposed, 1 MWh co-located ESS attachments will be modelled for numerous British wind farms. Policy makers may consider these in isolation, or as a component of a larger ESS attachment or storage strategy. ESS specifications will be as per Section 2.3, however, a broader framework exists to facilitate data collection, along with the behaviour of the simulated ESSs themselves.

3.1 Wind farm and market data

The Balancing Mechanism Reporting Service (BMRS)[16] reports extensively on British energy and energy market data. This includes market data such as energy prices and bidding,[14,77] as well as generator data such as exports,[51] curtailments,[14] and further unit data.[52] Time series data is therein reported at a half-hourly frequency. Using EIC data,[78] and validating using background information from DUKES,[79] this information is mapped and stored in a knowledge graph. The capacity and installation of these farms varies, so for the sake of this paper 2021 wind farm information for mapped sites with capacities >50 MW was used. This resulted in a selection of 47 wind farms throughout Britain.

3.2 Emissions intensity rates

Emissions rates will be used in the analysis of the imbalance market, and displaced emissions intensities. National Grid ESO reports on UK emissions by generation type. These are used to determine the marginal seller's emissions intensity rate and are shown in Table 1.[80–86] A forecasting partnership between Environmental Defence Fund Europe, WWF, and National Grid ESO, using Met Office weather data, provide a summary of these emissions intensities.[84] Emissions intensities (such as that of the imbalance market) are calculated *via* the proportional contribution of the generation types' carbon intensities.

Table 1 (UK) National Grid ESO Emissions Intensities[84]

Fuel type	Carbon intensity (gCO_2 per kW h)
Biomass	120
Coal	937
Gas (Combined cycle)	394
Gas (Open cycle)	651
Hydro	0
Nuclear	0
Oil	935
Other	300
Solar	0
Wind	0
Pumped storage	0
French imports	Approx. 53
Dutch imports	Approx. 474
Belgium imports	Approx. 179
Irish imports	Approx. 458

While this study utilises generation emissions in accordance with the reporting of the above sources, it should be noted for future investigations seeking to investigate lifecycle emissions, that more sources may be considered. These include upstream emissions from mining and extraction, including the emission of more potent greenhouse gasses such as methane. Emissions associated with the mining, refining, and manufacturing of ESSs may also be of interest. Due to its shorter time-span, these sources fall out of the scope of this investigation, but are still noteworthy.

3.3 Knowledge graph framework

A knowledge graph approach is used to create digital twin ESS models. Digital twins may be used to model changes in the real (base) world.[87] Data to and from these simulations may be organised *via* a knowledge graph, including in ESS applications.[88]

By using this unique approach a variety of data sources and agents may be coordinated, allowing more sophisticated analyses to be performed. In this manner data on electricity exports, electricity curtailment, electricity price, and the specific station or generators supplying this energy is collected and stored. This is combined with further information on batteries and emissions taken from other sources. Finally, an interconnected ESS agent is utilised to simulate ESS attachments. The outputs of this simulation serve as the basis for this investigation's conclusions.

This paper proposes two main data framework expansions to facilitate its analysis.

The first of these is a representation of the output (export and curtailment) of energy/power. This may be seen in Fig. 1.

Fig. 1 displays an ontology structure which breaks down generated electricity in terms of:

- Generation infrastructure: power plants may consist of multiple power generators, which generate electricity. These may be identified based on their registered resource names (RRNs) or energy identification code (EICs).
- Generated electricity: this generation is split into its active and reactive components, which may be quantified in terms of power or energy.
- Curtailed/exported electricity: active power/energy (as equivalent data isn't known or required by this investigation for reactive power/energy) is further divided into curtailed and exported sub-classes.
- Stored data: the values of this generated electricity are stored as time-series datasets with associated units. This includes curtailed and exported electricity values, which inherit these properties as sub-classes.

Secondly, the properties of the ESS attachment may also be represented, as is shown in Fig. 2. This builds upon the ontology developments of prior literature.[88] Fig. 2 stores information for energy storage systems and a broader energy system (with respect to its point of grid connection) in terms of:

- Energy system (grid connection):
  – Energy flows: energy exported (negative if imported) is defined for energy systems as a time-series dataset, with defined units.
  – Contract: the remaining properties are defined in terms of an energy contract. These include export/import limits (with units), and export/import prices (time-series datasets with units).
- Energy storage system:
  – Energy storage system properties: a variety of properties are defined for energy storage systems including capacity, efficiency, charge/discharge limits, and minimum/maximum states of charge. Where applicable these have defined units.
  – Energy storage system time-series values: energy discharge (negative value when charging) and the state of charge are also defined. These have defined units and have their values stored as time-series datasets.

3.4 ESS model

A linear optimisation model is created using Python's PuLP library.[89] Using time series data (half-hourly) for the energy price, wind farm energy exports, and wind farm energy curtailments, the revenue maximising behaviour of the ESS is calculated. ESS configurations (see Section 2.3) are also required as inputs. This model was run on fortnightly windows for the year of 2021 for each wind farm to schedule their charging and discharging. A full year was selected given the significance of price and price spread seasonality between summer and winter months. The configuration of this model is as follows.

3.4.1 Objective. The objective of the optimisation is to maximise financial returns as per the function:

$$\text{obj:} \sum_{n=1}^{n} \pi_t^{\mathrm{b}} \times E_t^{\mathrm{gd}+} - \pi_t^{\mathrm{s}} \times E_t^{\mathrm{gd}-} \tag{1}$$

where:

- The set of time instances are defined as $t \in T$, from $t = 1$ to $t = n$, with $t = 0$ being the time-step prior to the set over which the optimisation occurs (time periods in this investigation being half an hour in length);
- π_t^{b} and π_t^{s} are price of buying and selling energy at time t, and,

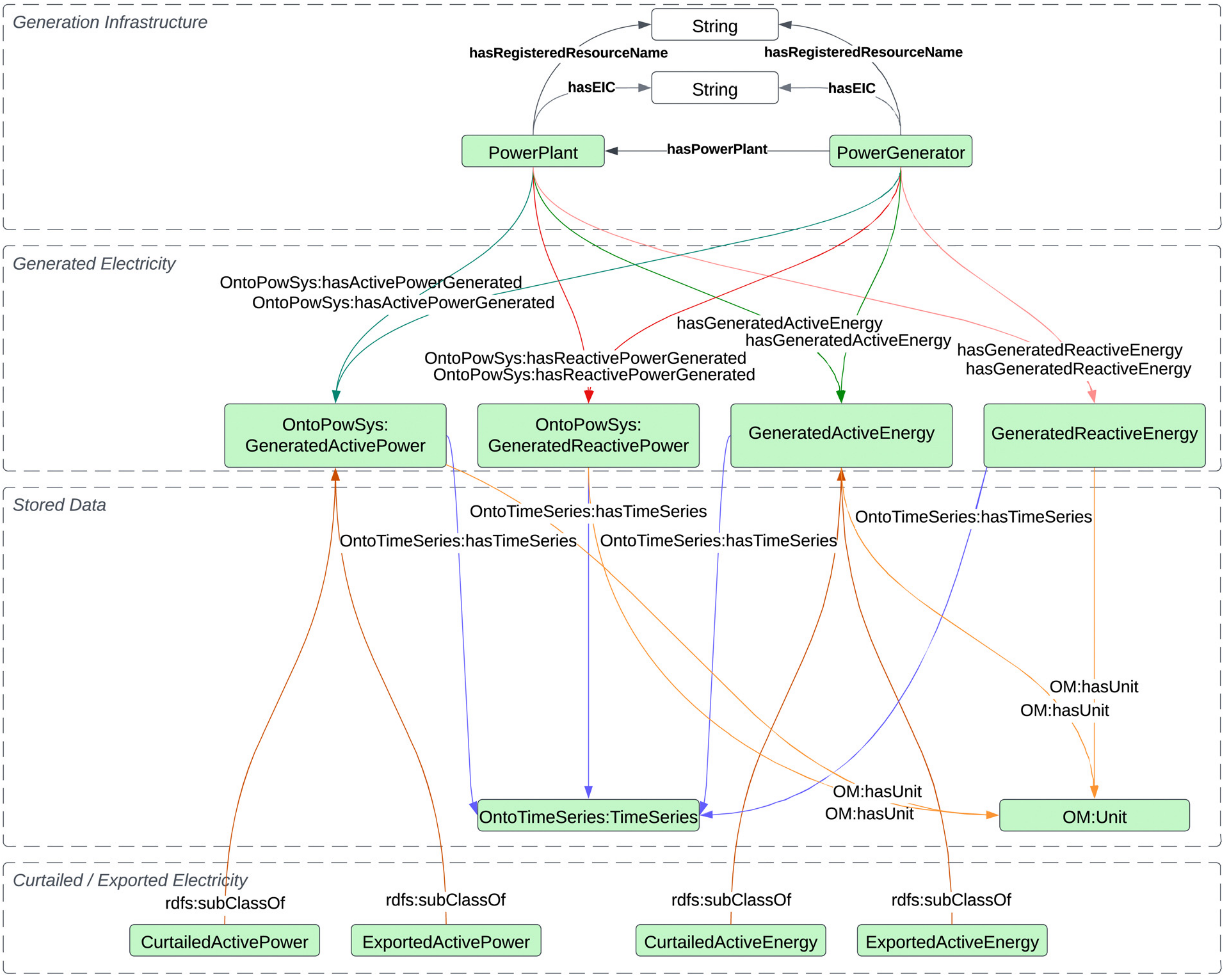

Fig. 1 Ontology of generated power/energy. Boxes represent categories/items while the colour coded lines between them represent instances/relationships.

