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Comparison of Two Energy Storage Options for Optimum Balancing of Wind Farm Power Outputs

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Abstract: This paper presents a simple methodology for analysing and optimizing combined wind generation and storage schemes, using both technical and economic performance criteria. The paper provides a detailed analysis of the performance of two storage options for such a scheme: Pumped Storage Hydro (PSH) and Battery Energy Storage Systems (BESS). The analysis is carried out using recorded data from an actual UK wind farm, information on the UK electricity market and currently available PSH and BESS storage technologies to estimate and compare performance of the considered wind generation-storage schemes over the entire lifetime. The results show that an optimized generation-storage scheme can significantly reduce the variability of power outputs and increase the profitability of the wind farm. It is further shown that optimized PSH-based schemes have better economic performance than BESS schemes, as the latter are limited by the short discharge times. The approach developed in this paper could be used during the initial design and planning stages, in order to select and optimize the type and size of energy storage for a combined wind generation-storage scheme.

Keywords—Energy storage, wind power, performance evaluation, economics.

1. INTRODUCTION

Variability of power outputs of renewable-based distributed generation (DG) systems, particularly those utilizing wind and solar energy as the inputs, is a significant challenge for the UK to successfully deliver target of supplying 15% of total energy consumption from renewable sources by 2020 [1]. This is true regardless of the actual size of these systems, which are currently installed in a wide range of powers, from highly distributed micro and small-scale individual photovoltaic (PV) panels and wind turbines (WTs), to medium size wind/PV parks, to large-scale wind/PV farms.

Energy storage systems have significant potential to efficiently balance variable outputs of renewable generation and, depending on type of storage and implemented control, to respond rapidly to changes in system loading and operating conditions. Traditionally in the UK, energy storage systems were limited to a small number of large pumped-storage hydro (PSH) plants and flexibility for balancing variable renewable generation was mostly provided by expensive and carbon-intensive fast-response thermal (e.g. gas-fired) power plants. The recent increase in numbers of smaller to medium scale wind and PV generation poses challenges for the grid and for the developers, who might consider dedicated energy storage not just for balancing renewable generation, but also as a promising option for maximizing return of their investments in wind/PV systems. These issues are considered in a number of references, related to both general and specific characteristics of different energy storage systems, including their benefits and potential for grid integration. For example, [2-10] compare different energy storage technologies, [11-15] discuss operation of PSH systems, while [16-25] analyse battery energy storage systems (BESS) – all these references, with additional relevant ones, are discussed in more detail in further text.

This paper investigates feasibility of combining small and medium size wind-based DG technologies with a conventional, but smaller size PSH scheme, and an also conventional, but larger size inverter-interfaced BESS scheme. After this introduction, Section 2 reviews main characteristics of PSH and BESS technologies, Section 3 discusses modelling of wind energy resources (input wind speeds and output powers), while Section 4 describes methodology for evaluating combined generation-storage systems. The results for considered PSH and BESS schemes are presented in Sections 5 and 6, while Section 7 provides comparison of their performance for same-size schemes. Section 8 gives main conclusions.

The presented approach for techno-economic comparison of different technologies is designed for use during project planning stages and does not require complex or licensed software packages, as it can be easily implemented using standard office spreadsheet software. Accordingly, the presented methodology is designed for a simple but correct initial evaluation of energy storage options, considering the most important technical and economic aspects, which could be analysed further using more detailed information and more sophisticated modelling tools. The analysis is illustrated on examples of balancing outputs and maximizing benefits of several different-size wind farms (WFs), including one existing WF for which measured input wind speeds and output powers were available.

2. CONSIDERED PSH AND BESS ENERGY STORAGE TECHNOLOGIES

Energy storage is not a novel concept, as various commercial schemes have been available and operational for decades. The most common type of large-scale energy storage are PSH systems, representing almost 99% of worldwide storage capacity in 2013, [2]. More recently, other energy storage technologies, currently at earlier stages of development, have emerged for future grid-scale commercial applications, such as li-ion battery energy storage systems (BESS). In order to provide comparison of main characteristics of both well-established and newly-emerging technologies at the small to medium size scales, this paper presents analysis of several PSH and BESS schemes, assessing their feasibility for combining with WFs of different sizes.

2.1. Pumped Storage Hydro (PSH)

PSH schemes are usually large-scale systems that utilise gravitational potential energy available from stored water in an upper reservoir to generate electricity. The water is released through a turbine during periods of high demand and collected in a lower reservoir, known as “tail pond”. Typically, PSH schemes utilise off-peak electricity prices during periods of low demand to regenerate supply by pumping the water collected in the tail pond back uphill [12, 16].

Depending on the size, PSH systems achieve round-cycle efficiencies in the range of 75%-85% [3-4, 16] and can store potential energy in excess of 24 hours, featuring long discharge times. Two main problems with combining PSH scheme with a dedicated wind-based generation at small and medium scales are related to locating a suitable reservoir site and to high capital costs, resulting in long payback periods [3, 5]. Combining PSH with renewable generation is discussed in [11-15], including examples of existing applications. Additional concerns are related to flooding, associated with larger PSH schemes, causing nuisance to nearby communities and damaging local eco-systems. For these reasons, some alternative PSH schemes are recently investigated, such as underground PSH, utilizing disused mineshafts and abandoned quarries [37].

2.2 Battery Energy Storage Systems (BESS)

Batteries are also used for energy storage for a long time, but typically in smaller-scale applications, due to high costs involved with larger installations. Lead-acid batteries are the most mature BESS technology, with flooded lead-acid (FLA) and valve-regulated lead-acid (VRLA) technology improvements occurring over the past decades [6-7, 17].

Table 1 lists main characteristics of electro-chemical energy storage technologies, which are currently being investigated for use in grid-scale applications. Further discussion, including some examples of existing applications (Table 2) could be found in [16-25, 27, 36].

Table 1. Comparison of BESS technologies [6, 16, 35, 39].

Type	**Lifetime/cycles**	**Environmental Risk**	**Application Scale**	**Efficiency**	**Cost**
Lead-acid*	~1,000	Medium-High	Small-Medium	70-90%	\$300-\$700/kWh
Ni-Cd	2,000-2,500	Medium-High	Small-Medium	60-91%	\$800-1,500/kWh
Li-ion **	3,000***	Small-Medium	Small scale/EV	95%	\$250-\$800/kWh
ZEBRA	2,500-5,000	Small	Small scale/EV	85-90%	\$200-600/kWh
Redox Flow	10,000+	Small	Small-Medium	65-85%	\$500-1,500/kWh

Notes:
* up to 10 times lifecycle improvements for lead-carbon electrodes, [18-19]; VRLA is more expensive and with shorter lifetimes, but lower maintenance costs [7, 20].
** small size and lightweight [15, 21]; further safety improvements and cost reduction expected in grid-size applications [7, 22]; further cost reduction due to use for EVs [23], but prices impacted by lithium availability [9, 22].
*** At 80% depth of discharge [16], but deep discharge can be detrimental on lifetime [19].

Table 2. Two examples of grid-scale BESS applications, [27, 36].

