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Methodology for the economic optimisation of energy storage systems for frequency support in wind power plants ☆

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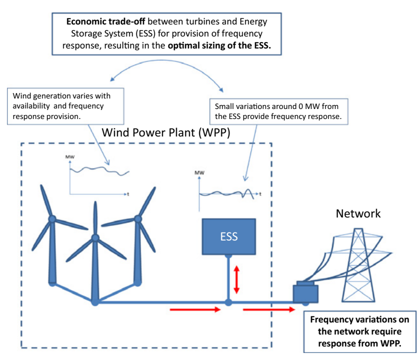
HIGHLIGHTS

- Optimisation of energy storage system with wind power plant for frequency response.
- Energy storage option considered could be economically viable.
- For a 50 MW wind farm, an energy storage system of 5.3 MW and 3 MW h was found.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper proposes a methodology for the economic optimisation of the sizing of Energy Storage Systems (ESSs) whilst enhancing the participation of Wind Power Plants (WPP) in network primary frequency control support. The methodology was designed flexibly, so it can be applied to different energy markets and to include different ESS technologies. The methodology includes the formulation and solving of a Linear Programming (LP) problem.

The methodology was applied to the particular case of a 50 MW WPP, equipped with a Vanadium Redox Flow battery (VRB) in the UK energy market. Analysis is performed considering real data on the UK regular energy market and the UK frequency response market. Data for wind power generation and energy storage costs are estimated from literature.

Results suggest that, under certain assumptions, ESSs can be profitable for the operator of a WPP that is providing frequency response. The ESS provides power reserves such that the WPP can generate close to the maximum energy available. The solution of the optimisation problem establishes that an ESS with a power rating of 5.3 MW and energy capacity of about 3 MW h would be enough to provide such service whilst maximising the incomes for the WPP operator considering the regular and frequency regulation UK markets.

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Nomenclature

Parameters

D	sample days
$E_{fr,t}$	requested frequency response, MW h
$E_{fr,t}^{max}$	maximum frequency response, MW h
$E_{max,t}$	energy available to turbines, MW h
N_s	number of samples
T_s	sample time, mins.
T_{sus}	sustain time for freq. response, mins.
u_t	frequency response sign, binary
Y	expected life of ESS, years
α_H	upper limit of state of charge
α_L	lower limit of state of charge
γ	ESS loss percentage
η^+	ESS charging efficiency
η^-	ESS discharge efficiency
λ_{cap}	price of storage by capacity, €/MW h
λ_{deg}	ESS degradation cost, €/MW h
$\lambda_{fr,t}$	frequency response price, €/MW h
$\lambda_{M,t}$	market price, €/MW h
λ_{pwr}	price of storage by power, €/MW

Variables

C_{deg}	ESS degradation costs, €
C_s	ESS capital costs, €
$I_{fr,t}$	income from frequency response, €
$I_{fr,t}^-$	income from low freq. response, €
$I_{fr,t}^+$	income from high freq. response, €
$I_{m,t}$	income from regular market, €
J	objective function, €
$P_{fr,t}$	turbine freq. response proportion
$P_{res,t}$	turbine reserve proportion
S_{cap}	ESS energy capacity, MW h
$S_{c,t}$	ESS charge, MW h
$S_{cu,t}$	ESS usable charge, MW h
$S_{fr,t}^-$	ESS low frequency response, MW h
$S_{fr,t}^+$	ESS high frequency response, MW h
S_{pwr}	ESS power, MW
$S_{loss,t}$	ESS energy loss, MW h
$W_{fr,t}^-$	turbine low freq. response, MW h
$W_{fr,t}^+$	turbine high freq. response, MW h
$W_{gen,t}$	turbine generation, MW h
$W_{res,t}$	turbine reserve, MW h
$\varepsilon_{fr,t}$	frequency response, MW h
$\varepsilon_{lc,t}$	ESS loss compensation, MW h
Θ_t	energy sold to grid, MW h

1. Introduction

Due to the stochastic nature of wind, the electrical power generated by Wind Power Plants (WPPs) is neither constant nor controllable. This affects network planning, as expected generation levels depend on unreliable wind forecasts. Power quality is also reduced, as the fast fluctuations of wind power can cause harmonics and flicker emissions [1–3]. For these reasons, network operators are gradually setting up more stringent requirements for the grid integration of wind power [5–7]. Amongst other restrictions, they require WPPs to withstand short-circuits and grid faults, to respect a threshold level with regards to the quality of the power generated, and to provide ancillary services to the grid such as frequency and voltage control. All these aspects require WPPs to behave in a similar manner to conventional network synchronised generators.

Network frequency control refers to the methods and capabilities to ensure a continuous balance between generation and power demand. In the case that generation exceeds the power demand, the rotating speed of synchronised generators throughout the network starts increasing, moving the electrical frequency above its set-point. The electrical frequency goes below its set-point in the case where power demand is greater than generation. Both the magnitude and the dynamics of electrical frequency have to be controlled for proper network operation and stability [4]. To match generation and demand, conventional synchronised generating units, such as gas-fired or hydro power plants, provide power reserves which are activated to maintain electrical frequency within admissible limits. These power reserves are distributed throughout different time scales, i.e. primary, secondary and tertiary reserves [8].

Primary frequency control refers to the automatic and local provision of primary power reserves by the generator's governor a short time after detecting a power imbalance in the network, i.e. after detecting an electrical frequency deviation from its set-point [8]. In the event of a frequency disturbance, the deployment of primary reserves recover the power balance in the network, thus stabilizing the frequency excursion at a new steady state level. In the case of a low frequency event, total power output must be raised, in the form of primary reserves, in order to balance the system frequency. Conversely, in the case of a high frequency event, the total output must be lowered. Primary reserves are delivered until replaced by other power reserves in the network, typically named secondary and tertiary reserves. The activation of these reserves bring the electrical frequency back to its initial set-point, whilst recovering active power interchanges between different control areas in the network to their set-points [8]. The deployment of power reserves in the event of a power imbalance in the network is graphically depicted in Fig. 1.

