

# WIND-PLUS-BATTERY SYSTEM OPTIMISATION FOR STACKING OF FREQUENCY RESPONSE AND BLACK START SERVICES IN THE UK

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## Abstract

The energy storage-friendly reforms of the ancillary service markets in the UK have heightened interest in co-locating battery energy storage systems (BESSs) with renewable power plants for the stacking of multiple revenue streams. This paper develops a modelling framework to simulate the operation of a wind farm (WF) and BESS co-location system where the BESS uses the existing connection point to deliver frequency responses (FRs) to the AC grid while sustaining a minimum energy level to assist the WF in supplying demand blocks in black start (BS) events. The BESS capacity and operating strategies are optimised to maximise the final net present value of the co-location project based on the UK perspective, addressing the trade-off between the BESS costs and the availability performance of FR and BS services. The modelling framework is demonstrated based on a particular transmission-connected WF in the UK combined with a weekly auctioned FR product, i.e., Dynamic Low High (DLH). The optimisation results are compared between the DLH-only provision and the stacking of BS and DLH, and discussed around the techno-economic feasibility of co-location projects, in particular, the BESS energy management and the minimum possible availability prices for DLH and BS services.

## 1 Introduction

The ancillary service markets in the UK have been undergoing reforms to lower the barrier to market entry and enable the procurement from diverse sources, especially energy-limited assets such as battery energy storage systems (BESSs) [1]-[3]. The National Grid Electricity System Operator (NGESO) has been reforming the frequency response (FR) service market by standardising FR procurement windows, introducing new fast-acting products, and procuring them closer to real-time [1], [2]. To increase the market transparency, procurement windows of the monthly tendered Firm FR (FFR) have been aligned with four-hourly electricity forward agreement (EFA) blocks since May 2018 [1]. Then part of the FFR volume was transferred to an interim FR product, i.e., Dynamic Low High (DLH), introduced in November 2019 to standardise the FFR with equal capacity of low and high FR and procured in a two-year weekly auction trial [2]. Eventually, the NGESO will replace the existing dynamic products with an integrated suite of end-state FR services, including Dynamic Containment (DC), Dynamic Moderation and Dynamic Regulation designed with standardised requirements to manage different frequency deviations. The DC is the first end-state product softly launched in October 2020, while the other two are expected to be introduced into the market in 2022 [4].

A BESS having fast responses in both import and export is suitable for FR service provision [5]. With the rapid development of battery energy storage technologies, the use of a BESS for FR delivery has been widely investigated in terms of the BESS sizing and energy management and bidding

strategies employed in FR auctions [6]-[10]. Compared with a stand-alone BESS, the BESS co-located with renewable power plants such as wind farms (WFs) can deliver FR to the AC grid via the connection point of the WF, making the most efficient use of the existing electrical infrastructure [10], [11].

While receiving payments from the FR provision, a BESS can stack additional revenue streams such as those from the energy arbitrage on electricity markets [8], [9] and the imbalance risk management [10]. The Black Start (BS) service [12] may also be stacked with the FR since a BESS can deliver FRs when not performing BS [13]. However, less attention was given to their stacking in part due to the large BESS energy capacity required to continuously supply demand blocks in a BS event. With the decommissioning of conventional BS providers (e.g., large, synchronous power stations), the NGESO has been looking for solutions to allow non-traditional technologies to enter the BS market [3]. The combination of various technologies such as the co-location of a WF and a BESS are expected to be one of the potential solutions that can mitigate uncertainties of the wind resource availability during the restoration process and the state of energy (SOE) level at the time of a shutdown [3]. In addition, from the economic point of view of BESS owners, they will be encouraged to always ensure a minimum SOE level in preparation for BS events if the availability payments cover the additional costs of operating at higher SOE levels [3].

To explore the feasibility of co-locating a BESS with a WF to stack the revenue streams from BS and FR, this paper develops a modelling framework to simulate the BESS always holding a minimum SOE level for the BS and using the energy capacity

above the minimum limit to deliver FRs through the existing connection point of the WF. A set of operating strategies are designed for the WF+BESS system with the objectives of (i) ensuring the FR delivery in contracted periods, (ii) restoring to an optimal SOE level of the BESS in uncontracted periods, and (iii) mitigating the wind resource uncertainty in BS events through the time shift of wind power. From the perspective of a particular transmission-connected WF owner, the cash flows of the co-location project are comprehensively modelled based on the UK perspective. The resulting net present value of the project is then maximised by the Particle Swarm Optimisation (PSO) method, suggesting the optimal BESS size, SOE levels for the BS event preparation and the energy management, as well as the DLH capacity and EFA blocks to be bid for in DLH weekly auctions. The optimisation results for the stacking of DLH and BS are also compared with those for the DLH-only provision, showing the impacts of the BESS always sustaining sufficient energy for BS events and the minimum possible BS availability price that may incentivise the BESS to do so.