Type (Country)	**Capacity/Rated Power**	**Application**	**Experience**
Flooded lead-acid (FLA) **BEWAG, Germany**	14MWh	frequency regulation and spinning reserve	operational 1986-1993; spinning reserve 1993-1995
Li-ion **Orkney Island, UK**	2 MW	grid-balancing of renewables	installed in 2013 after a two-year trial

3. MODELLING OF WIND ENERGY RESOURCES

Correct assessment of energy outputs of renewable-based DG systems essentially relies on accurate representation and modelling of their input energy resources. Main problems during such assessment are high levels of variability, which, if not properly modelled, will ultimately result in uncertainties and errors in calculated energy outputs. The presented analysis uses Markov Chain (MC) model for assessment of variability of input wind energy resources at both shorter and longer temporal scales (e.g. [26]). Inclusion of different temporal scales in the analysis is directly related not just to the actual performance of a wind-based generation system, but also to the type of energy storage and its ability to rapidly respond to control signals for changing operational state (from charging to discharging, and vice versa). Wind energy conversion process by WTs is modelled using available information on their power curves.

3.1 Wind Energy Model

Wind energy model is developed using 10-minute average wind speed measurements from WF located in East Scotland, covering period from January 2007 to January 2010. Available data set was firstly reviewed to identify missing data, e.g., due to unavailability of a recording system, or turbine maintenance, or faults. In cases of shorter periods (<8hr), missing values are extrapolated. Larger periods of missing data (>8hr) are assumed to have the same wind speeds as the corresponding periods from other available years.

Measured 10-minute average wind speeds are allocated to “bins”, defined in 1m/s bands. This allows for a direct application of MC-based analysis, where three years of measured data are used to generate synthetic wind speed profiles over the period of 40 years, assumed as the expected lifetime of WF (including WT replacement after 20-25 years of operation).

3.1.1 Markov Chain (MC) Model: is an analytical representation of a stochastic process, in which any future state is dependent only on its previous state. MC models are defined in terms of time and state space, and model is built by analysing state transition probabilities (1). These values are combined into a state transition matrix (2), describing probabilities of moving from any particular state to another in discrete state time and space. For MC wind modelling, the user specifies the number of states and order of MC model to represent range of wind speeds (typically up to 25-40 states, corresponding to one MC state for each 1 m/s wind speed increment).

$$p_{ij} \forall i, j \in S \ 1, 2, \ldots, n, \ and \sum_{j \in S} p_{ij} = 1 \tag{1}$$

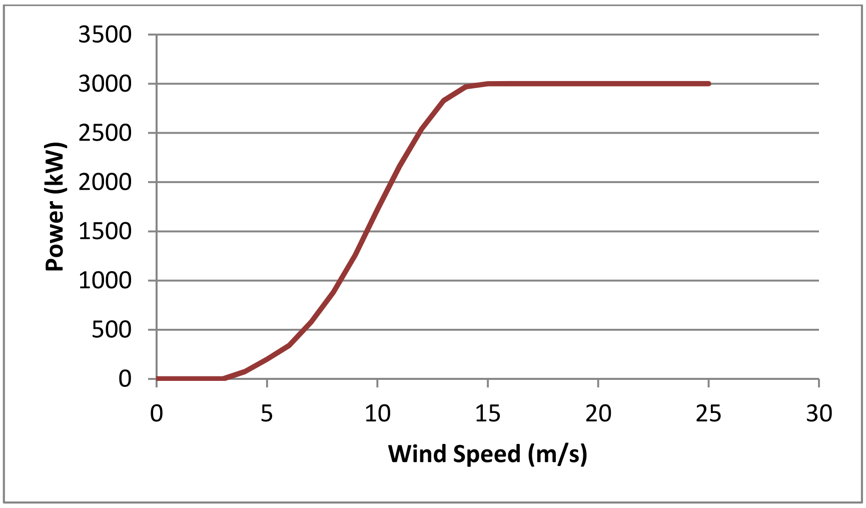
$$P_{t,t+1} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \cdot & \cdot & \cdots & \cdot \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \tag{2}$$

where: $P_{t,t+1}$ is state transition probability matrix, t and $t+1$ are current and next states, p_{ij} is transition probability from state i to state j, and S is the set of all possible n different states. The state transition matrix is built using recorded wind data, and resulting model can generate synthetic wind speed (or power output) time series of any length, in accordance with methodology in [26-28].

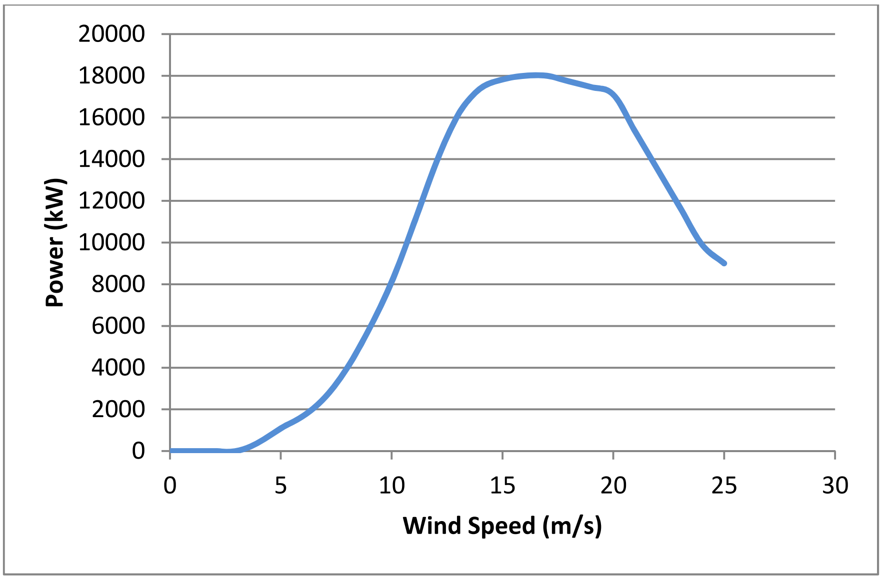
3.1.2 Generation of Synthetic Wind Profile (SWP): An SWP profile is required for assessing WF outputs at a given site. For that purpose, a cumulative transition matrix is developed first, by summing the transition probabilities for each wind speed bin/row of the transition probability matrix, which should add up to 1. Afterwards, a random number generator was applied to produce values between 0 and 1, which are then allocated to corresponding ranges of probabilities in the cumulative transition matrix, allowing to move from one 10-min state to another and to create annual SWP. Finally, the whole process is repeated for the expected WF operational lifetime of 40 years.

3.2 Wind Energy Conversion (Wind Turbine) Model

Modelling of wind energy conversion process, i.e. outputs of WTs, uses power curve of an individual WT (Figure 1a), obtained from manufacturer's specification [29]. Power curve was represented as a look-up table (rounded to the nearest integer) and used to calculate WT output powers for input wind speeds obtained from MC model. The actual power performance curve for an entire WF varies from the manufacturer's WT specification due to cut-in and cut-out effects over multiple turbines, array losses, and losses due to site-specific and terrain factors [30]-[32]. A detailed study of input wind speeds and power outputs for UK WFs of various sizes was carried out in [32], where an approach was developed for converting a single wind speed input into a power profile for an entire WF, considering cut-in/cut-out effects and array losses. For calculating power output of the entire WF, methodology in [32] is applied to create an aggregate power curve, Fig. 1b.



a) individual 3MW WT, [29]



b) whole WF (6x3MW WTs), [32]

Figure 1. Power curves used for the analysis.