Even though the power generated by wind turbines depends on the unreliable and difficult-to-predict wind speed, there are methods for WPPs to actually provide primary power reserves and thus to participate in grid frequency control. Conventionally, wind turbines are operated at maximum aerodynamic efficiency and therefore do not provide power reserves. Given a wind speed v_w, the power generated by a wind turbine is computed by

$$P = \frac{1}{2}\rho A C_p(\lambda, \beta) v_w^3, \quad (1)$$

where A is the area swept by the blades of the rotor, ρ is the air density and C_p is the aerodynamic power coefficient, which depends on the pitch angle β of the blades and the tip speed ratio λ. The latter is computed by

$$\lambda = \frac{\omega_t R}{v_w}, \quad (2)$$

where ω_t the rotor speed and R the radius of the blades. Normally, the rotor speed ω_t is regulated by acting on the controller of the power electronics of variable speed wind turbines so as to optimize the tip speed ratio and in turn maximize the coefficient C_p.

In the case that wind turbines are required to provide power reserves, they have to be operated so that the aerodynamic coefficient is not maximised, i.e. so that they turn at non-optimal rotating speeds. In such circumstances, wind turbines become

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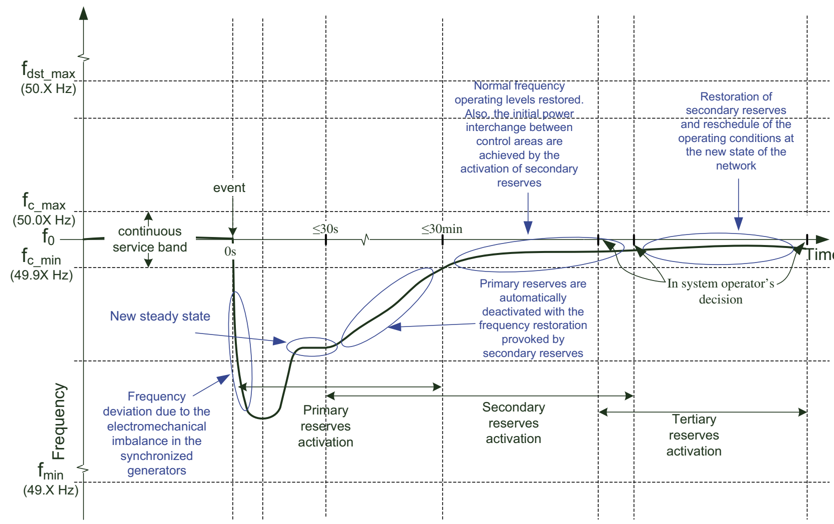

Fig. 1. Deployment of power reserves in the event of a network frequency disturbance.

de-rated to maintain a power margin, defined by the difference between the power they are extracting from the wind, and the power they could extract while operating at maximum C_p. This power margin can be rapidly regulated when required for frequency control purposes. Such a strategy can be performed in variable speed wind turbines in partial load operating region. At full load operating region, i.e. considering wind speeds above rated wind speed for the wind turbine, the power margin cannot be regulated by varying the rotor speed, but should be controlled by varying the pitch angle instead [9].

Therefore, WPPs can participate in frequency control by providing power reserves, and as such can comply with the latest Grid Codes of UK and Ireland [5,6], as well as the first European Grid Code by the ENTSO-E [7]. Particular control methods to de-rate variable speed wind turbines are also discussed in [10–14]. In general terms, these articles propose modifications to the previously described rotor speed and pitch angle regulations while concerning different operating regions of the wind turbines. Applying these controllers, the articles also discuss several aspects such as the development of dispatch functions for WPP central controllers, the mechanical limitations of wind turbines for speed variation, and the potential of wind power support to grid frequency control.

Another possibility for WPPs to participate in system frequency control, is to be equipped with an Energy Storage System (ESS). Such storage capabilities relieve wind turbines of reducing output, as the required power reserve for frequency control purposes is contained in the ESS. Several aspects must be taken into account when integrating an ESS within a WPP, such as the operation, size, technological capability, interaction with other systems, and regulatory framework which applies to the ESS.

Previous work has been completed which explores the sizing of storage systems. In [15,17], the optimal sizing of an ESS based on secondary batteries is addressed for voltage and frequency control purposes in an isolated grid with wind power generation. In [15], the size is determined by genetic algorithm and sequential simulations. In [17], size is determined from an analysis of historic data on severe mismatches between generation and demand in a microgrid. Adopting a different approach, [16] sizes the battery-based ESS for frequency regulation purposes in an island network comprising a hydro power plant, a thermal power plant and WPPs. In this case, the objective is to maximize the benefit for the ESS operator throughout the whole lifetime of the system. To this aim, an optimisation problem is formulated and solved, taking into account the capital and operating costs of the ESS and the revenues generated from the frequency regulation market and the excess energy sold on the spot market. An economic assessment of ESS while providing primary frequency regulation (and also peak shaving services) is also addressed in [18]. An optimisation problem is formulated for the isolated electrical islands in Spain's archipelagos, which contain an important share of renewable generation. Results highlight that the provision of primary reserves and peak-shaving services reduce grid operating costs with increasing size of the ESS. This happens up to a certain size of the ESS related to the generation mix of the island.

All revised articles, coincide in viewing ESSs as an important source of flexibility for the power system in general, and for the grid integration of renewables in particular. The fast response and relatively high energy and power capacity of batteries, flow batteries, compressed-air based systems and pumped hydro storage, amongst others, were identified as suitable technologies for the provision of power reserves for frequency regulation in [20].

The present article addresses the optimal sizing of an ESS, which is combined with a WPP such that it can exchange power with the output of the WPP to the grid. This exchange of power, both positive and negative, can facilitate the generating facility in providing the ancillary service of frequency regulation. Differentiating from the aforementioned articles on storage sizing, the present work explicitly adopts the aspect of the WPP operator while fulfilling the requirements for wind power grid integration. The impact that the ESS has on the WPP system as a whole, through providing frequency regulation services, is assessed through economic analyses.