- E_t^{gd+} and E_t^{gd-} are respectively the purchased/injected energy volumes into the grid (MWh) at time t.

3.4.2 Energy balance. To ensure the conservation of energy, inflows and outflows must be matched, as is described by the following equation:

$$0 = E_t^{gd+} - E_t^{gd-} + E_t^{ess+} - E_t^{ess-} + E_t^{vre} - E_t^{l} - E_t^{c} \tag{2}$$

where:

- E_t^{ess+} and E_t^{ess-} respectively represent energy (MWh) discharged/charged by the storage system at time t;
- E_t^{vre} symbolises the variable renewable energy (VRE) output (MWh) at time t (in this study, these are from onshore and offshore wind farms), including curtailments as per *output* = *export* + *curtailment*;
- E_t^{l} represents the load (MWh) at time t (local loads were not attached to any ESS, so these are all 0 in this investigation, though the model was designed as such for future investigations), and,
- E_t^{c} represents energy curtailed at time t (MWh), specifically the model output, rather than the initial level of curtailment before the addition of the attachment.

3.4.3 State of charge. The energy values balanced in eqn (2) are 'grid side' (or system side), rather than 'ESS side'. The state of charge (SOC) of an ESS unit ('ESS side') is subject to the inefficiencies of charging and discharging. This SOC is calculated as per the below equation:

$$\mathrm{SOC}_t = \mathrm{SOC}_{t-1} + (\eta^{ess-} \times E_t^{ess-} - E_t^{ess+}/\eta^{ess+}) \times 100/E^{ess} \tag{3}$$

where:

- SOC_t denotes the ESS's state of charge (%) at time t;
- η^{ess+} and η^{ess-} respectively symbolise the ESS discharge/charge efficiency (factor), and,
- E^{ess} is the ESS storage capacity (MWh).

Initial and final states of charge are defined, and set to equal one another ($\mathrm{SOC}_{t=0} = \mathrm{SOC}_{t=n}$).

3.4.4 Limits. Various limits are also enforced for the minimum and maximum values permitted for variables. These are listed below.

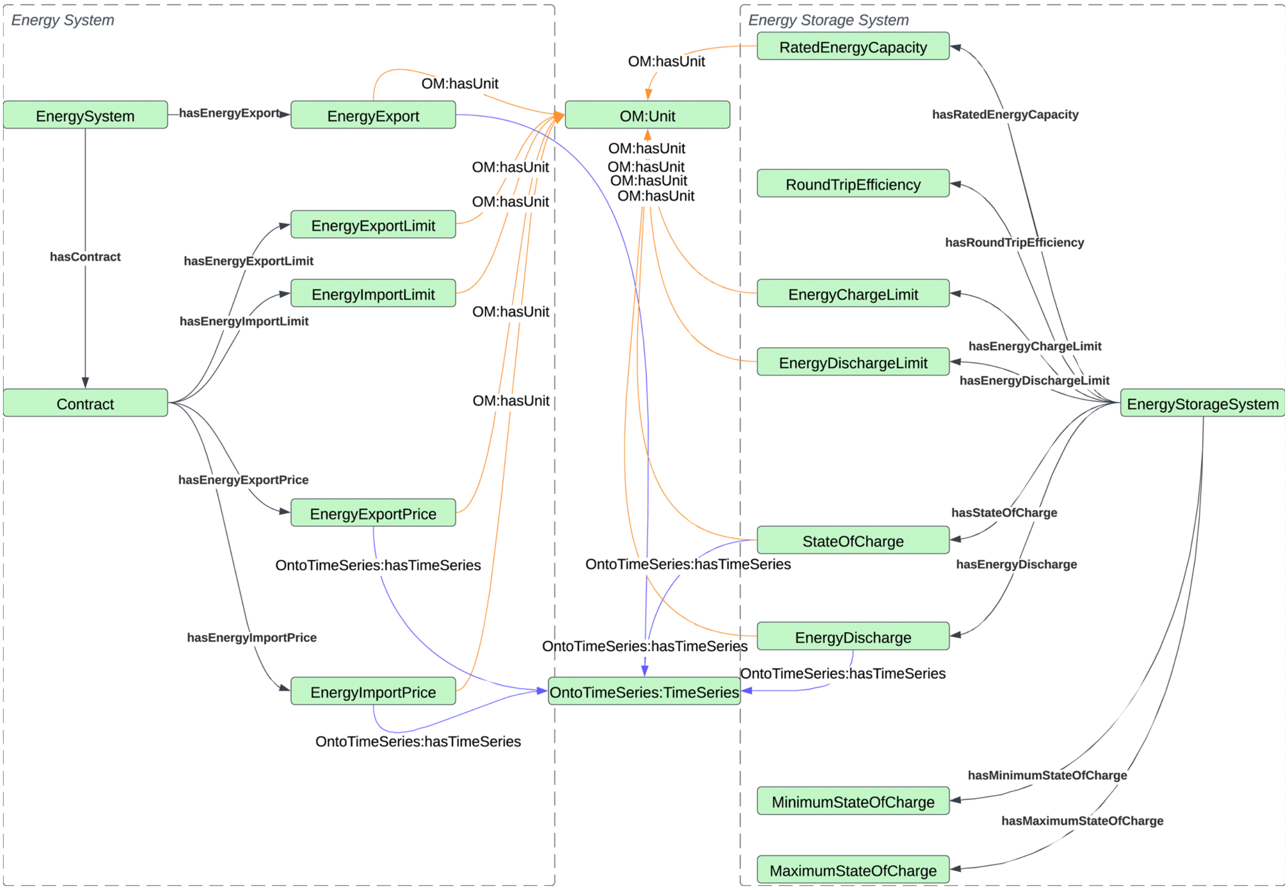

Fig. 2 Ontology of energy storage system specifications. Boxes represent categories/items while the colour coded lines between them represent instances/relationships.

ESS flow limits are:

$$0 \le E_t^{\text{ess}+} \le E_{\max}^{\text{ess}} \tag{4}$$

$$0 \le E_t^{\text{ess}-} \le E_{\min}^{\text{ess}} \tag{5}$$

where ESS charge and discharge limits (MWh) are defined as $E_{\min}^{\text{ess}}$ and $E_{\max}^{\text{ess}}$.

State of charge (SOC) limits are:

$$\text{SOC}_{\min}^{\text{ess}} \le \text{SOC}_t \le \text{SOC}_{\max}^{\text{ess}} \tag{6}$$

where minimum and maximum states of charge (%) of the ESS (used to enforce optimal DOD) are $\text{SOC}_{\min}^{\text{ess}}$ and $\text{SOC}_{\max}^{\text{ess}}$.

Grid limits are:

$$0 \le E_t^{\text{gd}+} \le E_{\max}^{\text{gd}} \tag{7}$$

$$0 \le E_t^{\text{gd}-} \le E_{\min}^{\text{gd}} \tag{8}$$

where the grid import/export limits (MWh) are $E_{\min}^{\text{gd}}$ and $E_{\max}^{\text{gd}}$ respectively. This limit is not reached in operation (with curtailments being handled separately), however it is still enforced.

3.4.5 Conditional mathematical formulation. While E_t^c from eqn (2) represents the calculated curtailment level after the optimisation of ESS behaviour, the pre-ESS attachment level of VRE curtailment (MWh) at time t is represented as E_t^{vrec}. In this study, these curtailments are from onshore and offshore wind farms.

For each time period t, if curtailment exists ($E_t^{\text{vrec}} \neq 0$), then an additional grid constraint is enforced. Under this constraint, the new amount exported from the system cannot exceed the previous amount exported during the period of curtailment ($E_t^{\text{vre}} - E_t^{\text{vrec}}$), *i.e.* curtailed energy can either be stored by the ESS during this time period, or continue to be curtailed. This yields the following constraint:

$$0 \le E_t^{\text{gd}+} - E_t^{\text{gd}-} + (E_t^{\text{vre}} - E_t^{\text{vrec}}). \tag{9}$$

3.4.6 Further configuration in mathematical formulation. The ESS model also has further configuration, such as the ability to disable charging of the ESS from the grid. Given the significance of curtailment to this study, which is highly influenced by transmission constraints, the ESS shouldn't place additional strain on the grid for simplicity. Furthermore, this study is particularly interested in ESSs as co-located attachments, rather than independent units which charge and discharge from the grid to smoother price or demand. As such a constraint is required. This constraint ensures the ESS cannot charge by more than the amount of energy produced by the wind farm to which is co-located:

$$0 \leq E_t^{\text{vre}} + E_t^{\text{ess+}} - E_t^{\text{ess-}} \tag{10}$$

It is recommended that the impact of ≤ 0 energy prices be validated, particularly in studies without limitations such as that described in eqn (10). For example, ESS degradation may be encouraged by repeatedly charging and curtailing (which may not be an intended behaviour).