4. SIZING AND OPTIMIZING ENERGY STORAGE SYSTEM

The main purpose of the combined wind generation-storage model in this paper is to determine an optimal size and type of such a scheme, taking into account two main aspects: a) minimize variations of wind farm outputs around the predicted or bid daily or hourly average values, and b) maximize profit from trading on a day-ahead and hour-ahead market. Developed model optimizes storage scheme by: minimizing amounts and periods of times when energy is curtailed (i.e. when WF output is higher than bidding) and when energy is insufficient (i.e. when WF output is lower than bidding), maximizing estimated net profit over the scheme's lifetime and optimizing utilization of the storage scheme.

4.1 Model Interface

A number of input parameters are incorporated into the model, in order to allow for a comparison of different types of energy storage technologies. Input parameters of storage system are: power rating; maximum discharge time; reaction time (switching between charging/discharging); capital cost of storage; annual O&M costs; and operational period. Input parameters for WF are: wind energy profile and either power curve and number of individual WTs, or aggregate power curve of the whole WF.

4.2 Optimization Parameters

The optimal scheme is determined by Overall Performance Factor (OPF), combining relevant technical and economic aspects. The OPF is defined as:

$$OPF = TPF \ x \ EPF \tag{3}$$

where: *TPF* and *EPF* are Technical Performance Factor and Economic Performance Factor.

Technical aspects focus on the utilization and operational conditions of the energy storage scheme, while economic aspects compare the overall net profits generated by the combined scheme and when the WF is operating alone. The optimization procedure was performed as a simple "selection/benchmarking study", allowing identification of "best candidates" among the available schemes in terms of their characteristics. The procedure calculates several techno-economic performance factors, in order to minimize amounts of both curtailed and unsupplied energy, while optimizing utilization of energy storage. Some parameters are assumed to be fixed (cost/MW, penalties, tariffs), while other are assumed to change as the design change (type/size of storage system, discharge times). The model/user then compares results for different schemes, with the largest OPF values indicating the best candidates.

4.2.1 Optimization: Technical Analysis: The objective of TPF is minimizing amounts of curtailed and unsupplied energy, while optimizing utilization of energy storage:

$$TPF = \frac{BEF}{SUF} \tag{4}$$

where: BEF is Balanced Energy Factor and SUF is Storage Utilization Factor.

The BEF evaluates differences between the bid and actual WF energy outputs as:

$$BEF = ECF \; x \; ESF = \; (1 - AACE) \; x \; (1 - AAIE) \tag{5}$$

where: ECF is Energy Conserved Factor and ESF is Energy Supplied Factor. For all annual bids n, average annual bid energy is calculated as: $\overline{P_d} = (\sum_n P_{d,n})/n$, while average annual actual energy is calculated as: $\overline{P_a} = (\sum_n P_{a,n})/n$. Afterwards, Average Annual Curtailed Energy is calculated as: $\text{AACE} = (\overline{P_a} - \overline{P_d}) \,/\overline{P_d}$ (for all bids when $P_{a,n} > P_{d,n}$), and Average Annual Insufficient Energy as: $\text{AAIE} = (\overline{P_d} - \overline{P_a}) \,/\overline{P_d}$ (for all bids when $P_{d,n} > P_{a,n}$).

Storage of any size will improve BEF by reducing both curtailed and unsupplied energy, as it will charge during periods of excessive WF outputs and then discharge available stored energy during periods of insufficient WF outputs. Increasing the size of energy storage will increase BEF (if unlimited storage is available, no energy will be curtailed), but larger storage will result both in the higher cost and in an increase of stored energy that might not be utilized. This is modelled using SUF, which describes operation of storage system in terms of the average annually discharged/charged energy (i.e. average state of the storage system):

$$SUF = \left(\sum_n \frac{S_{s,n}}{S_c}\right)/n \tag{6}$$

where: $S_{s,n}$ is storage state for bid n and S_c is storage capacity.

Larger than optimal schemes will have higher SUF values (their average charge state will be higher), indicating unnecessary and costly oversizing, possibly resulting in longer periods when stored energy is not (fully) discharged. Furthermore, it can be expected that WF operators will bid conservatively, to prevent penalties for unsupplied energy when WF output is lower than bid. Accordingly, optimization by (4) reduces TPF for larger storage systems (with higher SUF), preventing oversizing the scheme. It should be noted that presented analysis could be improved further, e.g. by preventing frequent charging-discharging for undersized storage schemes, which can significantly reduce their lifetime.

4.2.2 Optimization: Economic Analysis: Economic performance of combined scheme is determined as:

$$EPF = \frac{NP_S}{NP_W} \tag{5}$$

where: EPF=Economic Performance Factor, NP_S=Net-Profit with storage, NP_W=Net-Profit without storage.

The Net-Profit without storage considers WF only cumulative income, less cumulative expenses. The cumulative expenses consider capital cost of the scheme; O&M costs and under/overproducing penalties over the lifetime of the scheme. The capital costs of specific WF-storage schemes are very site-specific and presented calculations are based on the estimated costs per kW-installed.

4.2.3 Bidding Strategy: The cumulative income was calculated assuming that electricity was traded on APX Power UK Spot Exchange market, [34]. The baseline scenario assumes a day-ahead bid is made of 24 hourly values for each day, representing average predicted WF output for proceeding day.

Once WF bid has been accepted, the combined scheme is expected to supply this power. The electricity price was simplified to include only peak and off-peak tariffs. Off-peak tariff takes effect 19:00-07:00hrs at a rate of 0.04 £/kWh, whereas peak tariff is in effect 07:00-19:00hrs at a higher rate of 0.06 £/kWh, based on average daily off-peak/peak prices for 2013 from [34]. Undersupply will result in a penalty of 0.06 £/kWh, while oversupply will be curtailed on the WF's dumping load [32].

5. THE RESULTS: OPTIMISED WIND-PSH SCHEME

The presented energy storage model is used for optimizing a combined PSH-WF scheme for an example 150MW WF over a 50-year life-cycle, with PSH scheme ratings ranging from 25MW to 175MW. The maximum discharge time was limited to 24hrs, as PSH schemes are unlikely to exceed this value in practice.

5.1 Overall Performance Factor (OPF)

The optimal PSH scheme can be determined from the peak OPF values calculated for considered scheme capacities and ratings, Figure 2 and Table 3.