The adopted set-up would enable storage to exchange energy with the output of the turbines in response to frequency changes from the network, whilst also allowing the WPP to alter its output for the same purpose if it is more economically beneficial. The ESS would be able to store energy absorbed from high frequency response events and release it during low frequency events. This process would also allow the wind turbines to run at a rate closer to the maximum level of energy available, instead of having to maintain a large energy reserve ready for frequency response. In addition, the ESS would comply with the network regulations as stated by the System Operator (SO), therefore removing some restrictions on the turbines. Fig. 2 shows a conceptual diagram of what is being proposed. As can be seen, the ESS is expected to absorb and release small amounts of energy whilst the wind turbines vary a relatively small amount compared to their total output.

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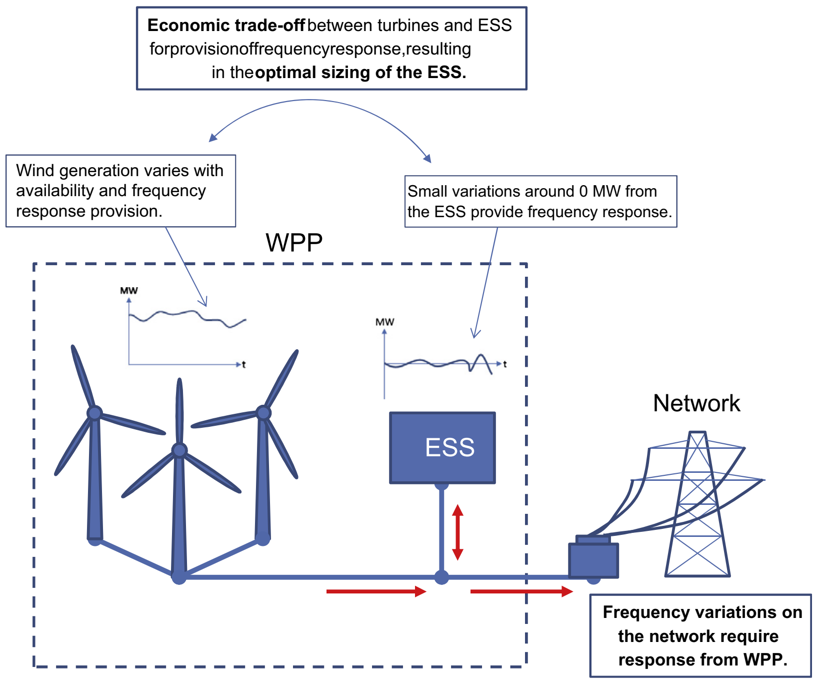

Fig. 2. Conceptual diagram which shows the basic principles of the proposed solution.

The article will give two contributions in relation to the development of this idea. These are:

1. Develop a modelling methodology for the optimal sizing of an ESS integrated within a WPP.
2. Explore the scenario with data and regulatory framework taken from the UK market to assess how the system would operate and to establish the viability of the idea.

2. Optimisation model formulation for storage sizing

As stated in the introduction, one of the aims of this study is to develop a methodology for the optimisation of the size of the ESS. The model developed was orientated towards the WPP operator, maximising for the combined system income. A generalised approach was taken, meaning the model is both technology neutral with respect to the ESS, and can be adapted for differing sizes of WPPs and energy markets. As the model is orientated around the point of view of the WPP operator, it therefore does not take into account dynamic interactions with overall system frequency. The electrical frequency is treated as an input for the WPP operator, not a variable, and thus the linear methodology employed is justified.

This methodology is explained in the following sections, starting with the definition of the objective function and associated terms. A summary of the sections is provided in the flow-diagram seen in Fig. 3.

2.1. Objective function

The net income for the wind power plant operator, J, is a function of the energy sold as wholesale electricity, the costs of the storage system employed and the income from provision of frequency response. This income is represented over a period determined by the expected life span of the storage unit. These terms are defined in this section. Fig. 4 has also been provided to aid understanding of some of the key variables, whose placements are shown graphically.

- Wholesale electricity sold at time t, in €, is given by

$$I_{m,t} = \lambda_{m,t} \Theta_t, \tag{3}$$

where Θ_t is the energy sold to the grid under regular market conditions, in MW h at the market price, $\lambda_{m,t}$, €/MW h.
The total cost of the ESS over the whole time period considered, is composed of the capital and operating costs, which are defined as follows.

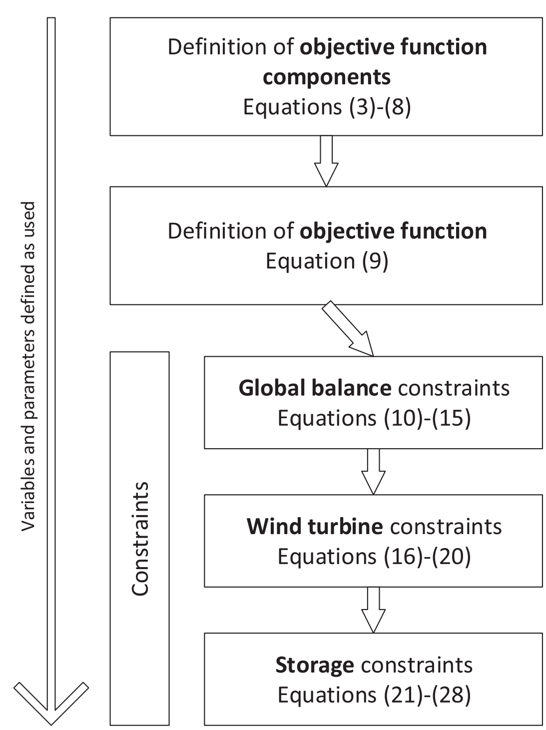

Fig. 3. Flow diagram demonstrating the structure of the methodology outlined in this article.