Furthermore, during periods of 0 GBP energy prices, all energy which can be exported, is exported (to prevent distortions in results from a financial indifference between curtailing or exporting during these periods). Finally and most importantly, for the effect of the ESS attachment to be properly understood, simulations are run with and without (no capacity) an ESS. This is because the ESS script would save money by curtailing exports during periods of negative price (which could occur), which would be counted as a financial gain, even though the ESS is not responsible for it. By running the model with and without an ESS, the results/returns specifically from the ESS may be determined.

Using this methodology, an ESS model is created which maximises financial returns. These financial returns are generated *via* the export of energy from the site (wind farm and/or ESS), with curtailment subsidies or fees not being considered. This model is run with and without an ESS to determine changes made by its co-location with the wind farm, as opposed to other motivated changes by the model. Potential additional strain on the grid by charging the ESS from the power network is prohibited, with co-location being the topic of interest, and permitted export levels are capped at their current levels during periods of curtailment. Using the outputs of this simulation, the financial returns, and curtailment reductions resulting from the ESS attachments are calculated. An example run using sample data may be found in the ESI.†

4 Results

For the 47 selected British wind farms and other datasets such as price and marginal generator type, figures are obtained for the year of 2021. To determine the effect of adding an ESS, systems with and without an attached ESS are compared for the differences in their outputs to be obtained. Results may be divided on the basis of flows (comparative systems inflows and outflows, with and without an ESS), payback (comparative system returns, with and without an ESS), and emissions (emissions intensity in the imbalance market, in which the ESS will operate).

4.1 Flows

The ESS model was run for the year of 2021 to simulate a 1 MWh ESS attachment on the wind farms listed in Table 2.

Geographic site locations may be found in the ESI.†

While later analysis will consider financial gains and emissions reductions from simulated installations, these initial results will simply display the net flow differences between running the model with and without an ESS for each wind farm. ESS behaviour was optimised to maximise financial returns, which are achieved through two means.

Table 2 For UK wind farms in 2021 this table displays the inefficiency losses from arbitrage (charging, discharging, conversion), curtailment reduction gains (otherwise curtailed) subject to losses, and their net effect, due to the attachment of a 1 MWh co-located ESS at each site

Farm	Loss	Gain	Net
Name	(MWh)	(MWh)	(MWh)
Aberdeen	−69.2	0	−69.2
Arecleoch	−66.51	26.22	−40.29
Baillie	−66.19	50.22	−15.97
Beatrice	−69.88	64.18	−5.69
Beinneun	−67.28	1.96	−65.32
Bhlaraidh	−61.28	66.04	4.75
Blackcraig	−70.05	0.82	−69.23
Black Law	−57.97	22.25	−35.73
Black Law II	−51.45	24.63	−26.82
Barrow	−71.39	2.78	−68.61
Burbo Extension	−72.32	10.14	−62.18
Braes of Doune	−60.02	51.86	−8.16
Berry Burn	−69.21	51.52	−17.68
Corriegarth	−59.64	48.51	−11.13
Clyde (Central)	−69.32	30.56	−38.76
Clyde (North)	−69.47	38.78	−30.69
Clyde (South)	−66.54	24.58	−41.96
Crystal Rig II	−58.46	6.38	−52.07
Dudgeon 1	−78.22	0	−78.22
Dersalloch	−64.65	41.9	−22.75
Dunmaglass	−66.4	32.22	−34.18
East Anglia One	−79.59	16.89	−62.71
Fallago Rig	−67.87	27.18	−40.69
Galawhistle	−57.34	22.94	−34.39
Gunfleet Sands 1 & 2	−73.93	2.46	−71.46
Greater Gabbard	−79.62	5.24	−74.38
Griffin	−58.91	58.93	0.02
Hadyard Hill	−63.23	19.72	−43.51
Humber Gateway	−75.55	11.19	−64.36
Hornsea 1	−78.84	21.85	−56.99
Harestanes	−62.25	34.59	−27.66
Kilbraur	−63.35	59.95	−3.4
Kilgallioch	−66.86	59.63	−7.23
Lochluichart	−61.09	38.29	−22.8
Millennium	−63.29	45.28	−18.01
Mark Hill	−63.92	13.65	−50.26
Race Bank	−76.58	12.56	−64.01
Rampion	−76.56	0	−76.56
Robin Rigg East	−63.34	0	−63.34
Robin Rigg West	−63.86	0	−63.86
Stronelairg	−69.8	28.76	−41.03
Strathy North	−61.48	87.99	26.51
Whitelee	−67.25	36.89	−30.36
Walney 1 & 2	−74.93	2.46	−72.47
Walney 3	−72.05	21.65	−50.4
Walney 4	−68.34	21.68	−46.66
Westermost Rough	−77.25	4.1	−73.15

The first is to charge during periods of lower energy prices and export during periods of higher energy prices, *i.e.* arbitrage. Due to the charging and discharging of the ESS this incurs losses due to inefficiency of the battery. An efficiency loss due to price arbitrage, however, is not inherently negative, as may promote price stabilisation, mitigate dispatchable fossil fuel use in the imbalance market, or enable the expansion of wind energy infrastructure by lowering the risk of cannibalisation.

The second mechanism for increasing revenues is to charge the ESS using curtailed energy. As with energy exports, energy curtailments are also recorded for the year of 2021. Instead of curtailing wind energy, this may instead be stored for later export. By doing so the system may export more energy than it otherwise would have. Both the systems with and without the ESS were permitted to curtail energy to ensure a fair test in comparing their financial results (*i.e.* if the plant exported during a period of negative price by default, this was permitted to be curtailed by the non-ESS system, as financial benefits due to this curtailment in the ESS system would be the result of permitting curtailment, rather than due to the ESS attachment itself).

In Table 2 only the Strathy North, Bhlaraidh, and Griffin wind farms obtained a net positive energy output to the grid due to prevented curtailment losses exceeding price arbitrage operation efficiency losses. These three wind farms unsurprisingly had the respectively largest curtailment rates for 2021. A net gain or loss does not explicitly imply a positive or negative ESS performance, but rather gives an indication of the relative price stabilisation *vs.* curtailment reduction roles performed by an ESS attachment. Conversely, wind farms without recorded