The paper is structured as follows: Section 2 describes bidding and operating strategies developed for the co-location system based on technical requirements of DLH and BS; Section 3 formulates revenue streams and costs of the co-location project as well as the objective function of the PSO method; Section 4 illustrates optimisation results for the stacking of DLH and BS and discusses the impacts of the BESS additionally providing the BS service. Finally, section 5 presents the conclusions of this research.

## 2 Bidding and Operating Strategies for the Stacking of DLH and BS Services

### 2.1 Dynamic Low High (DLH) Service and Bidding Strategy

**2.1.1 Technical Requirements:** the DLH product standardises the dynamic FFR and requires equal capacity of low and high FRs, as shown in Fig. 1 [14]. A provider must be able to sustain the DLH contracted capacity for at least 30 minutes in each direction, which specifies a minimum energy requirement for energy-limited assets [14].

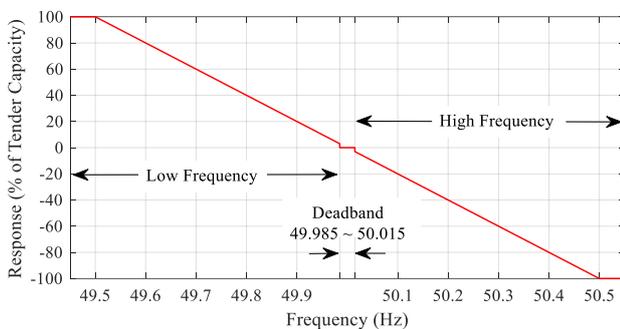


Fig. 1 A symmetrical FR curve of the DLH product.

**2.1.2 Weekly Pay-as-Clear Auctions:** the DLH is procured by 4-hourly EFA blocks in weekly auctions. In each EFA block, tenders are accepted in the price order to minimise the clearing price. The historic clearing prices in 42 blocks over each of the 52 service weeks in the first-year DLH operation are shown in

Fig. 2 [15], where the blocks from 23:00 to 07:00 (e.g., blocks 1, 2, 7 and 8) and those from 11:00 to 15:00 (e.g., blocks 4 and 10) usually witnessed lower clearing prices.

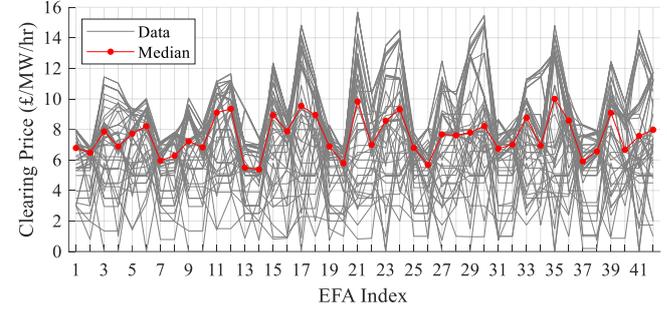


Fig. 2 Historic clearing prices in each service week during the first-year DLH operation.

**2.1.3 Bidding Strategy:** a BESS continuously following the FR curve (see Fig. 1) may result in a poor availability performance when it is close to the minimum or maximum SOE level. It is therefore necessary to leave some EFA blocks untendered and restore the BESS back to an optimal SOE level prior to the start of the subsequent contracted EFA block. Given that a 4-hourly block is sufficient for the SOE restoration, the bidding strategy is designed to tender for a constant DLH capacity  $P_{BID}^{DLH}$  (MW) in the same amount of consecutive EFA blocks  $N_m$  after each untendered block, starting from the first untendered EFA block  $EFA_u$ . The bid prices are preliminarily set at twice the medians of historic DLH clearing prices in Fig. 2. However, the minimum tender prices will be evaluated in Section 4.3.

### 2.2 Black Start (BS) Service and Bidding Strategy

**2.2.1 Technical Requirements:** before participating in the BS market, a provider or a combination of providers must meet several technical requirements [16] that are fundamentally categorised into the ability to self-start, then energise sections of the national electricity transmission system and accept the instantaneous loading of demand blocks [3]. This paper adopts three particular requirements to assess the service availability of a co-location system and estimate the minimum SOE level that should be held in the BESS to mitigate the uncertainty of wind generation. They include the capability of (i) supplying a minimum of 20 MW demand blocks (ii) for at least 10 hours in a BS event and (iii) ensuring the BS service availability over 90% of the time in a year [16]. Since the paper mainly deals with a BESS sizing problem, the potential equipment upgrade (e.g., installation of a grid-forming inverter if needed) is not discussed here.