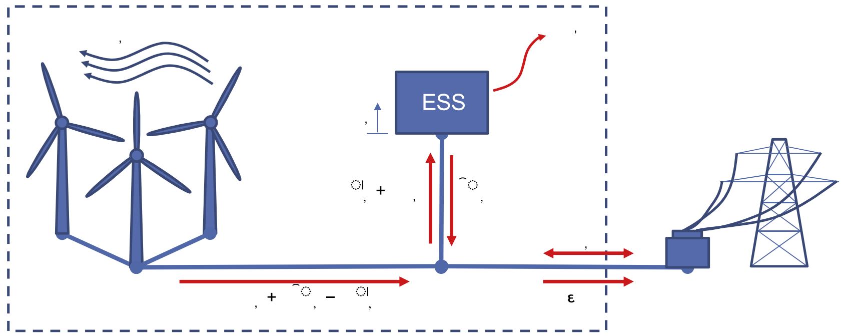

Fig. 4. Conceptual diagram which shows the significance of some important variables.

- The capital cost of the energy storage system, C_s, in €, is defined as

$$C_s = \lambda_{pwr} \cdot S_{pwr} + \lambda_{cap} \cdot S_{cap}, \tag{4}$$

where λ_{pwr} is the power specific storage capital cost in €/MW, λ_{cap} is the energy specific capital cost of storage in €/MW h [19]. S_{pwr} and S_{cap} are the power and energy capacity of the storage device, in MW and MW h respectively.

- The cost of storage degradation due to ageing effects related to cycling of charge, C_{deg}, in €, is calculated as

$$C_{deg,t} = (\varepsilon_{lc,t} + S^-_{fr,t} + S^+_{fr,t} + S_{loss,t}) \cdot \lambda_{deg}, \tag{5}$$

where $\varepsilon_{lc,t}$ is the energy sent to the ESS to cover losses during time t, in MW h. $S^-_{fr,t}$ is the energy discharged from the storage system when there is a high frequency event, in MW h. Similarly, $S^+_{fr,t}$ is the energy absorbed when a high frequency event occurs, in MW h. $S_{loss,t}$ is the loss from the ESS in each time step as a result of leakage of charge in MW h. Finally, λ_{deg} is the cost of degradation in €/MW h.
The incomes from frequency regulation are split between responses given in the events of low and high system frequencies. As previously explained, each situation requires the WPP, equipped with the ESS, to increase or decrease its total output.

- The income from an increase in output, I^+_{fr}, in €, is given by

$$I^+_{fr,t} = \lambda^+_{fr,t} \cdot \varepsilon_{fr,t}, \tag{6}$$

where $\varepsilon_{fr,t}$ is the energy provided by the system for frequency response, in MW h, within the period t and $\lambda^+_{fr,t}$ is the market price for this reserve in €/MW h.

- Similarly, the income for a reduction in output for a high frequency response is given by I^-_{fr}, in €, which is defined as

$$I^-_{fr,t} = \lambda^-_{fr,t} \cdot \varepsilon_{fr,t}, \tag{7}$$

where $\lambda^-_{fr,t}$ is the market price for this reduction in output in €/MW h.

- The total income from the provision of energy for frequency regulation, I_{fr}, in €, is

$$I_{fr,t} = u_t \cdot I^+_{fr,t} + (1 - u_t) \cdot I^-_{fr,t}, \tag{8}$$

where u_t is a parameter which is equal to one when the frequency response required is positive (i.e. there is a low frequency event), and zero in the contrary case.

The terms defined in Eqs. (3)–(8) are included in the function J,

$$J = -C_s + \frac{365Y}{D} \sum_{t=t_0}^{N_s} [I_{m,t} + I_{fr,t} - C_{deg,t}]. \tag{9}$$

This gives the total net income of the WPP with integrated ESS over an expected storage lifetime of Y years. D is the number of days that the sample data covers. The summation is done over the time period, t, which can be an irregular unit, such as the 15 s intervals used later in this paper. N_s is the total number of time intervals in the data, and hence represents the maximum time period analysed.

The function J leaves out terms affecting total income to the WPP operator, such as CAPEX and OPEX costs of wind turbines and other costs related to the long term operation of the system. For this reason, the value of J is used only for comparison purposes, in order to evaluate the application of the ESS.

By maximising the value of J, which considers capital and operational costs, incomes from the wholesale market and frequency response markets, the optimal sizing of the ESS can be established.

2.2. Constraints

Constraints were collected into the following three categories,

1. Global balances, which includes the constraints which concern general energy balances of the WPP and link energy fluctuations from the ESS and wind turbines.
2. Wind turbine balances, which includes specific constraints which control the operation of the wind turbines while providing power reserves for frequency regulation.
3. ESS balances, which is composed of all the constraints which managed the charge within the ESS and its response to changes in frequency.

Additionally, appropriate variables were constrained as non-negative.

2.2.1. Global balances

The following set of equations represent restrictions between the operation of the ESS and WPP in response to frequency changes and the regular market.

- The 'Grid Load Balance' defines the energy sold to the grid via the regular market (i.e. not through ancillary services) as

$$\Theta_t = W_{gen,t} - \varepsilon_{lc,t}/\eta^+, \tag{10}$$

where $W_{gen,t}$ is the wind turbine generation in MW h and η^+ is the charging efficiency of the battery.

- The 'Frequency Response Balance' defines the energy exchanged to provide frequency response services as

$$\varepsilon_{fr,t} = W^-_{fr,t} + S^-_{fr,t} \cdot \eta^- - W^+_{fr,t} - S^+_{fr,t}/\eta^+, \tag{11}$$

where $W^-_{fr,t}$ is the contribution from the wind turbines, in MW h, when a low frequency is seen on the grid, i.e. wind turbines increase output in order to raise grid frequency. Similarly, $W^+_{fr,t}$ is the contribution, in MW h, when there is a high frequency event, i.e. a reduction in output in order to reduce system

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frequency. Additionally η^- is the discharge efficiency of the storage unit.