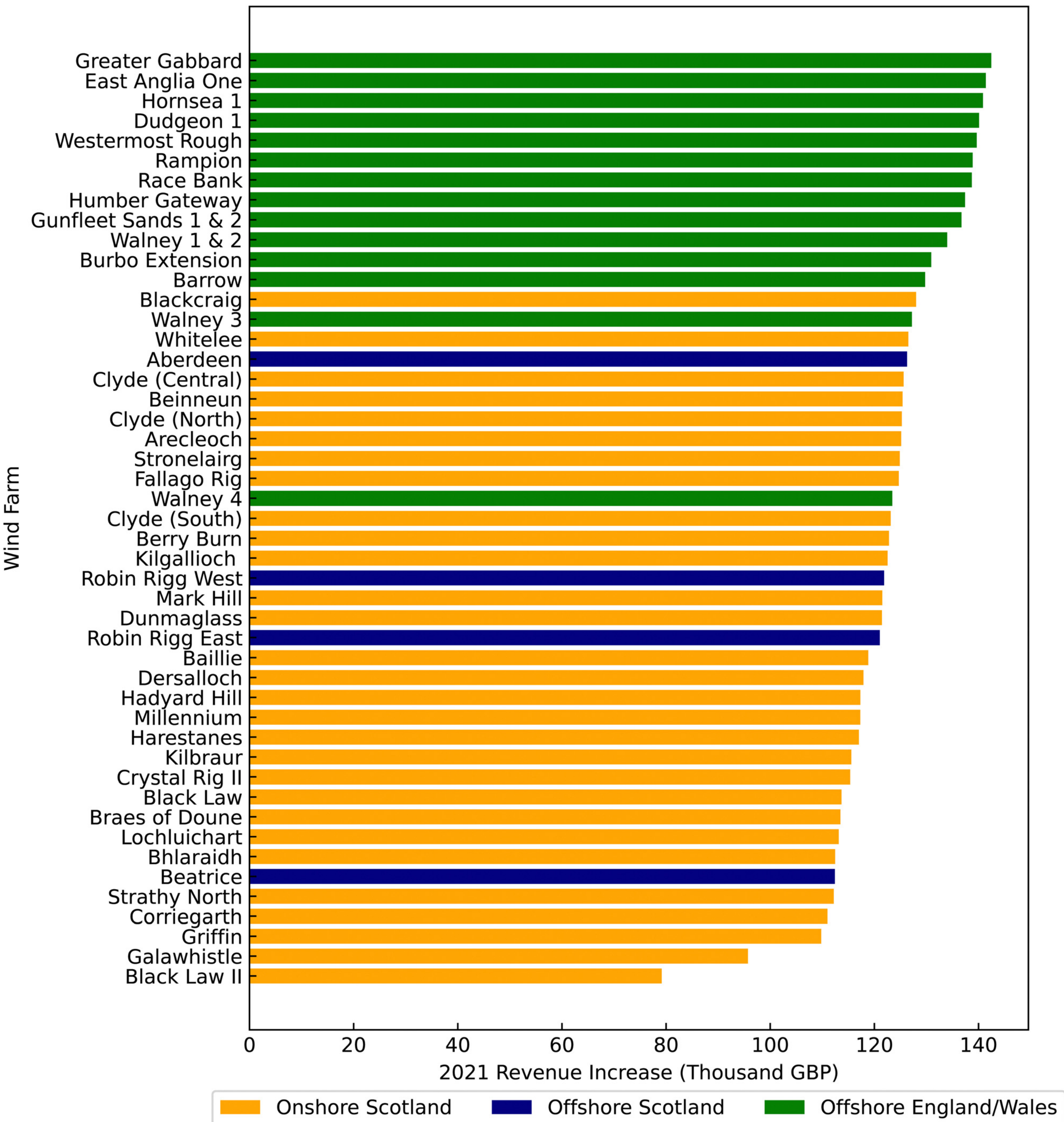

Fig. 3 2021 revenue increases modelled for an ESS attachment at various wind farm sites. No Onshore England/Wales wind farms are considered in this paper.

curtailment instances in 2021 had no curtailments to mitigate, and thus only arbitraged price.

4.2 Returns

The revenue increase estimated by the model is calculated for the wind farms from Table 2. These increases, due to ESS attachments, are displayed in Fig. 3.

These returns differ on a site by site basis. Relatively lower curtailment English/Welsh offshore wind farms tend to be the best performers. A breakdown of these factors is performed in the ESI.† While these factors (onshore *vs.* offshore, Scottish *vs.* English/Welsh) can't fully explain the differences between individual wind farms on a site specific level of granularity, some broad trends are observed.

As was noted with respect to Table 2, the role of price arbitrage tends to be more significant than curtailment reduction. Given that the ESS may only charge using locally generated energy, which is more consistently produced by English/Welsh offshore wind farms (enabling more opportunities for price arbitrage), these sites generate superior returns. Conversely, Scottish sites (which tend to be curtailed at higher rates) generate lower returns (though predictably higher curtailment reduction as noted in Table 2).

4.3 Emissions intensity

ESS participation in energy market could be as a marginal seller, due to its dispatchability. To identify the emissions reduction potential of this partial involvement the emissions intensity of this market for the examined year of 2021 should be determined. By mapping the majority of marginal sellers in the market, categorising them by type (Fig. 4), and applying the pollution levels (Table 1), this may be determined.

The most common marginal seller, and therefore generation type to be displaced if marginal selling was instead performed by an ESS, is combined cycle gas. The emissions intensity of gas is 394 gCO_2 per kW h. By comparison, the average marginal seller emissions rate is 396.45 gCO_2 per kW h.

Specific emissions rates may be determined on a site by site basis. When an ESS exports energy into the grid, the marginal seller type in the imbalance market (which sets the spot price of energy from the grid due to being the marginal generator, and may similarly be regarded as a marginal emitter which the ESS may displace) may be recorded. A breakdown similar to that of Fig. 4 may be performed, but on an ESS specific basis rather than for the entire grid. Thus, emissions reduction intensities may be estimated for each ESS attachment. More detail is provided in the ESI.†

Fig. 5 displays a breakdown of the marginal seller type during periods of ESS export. This may be used to determine site specific emissions (reduction) intensities; used later. The average composition across sites is 83.49% gas, 4.47% coal, 11.63% hydro, and 0.41% wind. This results in an average emissions (reduction) intensity of 370.84 gCO_2 per kW h. Site specific intensities used for later analysis are noted in the ESI.† This lower rate compared to the marginal seller average (though still significantly greater than that of the overall energy market) is primarily due to the higher proportion of hydro as the marginal seller when the ESS exports energy into the grid. These trends hold for each specific site.

In Fig. 5 the higher rate of hydro marginal selling during periods of ESS export, compared to the average rate of hydro marginal selling in imbalance market, may be seen. Using these results, Fig. 6 displays the emissions intensity of the average marginal seller for each site. As mentioned earlier, each of these may be seen to fall below the average marginal seller emissions intensity, due to attachments being more likely to export during periods of hydro marginal selling (which has a 0 gCO_2 per kW h emissions intensity). While hydro (*e.g.* pumped)

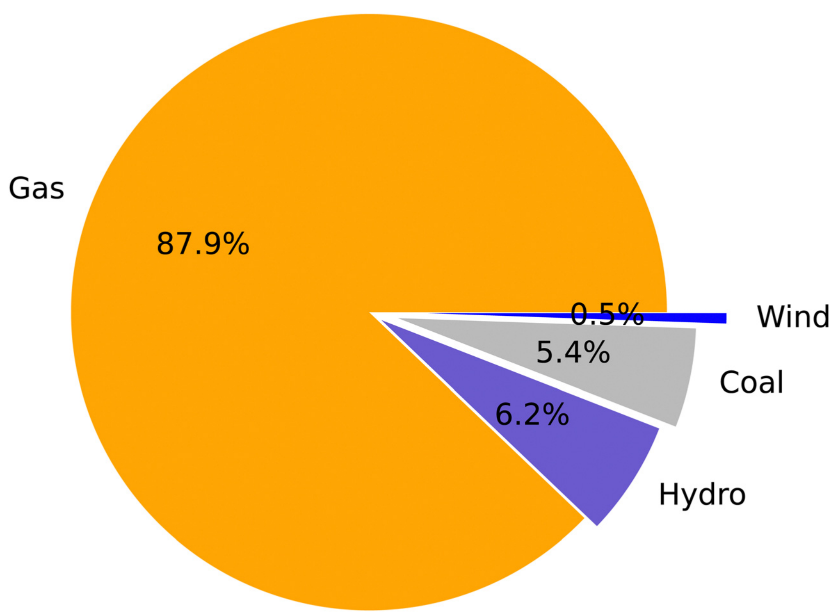

Fig. 4 Percentage of the time each generator type was the marginal seller in the imbalance market in 2021.