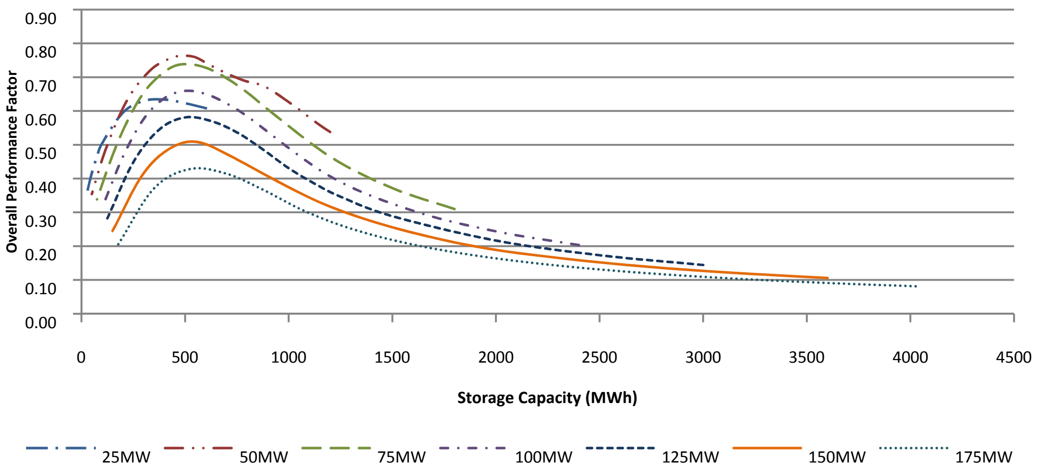


Figure 2. Illustration of optimizing PSH scheme.

Table 3. Peak OPF values for different PSH scheme ratings.

PSH Scheme Rating (MW)	Peak OPF values
25	0.64
50	0.75
75	0.74
100	0.66
125	0.58
150	0.51
175	0.43

Figure 2 shows that schemes with different sizes follow a similar trend. At low storage capacities (<400MWh), the OPF values initially increase, before reaching a peak value of around 500MWh, indicating optimal scheme size. Gradient of curves after the peak point decreases with increasing storage capacity, not just because of increased costs, but also because corresponding SUF values increase, while BEF values remain constant after storage capacity becomes large enough to harness most/all of the excess energy. As a result, OPF will decrease for larger than optimal PSH schemes.

Figure 2 indicates an approximate optimal storage size between 25-75MW. The exact value was determined in further simulations with various discharge times, using steps of 1hr, resulting in optimal PSH scheme capacity of 480MWh and rating of 60MW, Table 4.

Table 4. Characteristics of optimal WF-PSH scheme.

Rating (MW)	60
Discharge Time (hours)	8
Energy Capacity (MWh)	480
Lifetime Net Profit	£ 802,973,813
Payback Period (Years)	10
Energy Conserved (%)	98
Energy Supplied (%)	93
Overall Performance Factor	0.77

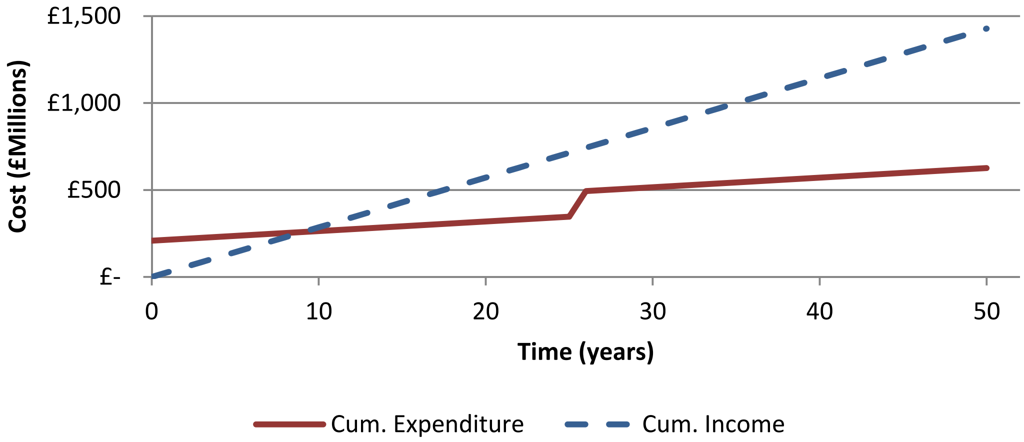
5.2 Economic Analysis

The financial benefits of the combined PSH-WF scheme are illustrated by comparing the economics of WF alone with the combined scheme, Table 5.

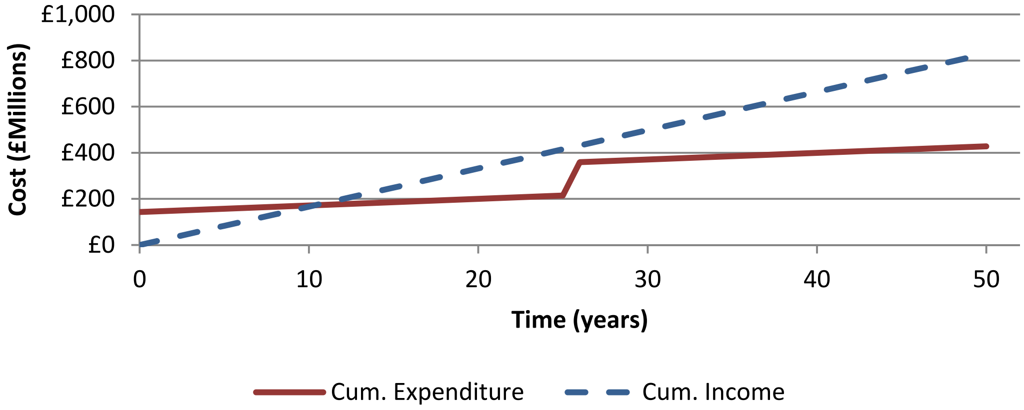
Table 5. Summary of optimized PSH-WF scheme economics.

Parameter	Wind Farm Alone	Combined WF-PSH Scheme
Capital Cost (£/kW)	950	-
Capital Cost (total)	£ 142,500,000	£ 208,500,000
Annual O & M Costs	£ 2,850,000	£ 5,490,000
Annual Net Profit	£ 16,595,187	£ 28,569,476
Lifetime Net Profit	£ 402,259,334	£ 802,973,813
Payback Period (years)	10	9

Table 5 estimates that the combined scheme generates 72% higher annual profit, doubling the profit over the scheme lifetime. This is a significant improvement and suggests that a combined scheme could provide a substantial economic benefit. In addition, the payback period is reduced by one year, minimizing risk and increasing feasibility for potential investors. This can be seen more clearly by comparing each scheme's economics in Figures 3a and 3b. The sudden increase in capital expenditure after 25years is due to "regeneration" (e.g. replacement of WTs) in WF, which however does not consider the cost of WT removal or the scrap value of the WTs.