- The 'Appropriate Reserve Level' equation ensures that there is always a level of reserve in the WPP system to respond to the maximum change in system frequency, as defined by the SO. This ensures the system can comply with technical requirements at all times, and is defined as

$$S_{cu,t} + W_{res,t} + W^-_{fr,t} - W^+_{fr,t} \geqslant E^{max}_{fr,t}, \tag{12}$$

where $W_{res,t}$ is reserve kept by the wind turbines, in MW h, for purposes of allowing variation in load. $E^{max}_{fr,t}$ is the equivalent energy requested, in MW h, if the change in frequency equated to the maximum required as part of an agreement between the SO and WPP. This ensures that between the charge in the battery, the reserve of the wind turbines and the frequency response provided by the wind turbine, there is sufficient capacity to provide response to the worst case frequency change. $S_{cu,t}$ is the usable charge, in MW h, in the battery at time t and is calculated using two definitions,

$$S_{cu,t} \leqslant S_{pwr} \cdot T_s/60, \tag{13}$$

$$S_{cu,t} \cdot T_{sus}/T_s \leqslant S_{c,t}, \tag{14}$$

where T_s is the length of sample time of the input data in minutes and $S_{c,t}$ is the charge held in the storage system at time t in MW h. Eq. (13) ensures that the usable energy in a time period cannot be greater than that which the power of the storage unit allows, whilst Eq. (14) specifies that there must be enough charge available to sustain a response for up to T_{sus}, given in minutes. This is specified in the regulations of the SO.

- The 'Full Response Provision' restriction, when activated, ensures that all energy exchanges asked for are complied with, such that a penalty is not incurred. This was formulated as

$$\varepsilon_{fr,t} - E_{fr,t} = 0, \tag{15}$$

and was activated after t =1. In the current approach, $\varepsilon_{fr,t}$ is totally determined by $E_{fr,t}$ but this constraint is included for the case in which a penalisation for non-supplied frequency regulation is introduced.

2.2.2. Wind turbine balances

The following set of equations represent restrictions on the operation of wind turbines, including responses to frequency regulation and regular market provision.

- The 'Wind Generation Balance' defines the relationship between the different elements that affect the amount of generation sold to the grid in the regular market, $W_{gen,t}$, as follows

$$W_{gen,t} = E_{max,t} - W_{res,t} - W^-_{fr,t}, \tag{16}$$

where $E_{max,t}$ is the maximum electrical energy available that the wind turbines could produce during time t, given in MW h.

- The 'Reserve Energy Balance' ensures that a reserve percentage set at the beginning of the day is either maintained or used throughout the day. This represents an operational decision taken based on expectations for the provision of frequency response services and defined as

$$P_{res,1} - P_{res,t} = P_{fr,t}, \tag{17}$$

where $P_{res,t}$ is the proportion of wind power reserve with respect to the maximum energy available at time t. This is given by

$$P_{res,t} = W_{res,t}/E_{max,t}. \tag{18}$$

$P_{fr,t}$ is the proportion of frequency response provided by the wind turbine with respect to the maximum energy available at time t, as detailed by

$$P_{fr,t} = (W^-_{fr,t} - W^+_{fr,t})/E_{max,t}. \tag{19}$$

Eq. (17) was activated after $t = 1$.

- The 'Reserve Limitation' restriction limits the wind turbine reserve as a proportion of the maximum energy available,

$$W_{res,t} \leqslant 0.2 \cdot E_{max,t}. \tag{20}$$

In this case, 20% of $E_{max,t}$ is considered a reasonable limit according to current regulations.

2.2.3. Storage balances

The following set of equations represent restrictions to the charge balance and resulting operation of the ESS, given its contribution to frequency response services.

- The 'Charge Balance' is a general balance of the change of the battery and its energy inputs and outputs, given by

$$S_{c,t} - S_{c,t-1} = \varepsilon_{lc,t} + S_{fr,t} - S_{loss,t}, \tag{21}$$

which was activated after $t = 1$ due to the use of the previous storage charge value, $S_{c,t-1}$. $S_{fr,t}$ is the net frequency response of the storage system provided at time t, and defined as

$$S_{fr,t} = S^+_{fr,t} - S^-_{fr,t}. \tag{22}$$

- The 'Charge Limitation' restriction is composed of two equations which ensure that the charge of the system stays within certain limits, which are given by

$$S_{c,t} \leqslant \alpha_H \cdot S_{cap}, \tag{23}$$

$$S_{c,t} \geqslant \alpha_L \cdot S_{cap}, \tag{24}$$

where α_H and α_L are the high and low percentage limits for the state of charge in relation to the storage capacity, S_{cap}.

- The 'Power limits' restrictions define the power of the storage unit by the maximum of the incoming and outgoing energy flows over the period of analysis through two equations, which are given as

$$(\varepsilon_{lc,t} + S^+_{fr,t}) \cdot 60/T_s \leqslant S_{pwr}, \tag{25}$$

$$(S_{loss,t} + S^-_{fr,t}) \cdot 60/T_s \leqslant S_{pwr}. \tag{26}$$

- Storage losses are accounted for and the loss compensation is restricted to a reasonable level by two equations,

$$S_{loss,t} = S_{c,t} \cdot \gamma, \tag{27}$$

$$\varepsilon_{lc,t} \leqslant 1.2 \cdot S_{loss,t}, \tag{28}$$

where γ is the loss percentage expected from the storage system in each time sample due to charge leakage.

2.2.4. Basic constraints

The following variables were restricted to non-negative values: $S_{pwr}, S_{cap}, \varepsilon_{lc,t}, S^+_{fr,t}, S^-_{fr,t}, W^-_{fr,t}, W^+_{fr,t}$ and $W_{res,t}$.