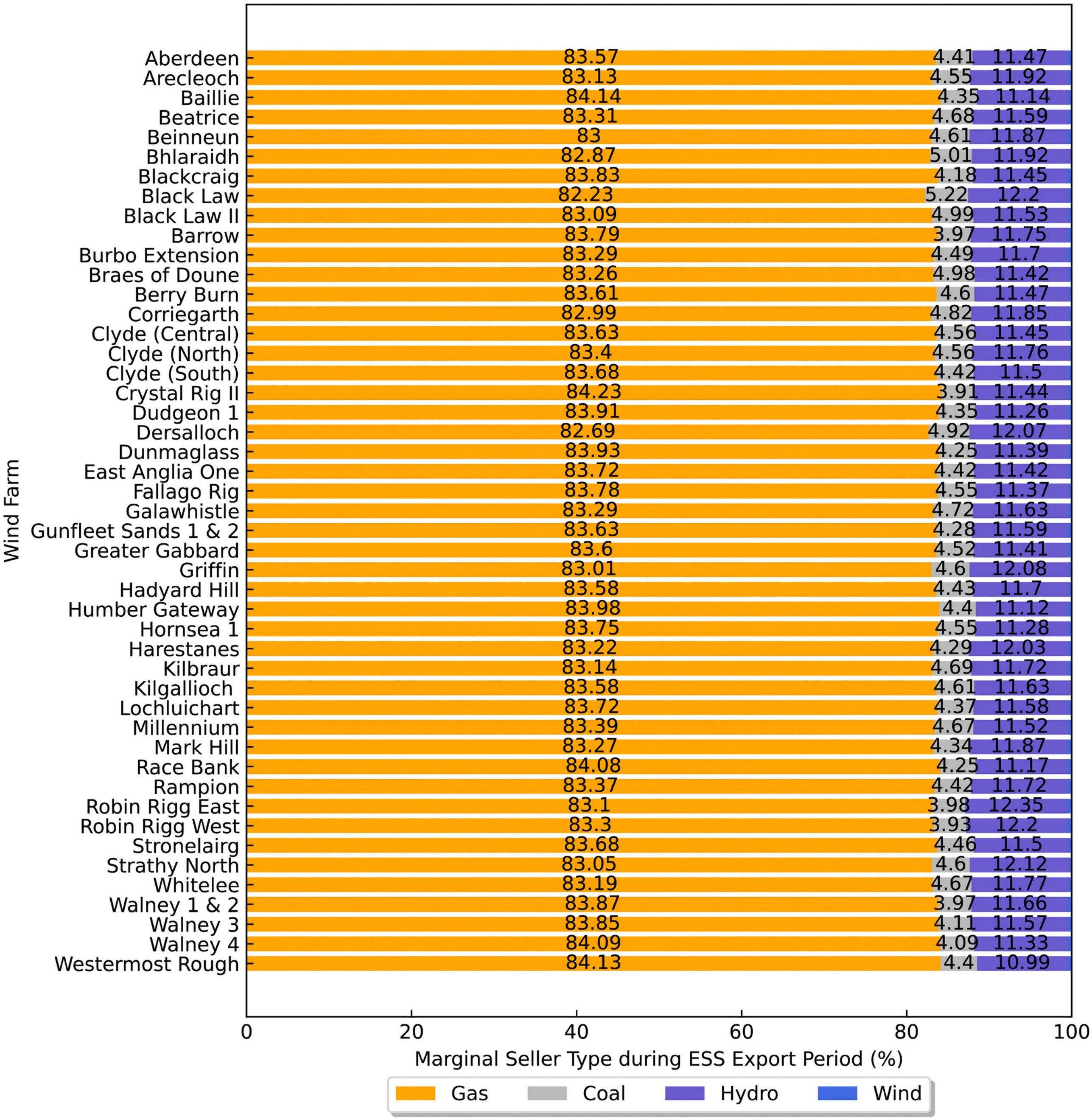

Fig. 5 Marginal seller type (percentage of the time) during the ESS exports at each site. These percentages are labelled for each type besides wind (to save space), though these may be seen in the ESI.†

is used for longer term storage applications than batteries, some competition evidently exists between the dispatching recommended by this model, and actual hydro deployment in the grid as the marginal seller.

5 Analysis

As the primary focus of the ESS model is to maximise financial returns from ESS attachments, the returns of these ESSs should be analysed in terms of estimated payback. Furthermore, given the emissions breakdown and data from the imbalance market, emissions reduction may also be considered.

5.1 Aggregate curtailment mitigation

By summing the results of Table 2 by country you obtain the results shown in Table 3. Though Scottish figures are broadly higher on account of the scale of built capacity, it is clear that proportional Scottish curtailment mitigation is far higher, owing to a higher (percentage) rate of curtailment which may be abated.

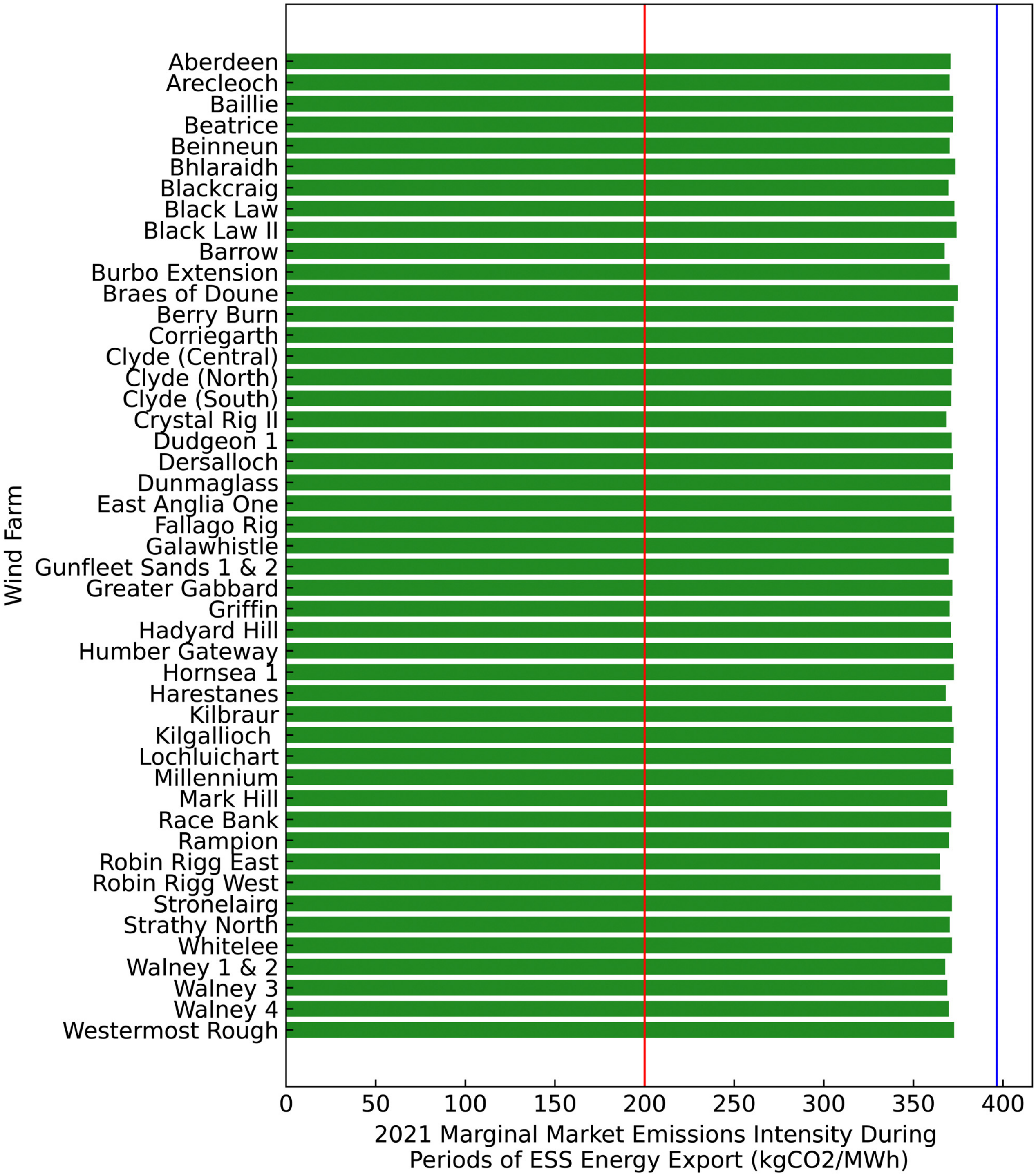

Fig. 6 Estimated imbalance market emissions intensity during ESS energy export periods for each wind farm gCO_2 per kW h. Energy imbalance market average (396.45 gCO_2 per kW h) is marked by the blue line. Overall energy market average (200.06 gCO_2 per kW h) is marked by the red line.

5.2 Payback

Given the revenue increase results from Section 4.2, do any of these attachments achieve payback, and if so, how long does take? For 2021 a 1 MWh ESS was estimated to cost 271,712 GBP, meaning no ESS would achieve payback within the studies year alone. If the year of 2021 is repeated, with revenues subject to a 10% annual discount rate, then the payback of the attachments may be estimated. Literature used to obtain specifications[30] notes lithium-ion batteries to have a 12 year and 4996 cycle lifespan (at optimal DOD, which was taken to be 80%,[72] and which the model enforced). If payback cannot be achieved within these limits, then it is not achieved. By maximising returns, the ESS model used by this paper primarily addresses the lifespan constraint by achieving payback as quickly as

Table 3 Summed results of Table 2 by country

Country	Loss (MWh)	Gain (MWh)	Net (MWh)
Scotland	−2117.36	1116.43	−1000.89
England	−1055.17	133	−922.16

possible. The cycle limit, however, may still be taken as a constraint for its own consideration.

Payback times are given in Table 4. Here, all ESS attachments are shown to achieve payback. All but three of these do so in 3000–3500 cycles, and all but two do so in 2–3 years. Attachments with higher returns (Fig. 3) naturally obtained faster paybacks (which the model attempts to minimise), however as a result there is no strong trend between a quick payback and a payback in the minimum number of cycles.

Table 4 Number of years/cycles to achieve ESS payback by wind farm site

Farm Name	Years to payback	Cycles to payback
Aberdeen	2.31	3250
Arecleoch	2.33	3168
Baillie	2.48	3343
Beatrice	2.64	3754
Beinneun	2.33	3195
Bhlaraidh	2.64	3301
Blackcraig	2.27	3242
Black Law	2.61	3086
Black Law II	3.99	4167
Barrow	2.24	3252
Burbo Extension	2.22	3261
Braes of Doune	2.61	3206
Berry Burn	2.39	3365
Corriegarth	2.68	3256
Clyde (Central)	2.32	3278
Clyde (North)	2.33	3294
Clyde (South)	2.38	3222
Crystal Rig II	2.56	3049
Dudgeon 1	2.05	3252
Dersalloch	2.50	3295
Dunmaglass	2.42	3269
East Anglia One	2.03	3274
Fallago Rig	2.34	3245
Galawhistle	3.18	3719
Gunfleet Sands 1 & 2	2.11	3168
Greater Gabbard	2.01	3247
Griffin	2.71	3263
Hadyard Hill	2.51	3244
Humber Gateway	2.10	3216
Hornsea 1	2.04	3258
Harestanes	2.52	3202
Kilbraur	2.56	3310
Kilgallioch	2.39	3262
Lochluichart	2.62	3272
Millennium	2.51	3249
Mark Hill	2.41	3150
Race Bank	2.07	3225
Rampion	2.07	3217
Robin Rigg East	2.43	3142
Robin Rigg West	2.41	3143
Stronelairg	2.34	3320
Strathy North	2.64	3310
Whitelee	2.31	3156
Walney 1 & 2	2.16	3288
Walney 3	2.29	3360
Walney 4	2.37	3294
Westermost Rough	2.06	3227

As such, quick paybacks (primarily due to price arbitrage) are noted for all attachments, though this is contingent on the limiting number of cycles specified for attachments. The specifications of this limit, however, vary between sources, so although the specifications taken from literature an inputs for this analysis proved sufficient, these results would vary based on advised changes in ESS specifications including their performance and lifespan.