**2.2.2 Bidding Strategy:** the NGENSO and a service provider will negotiate a contract that determines a fixed annual availability payment, which is then converted into the availability price in each half-hour settlement period (SP), denoted by  $\mathcal{P}^{BS}$  (£/SP). The provider can only receive the availability payment for the SP when its service availability has been declared [17]. Since  $\mathcal{P}^{BS}$  varying between providers is private, the bidding strategy preliminarily adopts  $\mathcal{P}^{BS}$  of £400/SP to assess the availability payment, though the minimum  $\mathcal{P}^{BS}$  that may incentive a BESS to ensure a minimum SOE level will be inferred in Section 4.3.

### 2.3 Operating Strategies for the Stacking of DLH and BS

**2.3.1 System Configuration:** Fig. 3 shows a particular WF and BESS co-location system configuration where the WF shares its existing connection point with the BESS that has power and energy capacity of  $P_B^R$  (MW) and  $E_B^R$  (MWh) respectively. The BESS always sustains a minimum SOE level  $E_{BS}$  (MWh) in preparation for a BS event and delivers DLH responses to the AC grid using the available energy capacity above  $E_{BS}$ . The energy capacity loss of the BESS will be daily updated based on the SOE time series in the day in combination with a battery degradation model [18] which estimates the remaining energy capacity  $E_B^{rm}$  (MWh) of a Lithium-Ion BESS as a combination of the calendar ageing and the cycle ageing. An additional (DLH) meter monitors power exchanges  $P_B^{DLH}$  (MW) between the BESS and the AC grid.

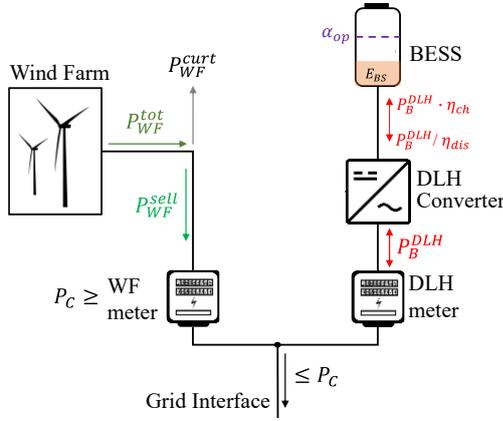


Fig. 3 A particular co-location system configuration.

**2.3.2 Operating Strategy in DLH Contracted Block:** the BESS response  $P_B^{DLH1}$  to the AC grid frequency signal in a contracted EFA block is determined based on the DLH curve (see Fig. 1). Given that only the energy capacity above  $E_{BS}$  is available for the DLH delivery,  $P_B^{DLH1}$  must be limited by (1) when the SOE of the BESS (denoted by  $SOE_0$ ) is close to  $E_{BS}$  or  $E_B^{rm}$ .

$$|P_B^{DLH1}| \leq \begin{cases} (SOE_0 - E_B^{rm}) \cdot \eta_{dis} / \Delta t, & \forall P_B^{DLH1} > 0 \\ (E_B^{rm} - SOE_0) / (\Delta t \cdot \eta_{ch}), & \forall P_B^{DLH1} < 0 \end{cases} \quad (1)$$

where terms  $\eta_{dis}$  and  $\eta_{ch}$  denote the discharging and charging efficiencies of the BESS, which are assumed here to be 95%, and  $\Delta t$  is the time step length in the simulation. Then the SOE of the BESS (denoted by  $SOE_n$ ) after the export or import of  $P_B^{DLH1}$  is updated by (2).

$$SOE_n = \begin{cases} SOE_0 - P_B^{DLH1} \cdot \Delta t / \eta_{dis}, & \forall P_B^{DLH1} \geq 0 \\ SOE_0 - P_B^{DLH1} \cdot \Delta t \cdot \eta_{ch}, & \forall P_B^{DLH1} < 0 \end{cases} \quad (2)$$