a) combined PSH-WF scheme

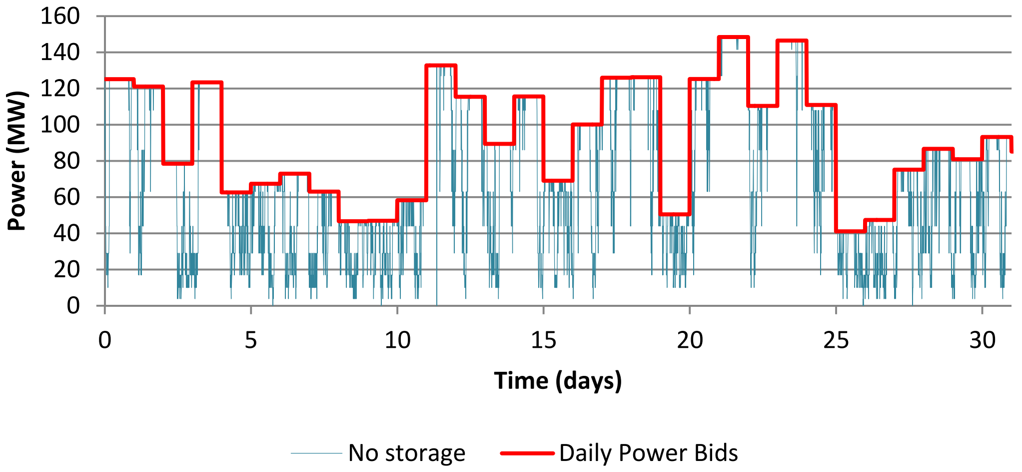


b) WF alone

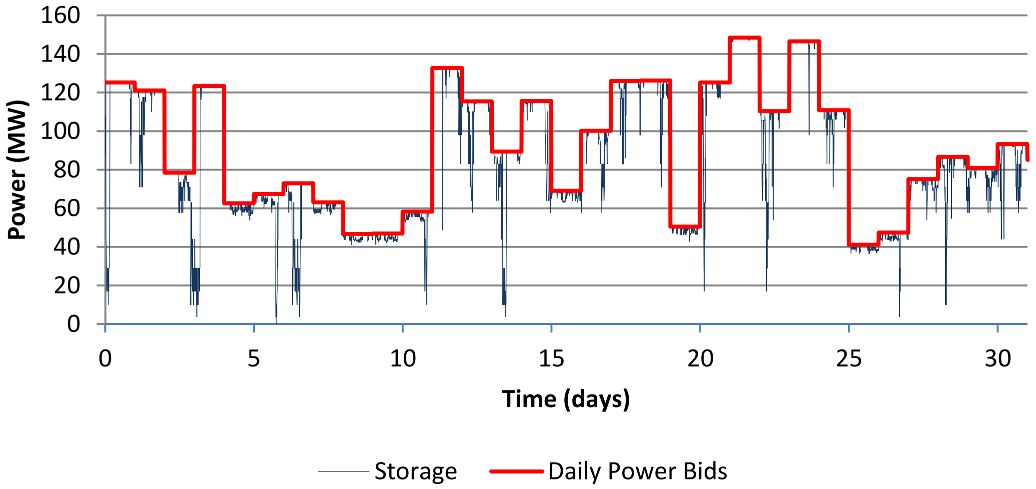
Figure 3. Calculation of payback periods.

5.3 Technical Performance

WF power output fluctuations are expressed as the difference between the actual and bid powers, with excess power dumped on internal load (no curtailment penalties). When optimal PSH scheme is combined with the WF, fluctuations reduce from around 25% to around 7% (calculated over scheme lifetime), demonstrating effectiveness of PSH scheme, as illustrated in Figures 4a and 4b.



a) WF alone



b) optimal WF-PSH scheme

Figure 4. WF output powers and biddings over one month period.

6. THE RESULTS: OPTIMISED WIND-BESS SCHEME

For optimizing the combined BESS-WF scheme, a smaller size system, related to an individual 3 MW WT, is analysed first. Two technologies are analysed: lithium-ion and advanced lead-acid batteries. The maximum discharge time of around one hour is assumed as a practically feasible value, regarding both capital cost and preserving the minimum state of charge in the BESS. Afterwards, an additional analysis is performed in Section 6.4, showing results if maximum discharge time is extended.

6.1 Overall Performance Factor (OPF)

Figure 5 shows optimization process based on the OPF plots for both storage types at different considered capacities.

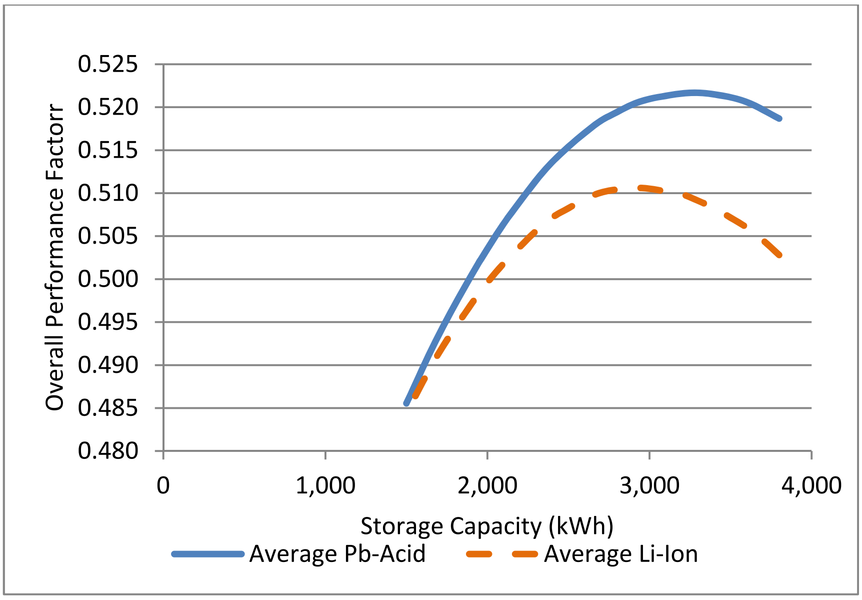
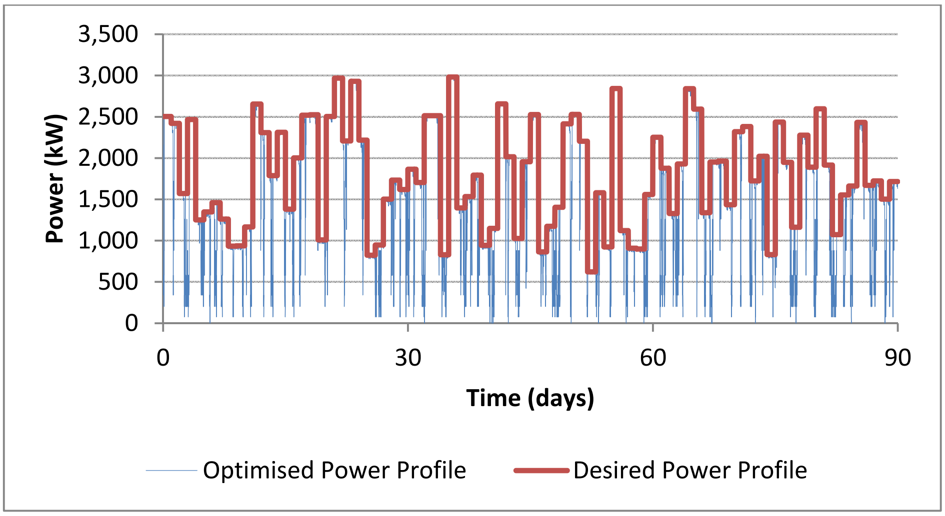


Figure5. Illustration of optimizing BESS scheme for 3MW WT.