5.3 Emissions change

In the context of this investigation, a reduction in the carbon intensity of the energy system may be achieved primarily through the reduction of fossil fuel use. ESS operations in the imbalance market are noted to overwhelmingly displace gas. This may occur through either of the two functions facilitated by the ESS: price arbitrage, and curtailment reduction.

The broader effects of price arbitrage, and its price stabilising behaviour (and potential complementary role alongside existing and new VRE deployments *via* reduced cannibalisation) are not investigated in this analysis. Instead, this paper investigates ESS performance on a site by site basis, thereby focusing instead on the returns generated by arbitrage rather than secondary effects. Other impacts, such as the impacts on hydro storage behaviour *via* the disproportionate competition with battery attachments, also fall out of the scope of this study. Curtailment reduction, however, may be more directly understood on a site by site scale.

Emissions reductions estimated by this paper, therefore, are calculated using the site specific emissions rates from Section 4.3 and the wind farm curtailment reductions from Section 4.1. Due to similarity across sites in the results of Fig. 6, these reductions are primarily the result of the volume of curtailment reduction. These estimated emissions reductions may be seen in Fig. 7.

The emissions reductions shown in Fig. 7 refer only to reduced curtailment volumes multiplied by the average imbalance market emissions intensities for each ESS. The decarbonisation role of ESSs is much more extensive, with this study focusing on direct and site specific flows (such as curtailment reduction).

5.4 Site recommendations

Battery attachments perform two main roles in this analysis: price arbitrage, and curtailment reduction. Price arbitrage stores generated energy to be exported during another time period, incurring inefficiency losses, but generating the bulk of financial returns (increasing system returns). Curtailment incurs these same inefficiency losses, but on energy that could have otherwise been wasted entirely (increasing exported energy volumes).

The sites where battery attachments have most increased financial returns or system exports, differ. This may be visually represented by mapping the top 10 sites with respect to the criteria of shortest payback time, and emissions reduction *via*

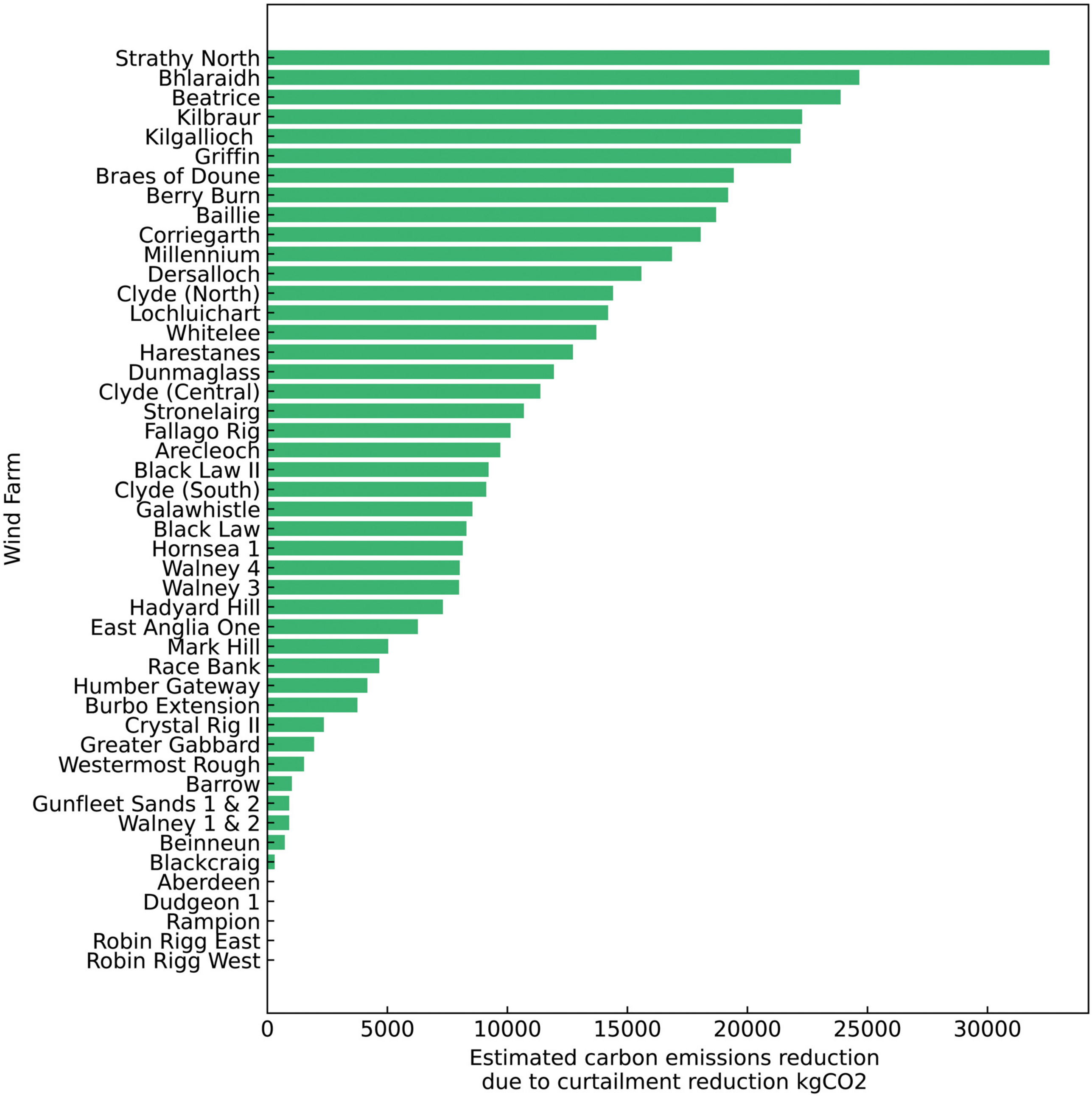

Fig. 7 2021 carbon emissions reduction *via* curtailment mitigation, using site specific emissions displacement intensities, as determined by the difference between an ESS which can and can't charge using curtailed energy.

curtailment mitigation. Fig. 8 displays these sites alongside operation/under construction wind farm battery attachments. These operation/under construction ESSs are taken from the Renewable Energy Planning Database[6] list, where numerous 'Co-located with RE' batteries are listed for wind, solar, hydro, and biomass. Of these, those co-located (or planned to be) with wind farms were used.

Other assets are also provided by this database, such as rejected batteries, and ESSs in earlier stages of planning. Energy storage projects which are not co-located with generators are also provided. This analysis, however, does not permit ESSs which increase demand (*i.e.* charge from the grid), and as such only co-located batteries (which may charge from the wind farms to which they are attached) are considered.

Fig. 8 shows the leading curtailment reducing (and by extension, directly CO_2 mitigating) ESS co-location sites to be in Scotland. Conversely, the batteries which achieved the quickest paybacks are located off the English/Welsh coast. When examining constructed, or under construction ESSs which are co-located with wind farms, however, deployments can be seen to have been made in both locations (though there only 5 examples).