The power flow  $P_{WF}^{sell1}$  across WF meter is constrained here by the available ampacity of the common connection point only, i.e.,  $(P_C - P_B^{DLH1})$  where  $P_C$  is the connection size as shown in Fig. 3. To avoid high-frequency (HF) responses ( $P_B^{DLH1} < 0$ ) unexpectedly coming from the rise of the available wind power  $P_{WF}^{tot}$  above  $P_C$  which should be curtailed,  $P_{WF}^{sell}$  is additionally limited by  $P_C$  as formulated by (3). Then the curtailment  $P_{WF}^{curt}$  is determined as the difference between  $P_{WF}^{tot}$  and  $P_{WF}^{sell1}$ .

$$P_{WF}^{sell1} = \min(P_{WF}^{tot}, (P_C - P_B^{DLH1}), P_C) \quad (3)$$

**2.3.3 Operating Strategy in Untendered Block:** in untendered EFA blocks, the SOE will be restored to an optimal level  $SOE_{op}$  equalling  $[\alpha_{op} \times (E_B^{rm} - E_{BS}) + E_{BS}]$  where  $\alpha_{op}$  is a variable to be optimised within a unit interval. Given  $N_{\Delta t}$  time steps prior to the end of an untendered block, if the BESS with  $SOE_0 > SOE_{op}$  can discharge the surplus energy during the remaining  $(N_{\Delta t} - 1)$  time steps, its export (i.e.,  $P_B^{DLH0} > 0$ ) in the present  $\Delta t$  is constrained by the rise of  $P_C$  above  $P_{WF}^{tot}$  so as to avoid the wind curtailment. Otherwise, the surplus energy will be evenly discharged across  $N_{\Delta t}$  time steps. For  $SOE_0 < SOE_{op}$ , the energy required for the restoration will be evenly charged at a rate of  $P_B^{DLH0} < 0$  across  $N_{\Delta t}$  time steps. Then the new SOE and the wind power  $P_{WF}^{sell0}$  flowing across WF meter are computed by (2) and (3) based on  $P_B^{DLH0}$ .

**2.3.4 Operating Strategy in BS Event:** at the start of each time step, the BS service availability of the co-location system is examined in terms of the energy requirement, i.e., supplying 20 MW demand blocks for 10 hours, as was noted in Section 2.2.1. In a continuous 10-hour period, the BESS imports the rise of  $P_{WF}^{tot}$  above 20 MW subject to  $P_B^R$  and  $E_B^{rm}$  and exports to the grid at the time of  $P_{WF}^{tot}$  falling below 20 MW, mitigating the wind resource uncertainty. If the energy stored in the BESS is used up before the end of the 10-hour period, the co-location system is deemed unavailable to the BS service. When the co-location system can support the presumed BS event occurring at the start of each  $\Delta t$  within a SP, the BS service availability will be declared for that SP.

## 3 Economic Optimisation by PSO Method

### 3.1 Revenue and Cost Components

**3.1.1 DLH Availability Payment:** the weekly performance of a DLH service provider is reflected by a percentage performance measure (PPM) which is the ratio between the aggregate spot values of actual DLH delivery and those that are required over a random half-hour sample period within any contracted EFA block in a service week  $w$ . The PPM will be translated into a performance factor  $K_w$  based on Table 1, which is then used to evaluate the availability payment  $R_w^{DLH}$  in the week  $w$  [14]:

$$R_w^{DLH} = (\sum_e \mathcal{P}_{w,e}^{DLH} \cdot P_{BID}^{DLH} \cdot H_{w,e}) \cdot K_w \quad (4)$$

where  $\mathcal{P}_{w,e}^{DLH}$  is the clearing price (£/MW/h) in an EFA block  $e$  within the service week  $w$ , and  $H_{w,e}$  is equal to  $\sum_j A_{w,e,j}$  with  $A_{w,e,j} = 0.5$  h if a provider is contracted and has delivered the required DLH responses throughout a SP  $j$  in the EFA block  $e$ .

Table 1 Conversion from PPM to performance factor  $K_w$

PPM	0 – 10%	10 – 60%	60% – 95%	95% – 100%
$K_w$	0	0.5	0.75	1

To mitigate the financial risk presented by the NGESO inferring the weekly  $K_w$  from the availability performance in a

random sample period, the minimum of PPMs over all the sample periods within the contracted blocks in a service week is adopted here to estimate the worst-case  $R_w^{DLH}$ .