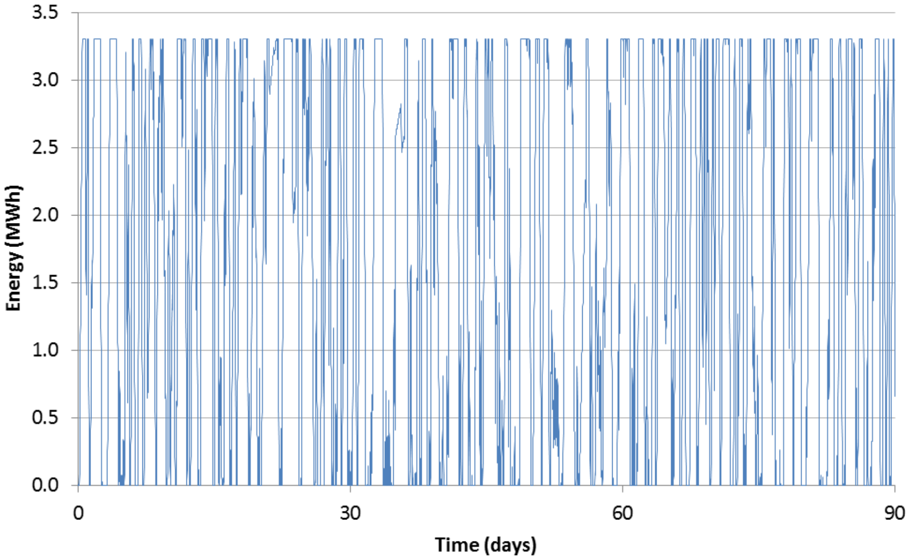
Due to assumed higher cost of Li-ion BESS ($750 vs. $660 for lead-acid), the lead-acid battery achieves higher OPF values, which is more evidenced as storage capacity increases. Optimal capacity of lead-acid BESS scheme is found as 3.3MWh (2.9MWh for Li-ion) and Figure 6a compares WT power profile for this BESS with a “desired power profile” (when all bids are met). Percentage fluctuations of power outputs show that 12% of bid power is not met, which is still much better than 25%, corresponding to WT alone. Figure 6b shows changes in BESS state, where number of charging-discharging cycles indicates frequent deep discharges, which can reduce long-term battery capacity.

6.2 Technical Performance

The characteristics of the optimal 3.3MW lead-acid BESS-WT scheme are summarized in Table 6.



a) power profiles



b) operational state-of-charge values

Figure 6. Performance of WT with optimized lead-acid BESS system.

Table 6 Characteristics of the optimal BESS-WT scheme.

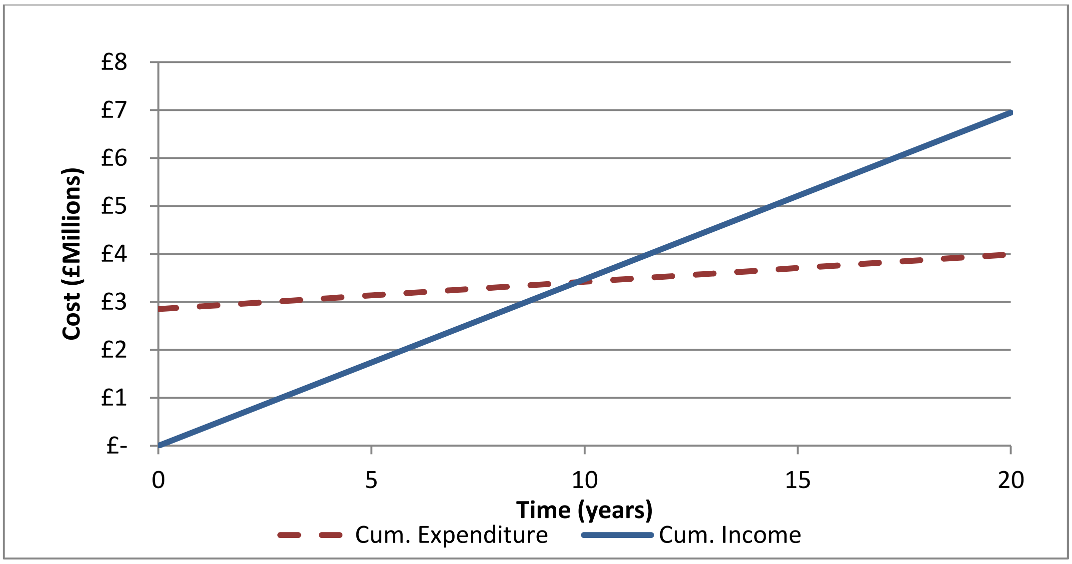
Rating (MW)	3.3
Discharge Time (hrs)	1
Energy Capacity (MWh)	3.3
Lifetime Net Profit	£ 3,966,866
Payback Period (Years)	11
Energy Conserved (%)	0.89
Energy Supplied (%)	0.88
Overall Performance Factor	0.52

6.3 Economic Analysis

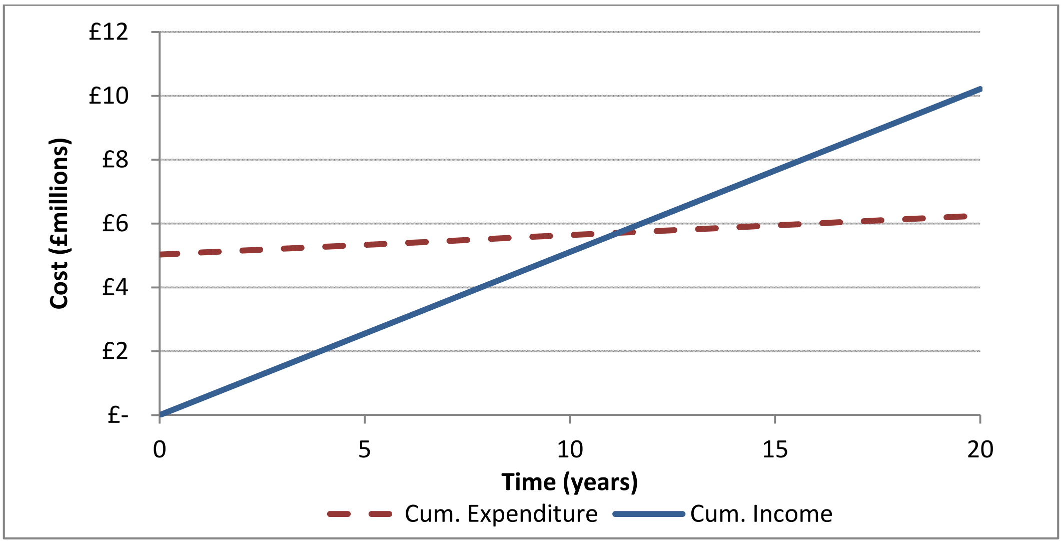
Table 7 shows that the combined BESS-WT scheme is estimated to generate 47% higher annual profit and 33% higher profit over the scheme lifetime, providing substantial economic benefit despite a 1-year longer payback period. Figures 7a and 7b show each scheme's economics, again without considering the cost of WT removal or the scrap value of the WTs.

Table 7. Summary of optimized BESS scheme economics.