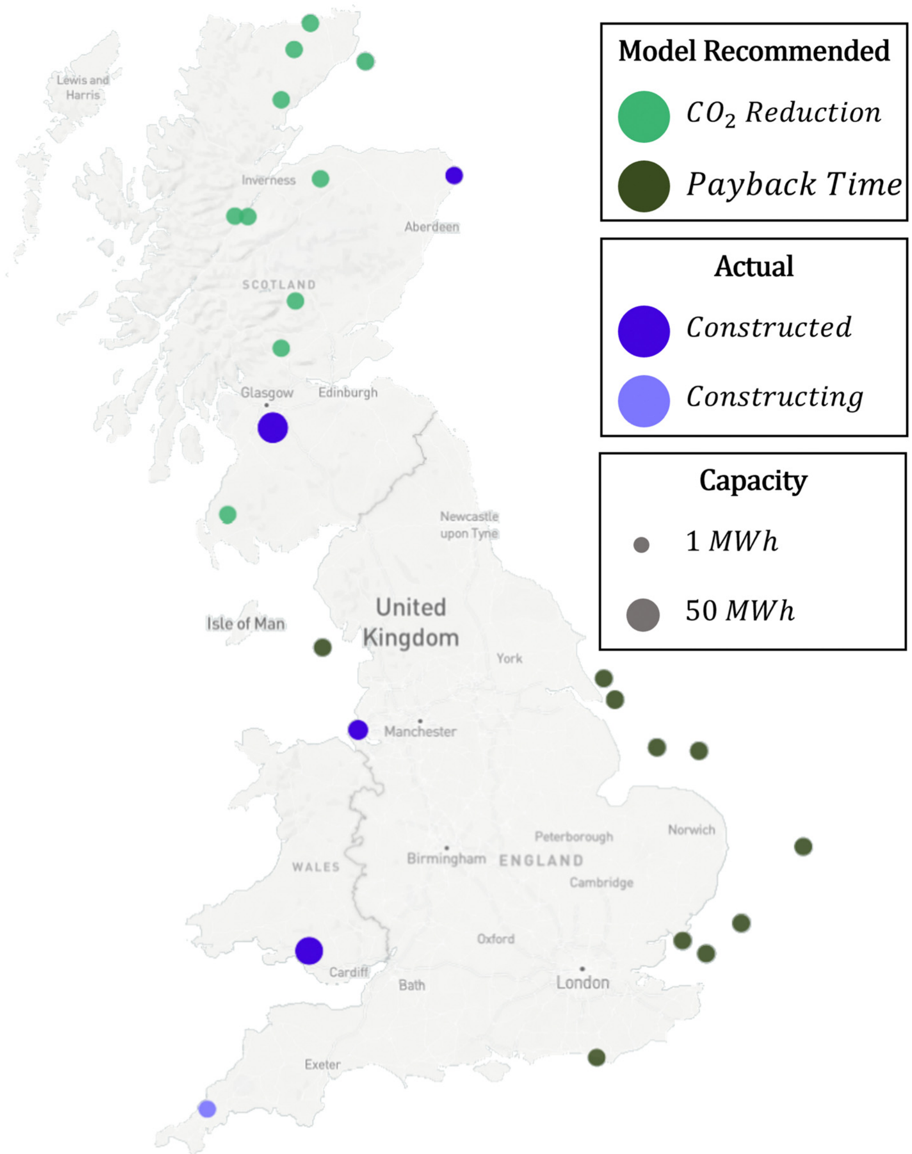

Fig. 8 The markers on the map show the top 10 model recommended locations for 1 MWh ESSs to be collocated with wind farms. These recommendations are determined based on sites with the greatest CO_2 reduction (from exporting otherwise curtailed energy) and quickest payback times (partially achieved *via* the export of otherwise curtailed energy, but primarily from price arbitrage). Constructed and under construction co-located battery attachments with wind farms reported externally are also displayed.[6,90] Circle markers are scaled by ESS size (with modelled ESSs all being 1 MWh). Offshore wind farm ESSs are shown on site, while in practice they may be placed near a coastal point of connection.

For ESSs co-located with wind farms in 2021, however, two key clusters are visible. In England/Wales, ESSs co-located with high capacity factor offshore wind farms had more opportunities to arbitrage energy prices. Note that ESSs in this study were permitted to charge only from their co-located generators. Given that price arbitrage was found to be more economically significant than curtailment reduction, these sites achieved the quickest payback times.

In Scotland, where more curtailment exists, so too is there more curtailment reduction. The financial benefit of exporting curtailed energy was less significant than price arbitrage, though these farms also achieved payback. In three instances, curtailment reductions were high enough to exceed energy losses from battery inefficiency. This is despite most ESS operations being the result of charging and discharging due to price levels, rather than charging using curtailed energy. ESS curtailment reduction at Strathy North, Bhlaraidh, and Griffin was therefore significant enough, in a price optimising model framework, to result in a net increase in energy exports. For the remaining sites, storage behaved more typically, by dispatching in response to price, but at a loss due to inefficiency.

5.5 Further curtailment analysis

Given the significance of regional curtailment differences in determining which farms achieved greater emissions reduction rates *via* curtailment mitigation, the curtailment rates are provided in Fig. 9. Here curtailment rates are graphed using data obtained from BMRS, as well as from the Renewable Energy Foundation. Given that Moray East and Beatrice consist the vast majority of offshore Scottish wind capacity and fall within onshore Scottish curtailment rates, it can clearly be seen that Scottish wind farms exhibit higher rates of curtailment (onshore or offshore).

More detail on curtailment, with respect to geographic site placements and differing curtailment rates in different sources, may be found in the ESI.†

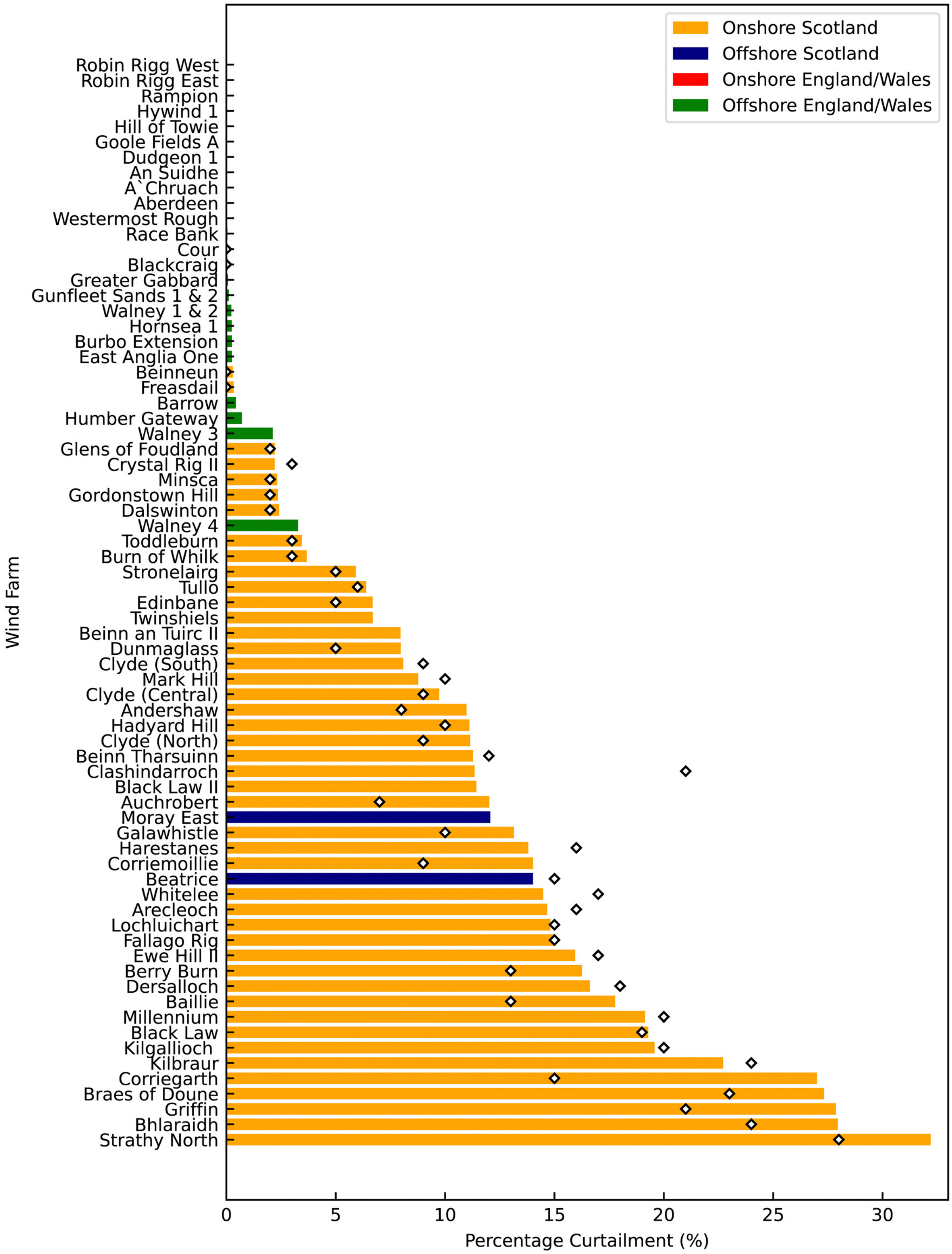

Fig. 9 Bars represent: curtailment percentage (%) of British Wind Farms in 2021.[14–16,51,52,77] Bar colours represent: farm type/location. Diamonds represent: renewable Energy Foundation values (only available for some farms).[17,91,92]

Table 5 Annual Return of ESSs of different sizes (Thousand GBP per MWh)

Name	1 MWh	2 MWh	3 MWh	4 MWh
Greater Gabbard	144	143	143	143
East Anglia One	143	143	143	142
Hornsea 1	142	142	142	142
Dudgeon 1	141	141	141	140
Westermost Rough	141	141	140	139
Race Bank	140	140	140	139
Rampion	140	140	139	139
Humber Gateway	139	138	137	136
Gunfleet Sands 1 & 2	138	137	137	136
Walney 1 & 2	135	135	134	134

5.6 ESS size sensitivity

Batteries sized at 1 MWh were selected as these are the most common size in practice.[6,90] It is important, particularly for the sites recommended for payback time in Fig. 8, that this does not have a distortions effect on ESS returns.