**3.1.2 BS Availability Payment:** as was noted in Section 2.2.2, the BS availability fee is only paid to the SP that a provider has declared its availability. Given a binary variable  $B_{w,e,j}$  with a value of one indicating the BS availability in the SP  $j$ , the BS availability payment  $R_w^{BS}$  in the week  $w$  is estimated by (5).

$$R_w^{BS} = \sum_e \sum_j \mathcal{P}^{BS} \cdot B_{w,e,j} \quad (5)$$

**3.1.3 Green Subsidy:** due to the limited connection ampacity, the low-frequency (LF) response may result in wind power curtailment, especially during high wind periods, reducing the green subsidy received by the WF. Presuming that the WF has been participating in the Renewables Obligation (RO) scheme [19], a unit green subsidy price of £100.1/MWh [10] is adopted here to estimate the subsidy variation after the co-location.

**3.1.4 Energy Imbalance Charge (EIC):** the transmission-level WF in the GB electricity market must pay an EIC for its net deficit of energy imbalance in a SP [20] caused by curtailing its outputs to accommodate the LF delivery of the BESS. The power flows across the DLH meter will also incur in EICs, according to [14].

**3.1.5 BESS and Connection Charges:** the capital expenditure (CAPEX)  $C_{CAPEX}$  of the Lithium-Ion BESS mainly comprises costs of battery and converter whose unit prices are presumed to be £166.4k/MWh and £85.8k/MW respectively. The annual operational expense (OPEX)  $C_{OPEX}$  of the BESS is assumed to be 2% of  $C_{OPEX}$  [10]. In addition, the co-location of the BESS will not only incur in an application fee  $C_{APP}$  but also increase transmission network use of system (TNUoS) and balancing services use of system (BSUoS) charges paid by the entire co-location system. Without varying the connection point size, the one-off payment  $C_{APP}$  is presumed to be about £2.6k that is the median of base costs of six connection zones in the GB [21]. The TNUoS charges paid for the electricity transfer across the GB TN depend on the (predominant) fuel type and annual load factor (ALF) of a (multi-fuel) power station. The BESS cycles are assumed to increase the ALF of the co-location system by  $10.8\% \times P_B^R / P_C$  presuming that a BESS has an ALF of 10.8% [22]. This will result in an annual TNUoS charge growth of  $\delta C_{TN} = \text{£}919.6/\text{MW} \times P_B^R$  based on the TNUoS tariffs issued to a particular generation zone in 2019/20 [22]. It is noted that the actual ALF will be used to estimate annual TNUoS charges in practice when historical measurements are available. The BSUoS charge growth due to the BESS operation in a SP will be calculated based on the BSUoS unit price issued to the SP [23] combined with the difference in net energy flow across the connection point between a co-location system and a single WF in that SP.

### 3.2 Implementation of Particle Swarm Optimisation (PSO)

The co-location system operation and the resulting cash flows of the project are simulated based on a vector of optimisation variables until  $E_B^r$  drops below a retention limit of 80% or

cannot sustain  $P_{BID}^{DLH}$  for the required half-hour while keeping  $E_{BS}$  for the BS. Then an objective function is defined by the net present value (NPV) of the co-location project based on an annual return of 8%:

$$NPV = -C_{CAPEX} - C_{APP} + \sum_m \frac{\sum_w (R_{m,w}^{DLH} + R_{m,w}^{BS} + \delta R_{m,w}^{RO} + \delta R_{m,w}^{EIC} - \delta C_{m,w}^{BS}) - \delta C_m^{TN} - C_m^{OPEX}}{(1+8\%)^{m/12}} \quad (6)$$

where  $\delta R_{m,w}^{RO}$ ,  $\delta R_{m,w}^{EIC}$ , and  $\delta C_{m,w}^{BS}$  are changes of green subsidy, EIC, and BSUoS charge in a service week  $w$  within a calendar month  $m$ . The latter two are estimated based on the imbalance price [24] and the BSUoS unit price [23] assigned to each SP respectively. Terms  $\delta C_m^{TN}$  and  $C_m^{OPEX}$  are the average TNUoS charge growth and the average OPEX of the BESS in a month, equalling  $\delta C_{TN}/12$  and  $C_{OPEX}/12$  respectively. Then a PSO method [25] is used to determine the vector of optimisation variables that maximise the NPV of the project subject to the technical requirements of DLH and BS:

$$1 \text{ MW} \leq P_{BID}^{DLH} \leq \min(50 \text{ MW}, P_B^R) \quad (7)$$

$$E_{BS} + P_{BID}^{DLH} \cdot 0.5 \text{ h} \cdot (\eta_{ch} + 1/\eta_{dis}) \leq E_B^R \quad (8)$$

$$\sum_m^{m+11} \sum_w \sum_e \sum_j B_{w,e,j} \geq 90\% \times N_{SP} \quad (9)$$

where a unit cap of 50 MW is adopted for DLH and  $N_{SP}$  is the total number of SPs in a year starting from the month  $m$ .