Parameters	3.0 MW Wind Turbine	Combined Scheme
Capital Cost (£/kW)	950	-
Capital Cost (total)	£ 2,850,000	£ 5,028,000
Annual O & M Costs	£ 57,000	£ 60,960
Annual Net Profit	£ 347,293	£ 510,703
Lifetime Net Profit	£ 2,955,862	£ 3,966,866



a) WT alone



b) combined WT-BESS (lead-acid) scheme

Figure 7. Calculation of payback periods.

6.4 *BESS Analysis with Maximum Discharge Time Limit Extended*

The OPF results for different discharge time limits (from 1 hr to 5hrs) are shown in Figure 8 for the advanced lead-acid BESS scheme. These results show that, based on the performance indicators proposed in this paper, there is no benefit in increasing the maximum discharge time limit beyond 1hr.

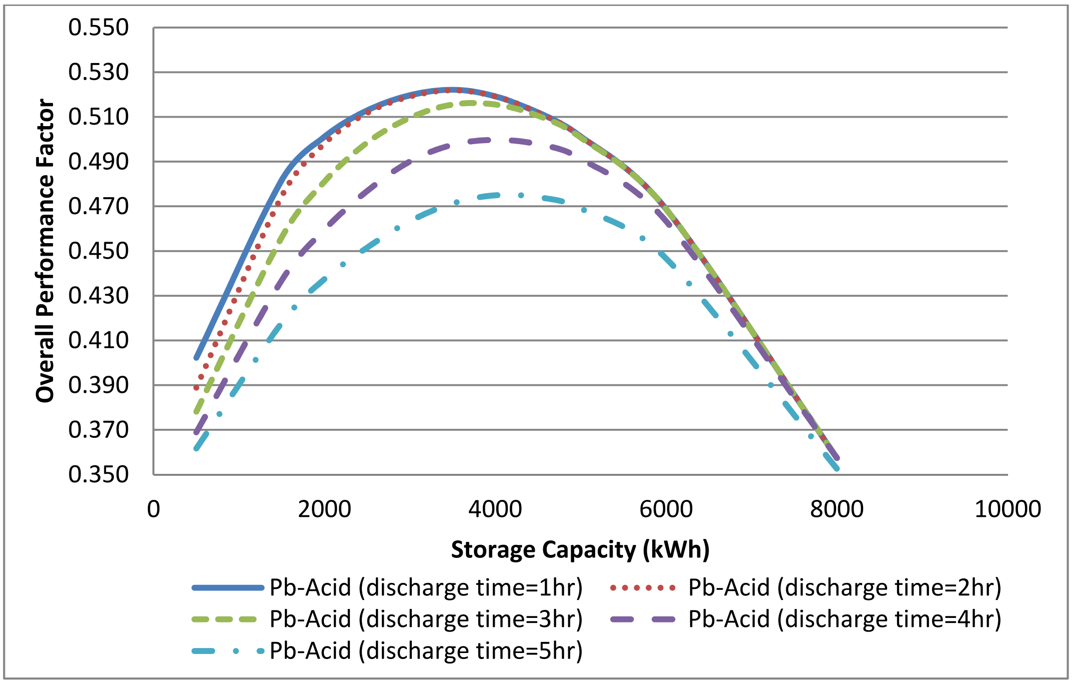


Figure 8. Additional BESS results with extended maximum discharge time limit.

7. THE RESULTS: DIRECT COMPARISON OF OPTIMIZED SAME-SIZE PSH AND BESS SCHEMES

Performance comparison of same-size PSH and BESS schemes is performed for a medium-size WF, consisting of fifteen 3MW WTs. As the lifetime of BESS scheme (advanced lead-acid battery) is assumed to be around 20 years, the same evaluation period is applied to PSH scheme. The sizes of optimal schemes were determined using procedure outlined in previous sections, with the main characteristics summarized in Table 8.

Table 8. Medium-size PSH/BESS scheme characteristics.

Storage Type	PSH	Lead-acid
Rating (MW)	18	49.5 (15x3.3MW)
Discharge Time (hours)	9	1
Energy capacity (MWh)	162	49.5

Table 8 shows that the characteristics of the two optimal schemes vary significantly: the PSH scheme is small, around 40% of the size of the WF, with long discharge times; advanced lead-acid BESS scheme has a larger rating, around 10% larger than WF, with much shorter discharge time. Consequently, capacity of PSH scheme is more than three times larger than the advanced lead-acid BESS scheme.

7.1 *Techno-Economic Comparison*

The results for both analysed schemes are summarized in Table 9.

Table 9. Comparison of performance characteristics.

Storage Type	PSH	Lead-acid
TPF	**0.38**	**0.37**
Charging/Discharging Effic. (%)	88/90	96.5/96.5
Reaction Time (minutes)	1-10*	0 (immediate)
Energy Conserved (%)	98	89
Energy Supplied (%)	93	88
EPF	**2.04**	**1.4**
Capital Cost (£/kW)	1100	660
O&M Cost	4% of Capital Cost	1.2 £/kW
Net Profit (20 years)	£ 77,950,973	55,481,750
Payback Period (years)	9	12
OPF (%)	**77**	**52**

Note:
* based on typical PSH response times from a detailed study in [40], which range between few minutes and few tens of minutes; shorter/sub-minute times stated e.g. in [37].

From a technical perspective, both schemes perform similarly, but have different advantages and disadvantages. BESS achieves a 16% higher round-trip efficiency than PSH and exhibits a much faster reaction time. Accordingly, BESS can substantially reduce energy losses during charging-discharging state transitions, reduce short-term WF power fluctuations and provide fast-response ancillary services. However, Table 9 shows that on average PSH is able to supply 5% more energy during periods of insufficient wind and is able to store 9% more excess energy than BESS. As a result, PSH scheme curtails only 2% of energy, whereas BESS curtails 11%. Furthermore, WF output power fluctuations decrease by 18% when combined with PSH scheme, whereas BESS reduces WF fluctuations by 13%. Over the considered 20-year period, the PSH-WF scheme is estimated to generate 40% higher net profit than the BESS-WF scheme, with a 3-year shorter payback period. However, existing WF sites might not be suitable for PSH schemes, which is generally not a limiting factor for BESS scheme.

8. CONCLUSIONS

This paper evaluates the feasibility of combining wind-based generation technologies with two energy storage schemes: a conventional PSH scheme of a smaller size, and an inverter-interfaced BESS scheme of a larger size. The analysis is illustrated using a case study of balancing outputs and maximizing benefits of both an existing WF, for which measured data are available, and for several theoretical study cases.

The main contribution of the paper is a detailed description of a simple but correct methodology for sizing, optimizing and direct comparison of different generation-storage schemes. The presented approach does not require complex or licensed software packages, as all results in this paper are obtained using standard office spreadsheet software. The presented wind energy input, power output and energy storage models, together with the related optimization/selection procedure for techno-economic comparison of different technologies could be used during design and planning stages for initial evaluation of available or feasible energy storage options, which then could be further analysed using more detailed information and sophisticated modelling tools.

The analysis assumes that WF operators will trade on a day-ahead electricity market and that optimal energy storage scheme (size and type) can be identified based on considered technical and economic performance criteria. The optimization can be performed at multiple scales, allowing to analyse WFs of different sizes in terms of curtailed/unsupplied energy and utilization of energy storage (technical performance), as well as increased net profit over the scheme lifetime (economic performance).