The following variables had initial values set equal to zero in order for some previous restrictions to function: $\varepsilon_{lc,t}, S^+_{fr,t}, S^-_{fr,t}, W^-_{fr,t}$ and $W^+_{fr,t}$.

3. Case used: 50 MW WPP within UK market

The basic assumptions made for the application of the previously described model were that a 50 MW wind park, equipped with variable speed turbines, was used within the UK market and under UK regulations. In addition, the WPP is equipped with an ESS composed of a VRB. The following section explains the implications of these assumptions and presents the specific data used in combination with the optimisation model.

3.1. UK market

In the UK, there exists a mandated level of frequency regulation to be provided from each operating site, as well as a market for extra provision, named Firm Frequency Response (FFR). Additionally, there exists a market for Frequency Control Demand Management (FCDM) which uses demand reduction to regulate high frequency events.

Payment methods differ between the mandatory response and FFR markets; however, as this paper focuses on implementing storage with wind turbines, the payments structure used is that of mandatory frequency response. This market consists of two main elements; payment of response energy provision and holding period payments. A 'holding period' is the time that a unit has been directed into preparing to provide frequency response by the SO. Technical denominations of the regulation in the UK are split into the following [25]:

- Primary response to a low frequency event (increase in generation) within 10 s, sustained for up to 30 min.
- Secondary response to a low frequency event (increase in generation) within 30 s and sustained for up to 30 min.
- High response to a high frequency event (decrease in generation). Achieved within 10 s and sustained until no longer necessary.

This paper focuses on using the mandatory frequency response market to simulate the provision of primary, secondary and high frequency response services. Although the UK terminology includes these three terms, they are all included within the 'primary power reserve' and 'primary frequency control' service, as discussed in the introduction. This difference in terminology between UK regulation [5] and ENTSOE studies [8] should be taken into account. Holding periods have been neglected from the analysis, both due to lack of data availability and, being a constant value, it would not affect the result of the optimisation.

Since the system must be able to sustain primary and secondary responses (i.e. primary reserves) for up to 30 min after a change in frequency, the value of T_{sus} must reflect this. This will affect the results of the model to a large extent, due to Eq. (14).

3.2. Data used

The following section describes the data obtained for the case analysed and the related assumptions made for the model. The single-value parameters used for the nominal model can be seen in Table 1.

Table 1
Values of parameters used the model for the nominal case.

Parameter	Value
N_s	5760
λ_{pwr}	400 €/kW
λ_{cap}	600 €/kW h
α_L	0.1
α_H	1.0
η^-	0.80
η^+	0.80
Y	15 years
D	1 day
T_s	0.25 min.
γ	0.03
λ_{deg}	0.180 €/kW h
T_{sus}	30 min.

The storage specific parameters, $\lambda_{pwr}, \lambda_{cap}, \eta^-, \eta^+, Y$, were obtained from [20] by assuming a VRB and chosen to match the cost model assumed in Eq. (4). This type of storage medium was chosen due to two main reasons [20]:

- The high cyclability of VRB allows for up to 10,000 charge and discharge cycles at nearly 100% depth of discharge. These charging and discharging processes can be performed with relatively high ramp power rates and short time responses (less than a second). These characteristics define VRB as well suited for frequency regulation purposes (note the fast dynamics of the electrical frequency in case of a network disturbance in Fig. 1).
- VRB can be easily scaled, reaching tens of MW of power capacity and tens of MW h of energy capacity. It can therefore be sized such that it can exchange tens of MW for a few hours. Moreover, power capacity and energy capacity are independent characteristics: the energy capacity of the battery simply depends on the size of the electrolyte tanks while the power capacity depends on the size of the fuel cell used. The size of the storage system and its scalability make it suitable for frequency regulation (note that according to Fig. 1 the provision of primary reserves can be extended up to 30 min).

Mean values of the VRB properties were taken where appropriate, and as can be seen from Table 1, equal charging and discharging efficiencies were assumed. The values for α_L and α_H were taken as estimations based on experience, as was the loss percentage, γ. The price of degradation, λ_{deg} can be calculated based on estimations based on a relationship given by

$$\lambda_{deg} = \lambda_{cap}/N_c, \tag{29}$$

where N_c is the number of cycles taken at an assumed depth of discharge. Here the price was obtained from [22]. Finally, it is worth noting that other types of storage mediums can be easily evaluated by simply changing the parameters in Table 1.

As previously noted, T_{sus} was taken in order to comply with regulations stipulated in [5]. The following parameters are based on temporal data, and as such, the values of N_s and T_s were based on the length of this data. As can be appreciated in Table 1, data for a 24 h period was chosen for each parameter, with a maximum temporal resolution of one sample every 15 s. All price conversions from \$ to € were done using a rate of 1:1.21, which was taken in January 2014.

The data sources for each of the continuous parameters are outlined below:

- Maximum generation, $E_{max,t}$. Wind power profile data was adapted from [21]. Data was initially taken from 01/01/2006 and additionally taken from the first day of each month of 2006 in order to compare wind power data variations. This data has a temporal resolution of 10 min per step. A 50 MW site was chosen as it represents the minimum size of a plant such that it has to comply with frequency response regulations, as seen in [27].
- Market price, $\lambda_{M,t}$. Historic pricing data for the UK market was obtained from [23] in the form of 'Market Index Data (MID)'. Prices are given every half-hour, and the specific day taken for analysis was 03/11/2013 from 00:00 to 23:30. This was chosen as a typical winter day, for which all data required was available.
- Requested frequency response energy, $E_{fr,t}$. This was obtained by calculation, based on the system frequency and maximum generation available during time period t. System frequency data came from [24] and was aligned with pricing data to cover 03/11/2013 for each 15 s period (T_s). From this frequency data, $E_{fr,t}$ was calculated from the UK Grid Code regulation which dictates the relationship between frequency, loading as a

percentage of rated capacity and required frequency response, which can be found in [28].