## 4 Optimisation and Simulation Results

The modelling framework is tested here based on a transmission-level 76 MW WF with  $P_C$  of 68.4 MW in the GB. Power flows within the WF+BESS system are dispatched by the operating strategies based on the 1-min average available wind power and 1-sec grid frequencies in the GB during four years from 2016 to 2019 [26]. The modelling of the co-location system operation and the implementation of the PSO are all accomplished using MATLAB/Simulink [27]. To reflect the influences of additionally providing the BS, the optimisation results will be compared between the stacking of BS and DLH (or DLH+BS) and the DLH-only provision. The DLH+BS scenario is optimised by following the procedures described in Sections 2 and 3, while the optimisation of the DLH-only scenario is performed by forcing  $E_{BS}$  to zero and excluding the BS-related revenue and constraints from the PSO process. For more details of the DLH-only scenario optimisation, the reader is referred to [28].

### 4.1 Optimisation Results

Table 2 lists the BESS size and strategy variables optimised in the DLH-only or DLH+BS scenario resulting in a project timescale of 9.6 or 9.3 years respectively. A 50 MW BESS is co-located in both scenarios to deliver the maximum allowable 50 MW DLH capacity. In the DLH-only scenario, the BESS has an energy-to-power ratio of 1.5 which meets the minimum energy requirement for DLH delivery, as was noted in Section 2.1.1. To ensure the DLH availability performance, the BESS delivers DLH responses in two consecutive EFA blocks and restores to around 47% of its remaining energy capacity in the

subsequent untended block. Given  $N_m = 2$  and  $EFA_u = 1$ , the untended blocks correspond to the periods from 23:00 to 03:00 and from 11:00 to 15:00, which usually witnessed lower clearing prices. In the DLH+BS scenario, the need of storing sufficient energy in the BESS for BS events results in a larger energy capacity of 320 MWh and an optimal SOE level at 63% of the available energy capacity above the minimum limit of 94 MWh. Fig. 4 shows the SOE level of the BESS fluctuating around the optimal level within the maximum/minimum limits in the two scenarios, respectively. Since the BESS is shown to have more available energy capacity to deliver DLH responses in the DLH+BS scenario, it can bid for 11 consecutive blocks and manage its SOE in the untended block corresponding to the periods between 03:00 and 07:00 that were also cleared at lower clearing prices (see Fig. 2).

Table 2 Optimal BESS Sizes and Strategy Variables

Variable	DLH-only	DLH+BS	Variable	DLH-only	DLH+BS
$P_B^R$ (MW)	50	50	$P_{BID}^{DLH}$ (MW)	50	50
$E_B^R$ (MWh)	75	320	$N_m$	2	11
$E_{BS}$ (MWh)	N/A	94	$EFA_u$	1	2
			$\alpha_{op}$	47%	63%

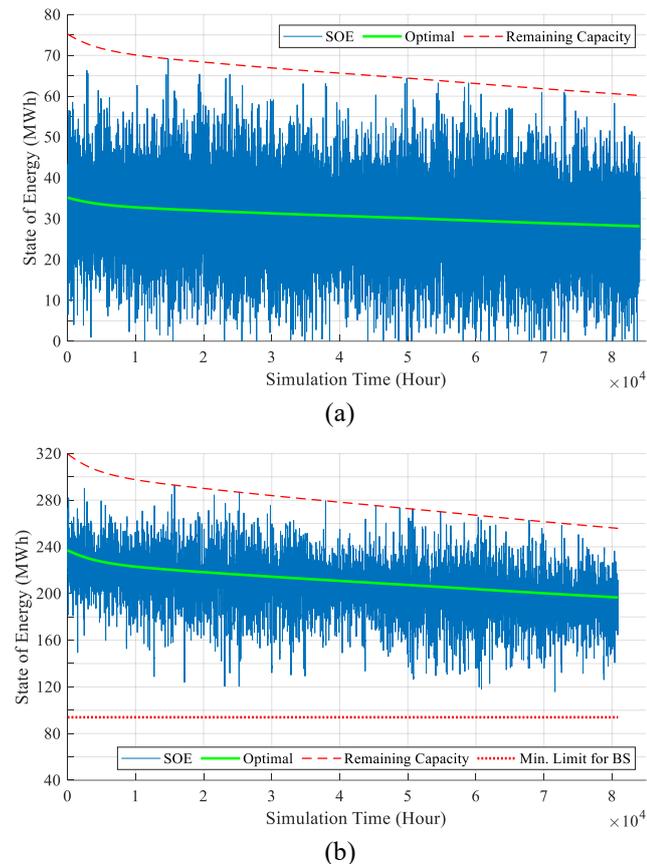


Fig. 4 The SOE (MWh) of the BESS around the optimal level within the boundaries defined by the remaining MWh capacity and/or the minimum SOE limit for BS in (a) the DLH-only or (b) the DLH+BS scenario