Table 5 displays the payback per MWh for these sites. Results therein are extremely consistent, with only minimal diminishing returns observed. This indicates modelled ESSs were suitably sized for the purposes of this study, with ESS size not distorting the results. As costs are linear, these differences similarly have a negligibly effect on payback times.

6 Discussion

By evaluating the performance of ESS attachments to UK wind farms this study assesses the viability of batteries on a site by site basis. By modelling a variety of these sites for the year of 2021, recommendations were made based on the ability of ESSs to generate an economic return and reduce curtailment. Closing discussion is warranted with respect to the comparative economic and environmental impacts of these batteries, as well as consideration of the limitations of this study and how future investigations may expand upon this research.

The output of these economic dispatch simulations are analysed with respect to their economic and environmental impacts. Opportunities for economic returns are made possible by price arbitrage and exporting (selling) otherwise curtailed energy at a later time. For economic returns, and therefore payback, price arbitrage was more significant. Emissions reduction is made possible by the combination of curtailment reduction and the emissions intensity (determined from imbalance market marginal selling) of displaced generation. With emissions intensities being relatively similar, curtailment reduction volumes are the most significant factor for these carbon emissions reductions *via* marginal generator displacement.

6.1 Economic performance

Due to significant economic returns from price arbitrage, all ESSs achieved payback. Depending on the farm this was possible in 16.75–33.25% of the quoted 12 year battery lifespan.[30] Though cycles were simply taken as a limit, with quicker payment times being optimised for by the model, as a consequence of maximising returns, it should be noted for completeness that payback was achieved in 61.03–83.41% of the quoted 4996 cycle limit (at the model's enforced 80% DOD[72]).

Given the significance of deferring wind energy exports during periods of lower energy prices, to periods with higher energy prices, exploiting these fluctuations has been the main source of ESS returns. While returns were generated by reducing curtailment, these were less significant from price arbitrage returns, to the extent that English/Welsh offshore wind farms, which have some of the lowest curtailment rates, achieved the fastest payback times. ESS performance is therefore primarily dependant upon price volatility providing opportunities for price arbitrage.

6.2 Environmental performance

As this paper focused on the investigation of individual sites, the broader effects of ESS implementations are not investigated as thoroughly as their direct effects. This topic is particularly complex with respect to emissions reduction, with this paper focusing on curtailment reduction. Certain conclusions, however, are drawn from the modelling performed by this study. Given the dispatchability of batteries, their exports are considered with respect to the imbalance market. By considering the average emissions intensity of the marginal seller in the imbalance market, the emissions displacement for ESS exports is estimated. These rates are found to be considerably higher than the emissions intensity of the overall market, as would be expected given the greater fossil fuel use in the imbalance market. Compared to the average emissions intensity of the imbalance market, however, their emissions intensities are lower due to competition with hydro (which also serves an energy storage role in the grid). Finally, these emissions intensity rates are broadly consistent with one another.

ESSs are broadly used for demand and price smoothing in grids, rather than to directly increase energy levels. Given the ability of attached ESSs to reduce curtailment, however, increased exports made available *via* curtailment reduction represent a direct increase in system energy output volumes. These volumes were used to determine the emissions reduction (*via* curtailment reduction) potential of each site. In three cases this effect was significant enough for ESS attachments to result in net energy volume export increases. In the remaining cases, however, while curtailment reductions could occur, losses from price arbitrage exceeded curtailment reduction. While the environmental impacts of this smoothing fall outside this paper's scope, which investigates emissions reduction *via* lowered curtailment in particular, their study is recommended in the context of future techno-economic VRE construction examinations.

6.3 Price arbitrage *vs.* curtailment reduction

As is summarised in Fig. 8, Scottish sites exhibited greater curtailment reduction and thus direct emissions displacement on the imbalance market, while English/Welsh installations achieved quicker payback times by having more opportunities to arbitrage the energy price. By performing both roles, ESSs otherwise incapable of achieving payback by only performing curtailment reduction could achieve payback using the returns from price arbitrage.

Taking the ESS which accomplished the greatest curtailment reduction, Strathy North, for example, payback from curtailment reduction alone would be insufficient. Strathy North reduced curtailment by 87.99 MWh, with an average export price of 168.81 GBP per MWh. If this were repeated for its 12 year lifespan at a 10% discount rate then it would only return 39.23% of its initial investment cost, *i.e.* payback would not be achieved. An average export price of 430 GBP per MWh would instead be required to break even using exclusively curtailment mitigation. By simultaneously performing the role of price arbitrage, payback was instead achieved in 2.64 years.

6.4 Future investigations

While this paper's individual site focus provides detailed and granular results using real market data, broader effects of battery installations fall out of scope. Investigating these effects using market and farm data would therefore be of great interest, particularly in determining the potentially diminishing returns of battery installations. Analysis in other applications such as providing ancillary services would also be of interest, as this can be both lucrative for ESSs and work in conjunction with wholesale operations. Forecasting, and associated markets (futures, day-ahead, pre-dispatch, *etc.*) would also be of interest such that the role of uncertainty is better understood.

This analysis concluded ESS installations would disproportionately compete with hydro-power in the imbalance market. Just as cannibalisation remains a topic of interest for future energy expansions, so too would this competition (with hydro, as well as batteries and other ESSs such as hydrogen, ammonia, compressed air energy storage, *etc.*) also be of interest. Though storage technologies dispatchable, as price smoothing would be an expected consequence of increased competition for price arbitrage, this may affect the payback times of battery units. Individual units modelled in this study were of a smaller 1 MWh size, but at larger scale these effects, such as lowering the peak spot prices of electricity would be expected to become more pronounced.

In addition to further modelling the economic impact of increased ESS applications in the imbalance market, the environmental consequences of price smoothing would also be a topic of future interest. If price smoothing reduced VRE price cannibalisation, for example, then it may enable further VRE expansion. Depending on the emissions opportunity cost of charging and discharging the battery, the lower emissions intensity scheduling of nuclear, hydro (or other, technologies), may also be facilitated such that net emissions were reduced despite losses to battery inefficiency. This paper, however, focuses on ESS scheduling and its role as a marginal seller, rather than broader changes in the expansion of or scheduling of other technologies. The environmental impacts of price arbitrage (positive or negative) are not assessed by this study, with only curtailment reduction being considered. As such the quantification of these questions in a market data framework remain of continued interest as generation and market changes continue.

Given the framework of this study permits both price arbitrage and curtailment reduction, ESSs may only be placed on site, and may only be charged from their local sites to minimise potential transmission constraint problems caused by these systems, particularly with respect to curtailment concerns. Studies with access to grid constraint data may consider placement options which are not co-located, or which charge externally. While this paper investigated lithium-ion batteries, given their projected dominance in existing literature, other existing and future technologies would still serve as a possible direction of expanded inquiry.

Finally, while this paper uses a uniquely extensive volume of data in its investigation of British wind energy storage, further detail may continue to be derived from new or more extensive data in future years. These same questions could also be examined with regards to other curtailed generation technologies such as solar, or even dispatchables such as gas where applicable.

7 Conclusion

This study modelled lithium-ion battery attachments at 47 UK wind farm sites for the year of 2021 on a half-hourly time resolution. It was determined that:

- All ESSs achieved payback, primarily due to price arbitrage, which comprises the vast majority of ESS operations, as opposed to curtailment reduction.
- English/Welsh offshore wind farm attachments achieved quicker paybacks, but lower curtailment reductions relative to Scottish wind farm battery attachments.
- At 3 of the 47 sites, curtailment reduction was significant enough for a net increase in energy exports to occur using an economic return optimising model framework.
- Scheduled ESS discharges to the grid disproportionately occurred during periods of time where hydro-power was the marginal seller. This resulted in lower average emissions displacement intensities than the average intensity of the imbalance market (though still much higher than the overall market).
- Due to these similar emissions intensities, adjusted emissions reductions resulting from mitigated curtailment closely tracked curtailment reductions themselves. A distinction therefore exists between farms with quicker payback, and those with greater emissions reduction due to lowering curtailment levels.

Policy makers in Britain and in countries with comparable energy systems should therefore be advised of the following. Price-exposed batteries are incentivised by market forces to complement the expansion of renewables and compete in the disproportionately fossil fuel dominated imbalance market. As a result, however, competition amongst storage technologies would also be expected. Finally, present returns make these projects financially viable.

Research data

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

Nomenclature

BESS	Battery energy storage system
BMRS	Balancing mechanism reporting service
C	C-rate
CREATE	Campus for research excellence and technological enterprise
DOD	Depth of discharge
DUKES	Digest of UK energy statistics
EIC	Energy identification code
EPSRC	Engineering and physical sciences research council
ESO	Electricity system operator
ESS	Energy storage system
ETH	Eidgenössische technische hochschule
EV	Electric vehicle
GBP	Great british pound(s)
IEA	International energy agency
MIT	Massachusetts institute of technology
MW	Megawatt(s)
RE	Renewable energy
RRN	Renewable energy
SOC	State Of charge
UK	United Kingdom
VRE	Variable renewable energy

Conflicts of interest

There are no conflicts to declare.

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