- Frequency response energy at maximum change, $E^{max}_{fr,t}$. This was calculated using the same method as for $E_{fr,t}$, but with the frequency difference from the UK baseline of 50 Hz set to −0.5 Hz throughout, as specified by the UK Grid Code [25].
- Utilised frequency response pricing, $\lambda_{fr,t}$. This was calculated based on equations outlined in [26] which define the payment for primary, secondary and high frequency response in the UK market.

In addition, it was decided to activate the 'full response provision' constraint (Eq. (15)). This was assumed due to the set-up of the UK market, which allows the provider to set high prices if they do not wish to provide frequency response. Therefore, it was assumed that a penalty would not be deliberately incurred for economic reasons as an operational decision.

3.3. Results

The optimisation problem formulated in Section 2, was solved in GAMS software, with the variables, constraints and execution time summarised in Table 2.

Firstly, the case in which the WPP is equipped with a VRB based storage system was studied using the data presented in Section 3.2. This gave the headline results seen in Table 3, which are compared to the base case, which does not use storage. The value of the objective function for both cases represents the income of the system over an artificial 15 year period, due to the assumed life of the ESS as previously discussed. The difference between the case with storage and base case is accounted for by the high reserve level in the case without storage, which is kept in order to comply with a regulation, represented by Eq. (12). The results also show that a storage unit of 3 MW h and 5.3 MW was found to be optimal, which is over 10% of the rated capacity of the wind turbines.

The operation profile of the model and the interaction between changes in wind output and the storage unit can be seen in Fig. 5. In Fig. 5a, it is clearly seen that the increase in wind output and storage output combine to comply with the regulation requested from a low frequency event. Fig. 5b shows a switch between provision from a decrease in wind turbine output to storage absorption for regulation requested from a high frequency event. In Fig. 5b, and less so in 5a, the effect of storage efficiency can be seen in the profiles, which differ from the frequency regulation requested. For clarity, the effect seen in Fig. 5b can be explained with the equation

$$E_{fr,t} = S^{-}_{fr,t}/\eta - . \tag{30}$$

The pattern of State of Charge (SoC) of the storage unit can be seen in Fig. 6. Variation is between 83% and 100%, signifying that the storage does not effectively use the extent of its assets. This is due to the regulation of being able to provide response to a −0.5 Hz deviation at any time, and sustaining that response for up to 30 min. The optimisation of the model takes into account that there would be a significant loss of revenue in maintaining sufficient reserve to be able to comply with this regulation only with the use of wind turbines. Therefore, storage is employed to provide the capacity necessary to comply with the regulation.

Table 2
The GAMS solution report.

Variables	Constraints	Execution Time
74,833	160,050	1182 s

Table 3
Resulting variables for nominal case compared to base case without storage.

Variable	Case with storage	Base case
J	2.25×10^8 (€)	1.91×10^8 (€)
S_{cap}	3020 (kW h)	0.0
S_{pwr}	5276 (kW)	0.0

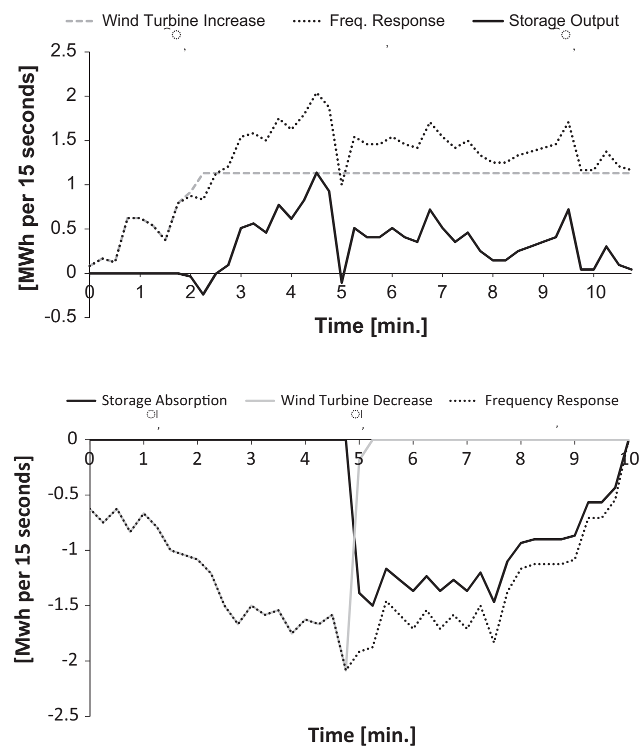

Fig. 5. Extracts which display the operation of storage in tandem with fluctuations in wind output for both low and high frequency responses. (a) Low frequency response. (b) High frequency response.

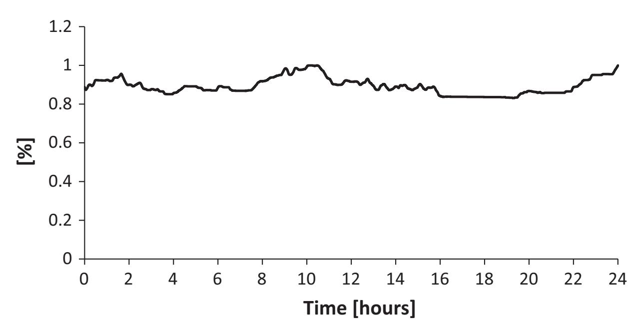

Fig. 6. The state of charge of the storage unit modelled over 24 h.

Power variations in the system can be seen in Figs. 7 and 8. Fig. 7 shows that the change in wind power output due to provision of frequency response is relatively small. The reserve maintained by the system can also be clearly visualised, with a steady gap between the wind generation and the maximum power available. This reserve is utilised by the provision of frequency response.