## 4.2 Optimisation-based Co-location System Operation

**4.2.1 WF-BESS Coordination under Normal Operation:** Fig. 5 shows the power outputs of WF and BESS and resulting SOE levels that are simulated based on the optimisation variables in the DLH+BS scenario during the simulation time of 4 h-56 h without the occurrence of an outage. When the BESS provides DLH in the contracted EFA blocks from 8 h to 52 h where the available wind power  $P_{WF}^{tot}$  mostly exceeds the connection size, the delivery of LF response (i.e.,  $P_B^{DLH} > 0$ ) via the connection point is shown to aggravate the curtailment of wind generation. In the first untended block over 4 h-8 h, the BESS is operated to evenly absorb energy from the grid to increase its SOE back to the optimal level. For the SOE exceeding the optimal level at the start of the second untended block over 52 h-56 h, the BESS aiming to reduce its SOE discharges the surplus energy only when  $P_{WF}^{tot}$  falls below the connection ampacity, avoiding the wind generation curtailment.

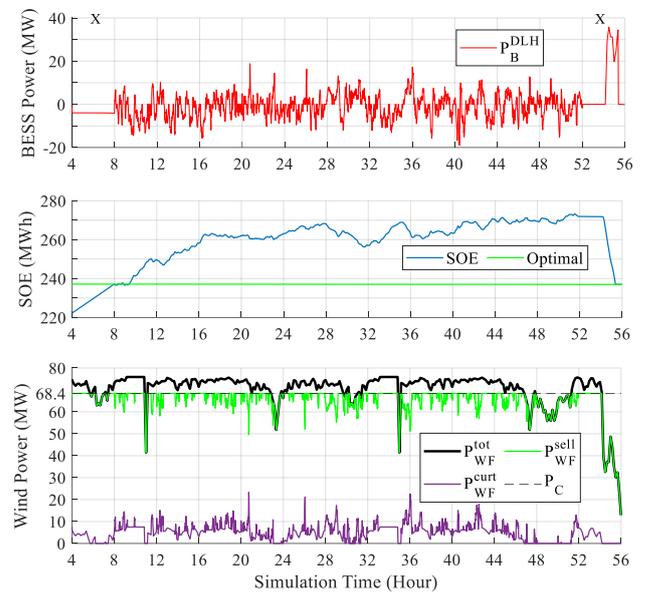


Fig. 5 Power outputs (MW) of WF and BESS and the resulting SOE levels (MWh) in the DLH+BS scenario over twelve EFA blocks from 4 h to 56 h (with symbols 'X' denoting untended EFA blocks).

**4.2.2 WF-BESS Coordination in BS Event:** Fig. 6 shows the power outputs of WF and BESS and resulting SOE levels in a presumed BS event starting from the simulation time of 120 h. The BESS is shown to import the surplus wind power or export to fill the wind power shortfall relative to the required 20 MW block loading. Since the BESS is able to help supply the block loading throughout the minimum required 10 hours in this case (i.e., the SOE being always greater than zero), the co-location system is deemed here to be available to the BS service at the time point of 120 h.

It is noted that the ramp rate limit on the BESS import/export is not introduced into the modelling framework which focuses more on the sizing problem at the planning stage. The BESS outputs scheduled by the operating strategies must be adjusted to fulfil the ramp rate requirement in the practical operation.

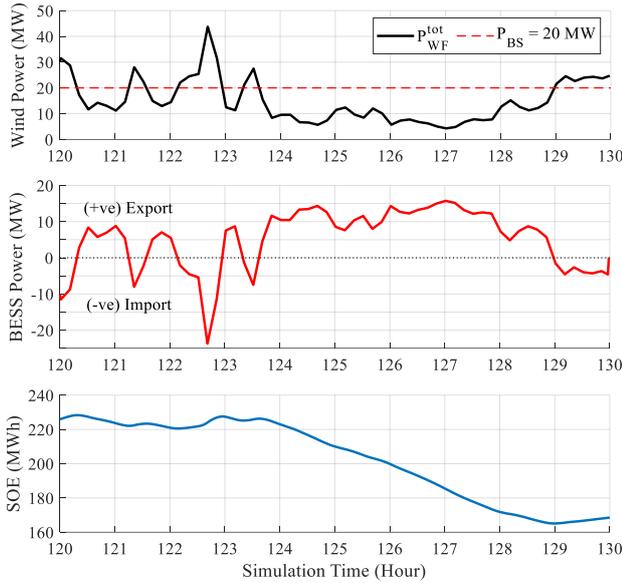


Fig. 6 Power outputs (MW) of WF and BESS and the resulting SOE levels (MWh) over a 10-hour restoration process starting from the occurrence of a presumed shutdown at 120 h.