In Fig. 8 it is clearly visible that the power supplied by the storage does not match the value calculated for sizing of around 5.3 MW. This is true throughout the data and can be explained by the affect of complying with the UK Grid Code regulation

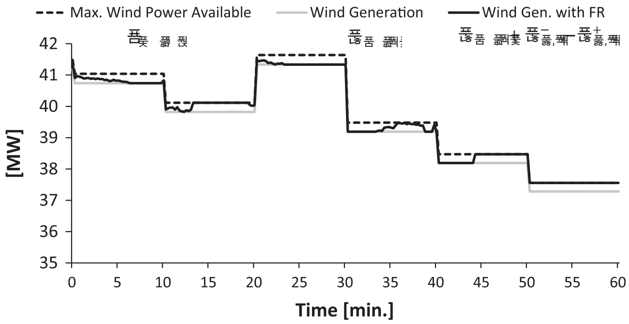

Fig. 7. Wind turbine power figures varying across 1 h. Frequency response contribution can be seen between the Wind Generation and Wind Power Available.

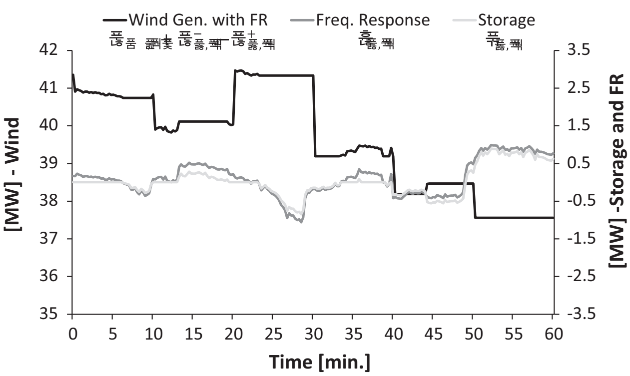

Fig. 8. Power comparison between wind, storage and frequency response powers. Power of frequency response and storage have been shown relating to the right hand side vertical axis. The axes are matched such that comparisons can be easily made.

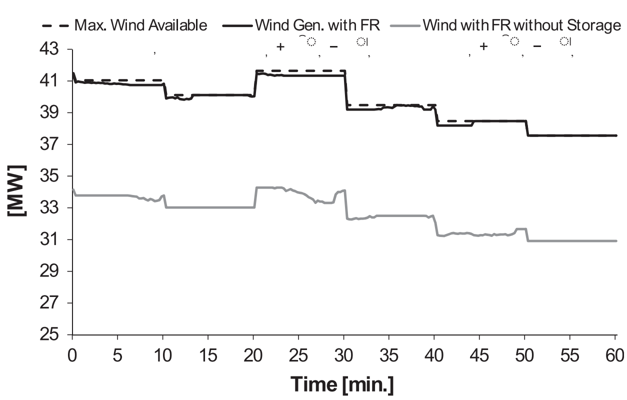

Fig. 9. Wind power profiles for the base case (without storage), vs. nominal case. The large gap is the reserved required by the regulations.

mentioned previously. As with energy capacity levels, seen to be artificially high in Fig. 6, compliance with the regulation significantly increases the amount of power supply needed by the storage.

A significant difference can be seen between the generation levels of the case with storage, and the base case (without storage). This is shown in Fig. 9. The regulatory framework, as it has been interpreted in this article, leads to a large power gap which ultimately causes the low revenue of the system for the base case.

Numerous wind data sets were considered in order to ensure that the results obtained could be considered valid across a range of data. This can be seen in Fig. 10 where a 24 h sample was taken

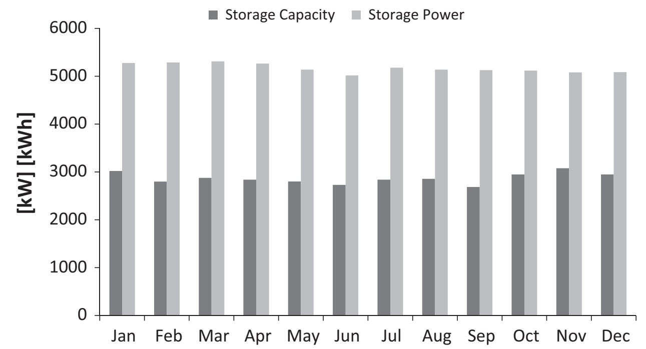

Fig. 10. Optimisation results using different wind power data samples, taken from the first of each month of 2006 at the same site. Little deviation is shown between the results from the different sets.

from the first day of each month of 2006. The variation in storage capacity and power is shown across the year. Very little variation is seen, both in capacity and power sizing. Again the effect of the UK Grid Code regulations is seen, as the regulation determines the sizing for the storage, ensuring that there is little variation throughout the year.

4. Conclusions

This paper has presented a methodology for the economic optimisation of the sizing of an ESS whilst supporting WPPs to provide the ancillary service of primary frequency regulation. The methodology can be applied to assess the sizing of different storage technologies in varied energy markets. This was shown in the formulation of the equation, which when applied in any robust optimisation solver, can provide a solution to large-scale linear programs. For the purposes of the article, the model was applied to the particular case of the UK market, considering the inclusion of a VRB in a 50 MW WPP.

The paper found that, under certain assumptions, storage can be economically used for provision of frequency response in combination with a WPP by relieving the turbines of provision of power reserves. Results depict that a storage system with a power capacity of approximately 10% of the rated power of the WPP, with an energy capacity enough to provide its rated power for up to 30 min would be enough for this purpose, addressing the requirements of the UK policy.

The active energy requirements for the installed ESS for frequency regulation were found to be relatively small, with reserves required for large frequency disturbance events. Therefore, the storage solution to be installed in the WPP could also be a combination of storage technologies with small energy capacity, high ramp power rates and short time responses, together with storage technologies with relatively high energy capacities.

To conclude, it is worth noting that overall, under currently UK market policy, it is still un-economical for wind power plants to provide frequency support, and as such these plants can price themselves out of the market. However, if response was required, with increasing wind penetration, storage could be an economical option to provide this support. Within this, the work also brings out questions surrounding the current UK regulation policy, which still does not include dedicated valuation schemes for the services that storage systems can provide to the network in general, and for the grid integration of renewables in particular.

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