#### 4.3 Cost-Benefit Analysis of Co-location Project

Table 3 compares the cumulative present values of monetary components of the co-location projects between the DLH-only and DLH+BS scenarios. Even though the use of a 320 MWh BESS results in significant CAPEX and OPEX of the BESS, it enables the BS service provision and the DLH delivery in more EFA blocks. The DLH payment growth and BS payments can cover the additional costs of using a larger BESS, achieving a higher NPV in the DLH+BS scenario. In addition, the BESS operation not only increases TNUoS and BSUoS charges but also causes the wind curtailment in particular LF events (see Fig. 5), reducing the green subsidy received by the WF while increasing the EIC paid by the WF, as shown in Table 3.

Table 3 Cumulative Present Value of Monetary Components (£m) Simulated based on Optimisation Variables

Item	DLH-only	DLH+BS	Item	DLH-only	DLH+BS
CAPEX	-16.81	-57.51	FR Pay	30.78	40.17
OPEX	-2.80	-9.34	BS Pay	N/A	44.15
App. Fee	-0.03	-0.03	$\delta$ Green	-1.15	-1.49
$\delta$ TNUoS	-0.31	-0.30	$\delta$ EIC	-1.39	-0.69
$\delta$ BSUoS	-0.44	-0.50	NPV	7.87	13.67

Given various lifetime between projects, the equivalent annual annuity (EAA) of the two scenarios is estimated to be around £1.19m and £2.14m, respectively. It is evaluated that, for the particular WF studied here, the minimum possible DLH tender prices would be 146% of the historic median clearing prices which ensure a positive EAA in the DLH-only scenario, and the minimum possible BS availability price would be £392/SP which provides the DLH+BS scenario having the same EAA as the DLH-only scenario. As was noted in Section 2.2.1, this

paper focuses on the energy management and sizing problem of a co-located BESS. It does not simulate the potential need of upgrading equipment for the BS. The additional equipment costs will reduce the project's net profit and raise the minimum possible BS availability price.

It is noted that the variations of financial elements (e.g., BESS unit prices and availability prices of DLH and BS) taken into the optimisation process could alter the trade-off between the revenue and costs of the co-location project and thus influence the optimal BESS size and strategy variables. The modelling framework developed here can help investigate the sensitivity of optimisation results to financial elements by examining the model responses to different input parameters. The sensitivity analysis will assist a WF owner in determining the co-located BESS capacity and designing bidding and operating strategies under uncertain circumstances.

## 5 Conclusion

With the energy storage-friendly reforms of the UK ancillary service markets, it becomes an attractive option to co-locate a battery energy storage system (BESS) within a wind farm (WF) to stack multiple revenue streams. This paper has developed a modelling framework to simulate a WF and BESS co-location system that provides Black Start (BS) and Dynamic Low High (DLH) frequency response services based on UK perspectives. The modelling framework designs a set of strategies to operate the WF+BESS system in different scenarios and optimises the BESS size and strategy variables to maximise the co-location project's final net present value (NPV).

The effectiveness of the proposed modelling framework has been illustrated based on a particular transmission-level WF in the GB. Compared with a co-location system that delivers the DLH only, the additional provision of the BS service requires a much larger BESS to ensure sufficient energy all the time so as to mitigate the wind resource uncertainty in the restoration process. However, the additional investment on a larger BESS has been compensated by the BS availability payment and the growth of the DLH payment in this work. This is because the larger BESS having a higher available energy capacity can bid for the DLH in more 4-hourly blocks in weekly auctions while ensuring its DLH availability performance. It is noted that the equipment upgrade (e.g., installation of grid-forming inverters) possibly required for the BS is not simulated here. However, their impacts on the project profitability should be considered if they are needed in practice. The modelling framework proposed here can be also applied to other BESS co-location systems in different regions, with some adaptations to reflect the specific mechanism and requirements of relevant ancillary service markets as well as local grid codes, connection charges and other revenue streams of the co-location systems.

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