The presented results indicate that an optimized generation-storage scheme can significantly reduce WF power fluctuations, increase annual and lifetime net profits and reduce payback periods. Performance comparison of same-size PSH and BESS schemes for a medium-sized WF shows that although characteristics of two optimal schemes vary significantly, they perform similarly from a technical perspective. Generally, optimized PSH-based schemes have better economic performance than BESS schemes, which are limited by short discharge times, but specific WF site might not be suitable for PSH scheme, which is not a limiting factor for BESS scheme. As any long-term planning study (40-50 years), the presented approach features significant uncertainties in some of the assumed aspects and parameters, such as market conditions and electricity prices, or future technological improvements.

One limitation of the presented analysis is that the day-ahead market bids made by the WF operators are expressed as daily average power outputs, in order to simplify the analysis. Future work will apply more realistic electricity market scenarios (actual hourly bids and power outputs) and will also consider corresponding wind forecast uncertainties. The analysis of storage utilization could be also further improved, e.g. by preventing frequent charging-discharging for undersized storage schemes, as this can significantly reduce their lifetime. Finally, it may be possible that, in addition to trading in the day-ahead market, a combined wind-storage scheme could offer ancillary services to the network operator, such as energy balancing and operating reserve services. Modelling the economic performance over the lifetime of a combined scheme which offers ancillary services (in addition to day-ahead energy trading) is another area for further research.

REFERENCES

[1] Department of Energy & Climate Change, DECC (2013). Energy Trends: June 2013, Special feature articles: Renewable energy in 2012. Renewable Statistics, pp. 49-60.

[2] European Commission. (2013). Overview of projects by country. [Online] http://ec.europa.eu/energy/infrastructure/pci/doc/2013_pci_projects_country.pdf.

[3] Ibrahim, H., Llinca, A., Perron, J. (2008). Energy storage systems-Characteristics and comparisons. Renewable and Sustainable Energy Reviews . 12 (5), pp. 1221-1250.

[4] IEA. (2009). Prospects for Large-Scale Energy Storage in Decarbonised Power Grids. [Online] http://www.iea.org/publications/freepublications/publication/energy_storage.pdf.

[5] Whittingham, M. S. (2012). History, Evolution, and Future Status of Energy Storage. Proceedings of the IEEE. 100, pp. 1518-1534.

[6] Evans, A., Strezov, V. (2012). Assessment of utility energy storage options for increased renewable energy penetration. Renewable and Sustainable Energy Reviews. 16 (6), pp. 4141-4147.

[7] Swierczynski, M., Teodorescu, R., Rasmussen, C.N., Rodriguez, P., Vikelgaard, H. (2010). Overview of the energy storage systems for wind power integration enhancement. IEEE Int. Symp. on Ind. Electronics (ISIE), Bari, 4-7 July 2010, pp. 3749-3756.

[8] Díaz-González F., Sumper A., Gomis-Bellmunt O., Villafáfila-Robles R. (2012) A review of energy storage technologies for wind power applications. Renewable and Sustainable Energy Reviews, 16 (4), pp. 2154-2171.

[9] Vazquez S., Lukic, M., Galvan, E., Franquelo, G., Carrasco, J. M. (2011). Energy storage systems for transport and grid applications. IEEE Trans. on Ind. Electronics, 57 (12), pp. 3881–3895.

[10] Alam, M. J., Muttaqi, K. M., Sutanto, D. (2014) A Novel Approach for Ramp-Rate Control of Solar PV Using Energy Storage to Mitigate Output Fluctuations Caused by Cloud Passing. IEEE Trans. on Energy Conversion, 29 (2), pp.507-518.

[11] Khodayar, M. E., Abreu, L., Shahidehpour, M. (2013). Transmission-constrained intrahour coordination of wind and pumped-storage hydro units. IET Generation, Transmission & Distribution, 7 (7), pp. 755-765.

[12] Bueno, C. & Carta, J.A. (2006). Wind powered pumped hydro storage systems: A means of increasing the penetration of renewable energy in the Canary Islands. Renewable and Sustainable Energy Reviews . 10 (4), pp. 312-340.

[13] Pickard, W.F. (2012). The History, Present State, and Future Prospects of Underground Pumped Hydro for Massive Energy Storage. Proceedings of the IEEE. 100 (3), pp.473-483.

[14] Kapsali M., Kaldellis J. K. (2010). Combining hydro and variable wind power generation by means of pumped-storage under economically viable terms. Applied Energy, 87 (11), pp. 3475-3485.

[15] Teixeira, F., Sousa, J., Faias, S. (2013) A pumped storage hydro unit operation with increasing degrees of market power: Standalone and portfolio integration. 10th Int. Conf. on the European Energy Market (EEM), Stockholm, 27-31 May 2013.

[16] Chen, H. Cong, T. Yang, W. Tan, C. Li, Y. Ding, Y. (2009). Progress in electrical energy storage system: A critical review .Progress in Natural Science. 19 (3), pp. 291-312.

[17] Devitt, J. (1997). An Account of the development of the first valve-regulated lead/acid cell. Journal of Power Sources, 64, pp.153-156.

[18] Leadbetter, J., Swan, L. (2012). Battery storage system for residential electricity peak demand shaving. Energy Buildings, 55, pp.685-692.

[19] Divya, K.C., Ostergaard, J. (2009). Battery energy storage technology for power systems: An overview. Electric Power Systems Research, 79, pp. 551-520.

[20] Chang, Y., Mao, X., Zhao. A., Feng, S., Chen, H., Finlow, D. (2009). Lead acid battery use in the development of renewable energy systems in China. Journal of Power Source, 191(1), pp.176-183.

[21] Dunn, B, Kamath, H., Tarascon, J-M. (2011). Electrical storage for the grid: A battery of choices. Science, 334, pp. 928-935.

[22] Armand, M., Tarascon, J.-M. (2008). Building better batteries. Nature, 451, pp/ 652-657.

[23] Bayar, T. (2011). Batteries for Energy Storage: New Developments Promise Grid Flexibility and Stability. Renewable Energy World, Aug. 2011.

[24] Parker, C. D. (2001). Lead–acid battery energy-storage systems for electricity supply networks. Journal of Power Sources. 100(1-2), pp. 18-28.

[25] Hill, C. A., Such, M. C., Dongmei C., Gonzalez, J., Grady, W. M. (2012). Battery Energy Storage for Enabling Integration of Distributed Solar Power Generation. IEEE Trans. on Smart Grid, 3 (2), pp. 850-857.

[26] Testa, A., Langella, R. Manco, T. (2011). Markovian Approaches to Model Wind Speed of a Site and Power Availability of a Wind Turbine. In Al-Bahadly, I. (Ed.), Wind Turbines, InTec.

[27] Hayes, B. P. (2013). Distributed generation and demand side management: Applications to transmission system operation, Ph. D. Thesis, The University of Edinburgh.

[28] Hayes, B. P., Djokic, S. Z. (2013). Advanced Markovian wind energy models for smart grid applications. 4th IEEE/PES Innovative Smart Grid Technologies Europe (ISGT EUROPE) Conf.

[29] Vestas. (2014). V90-3.0MW Wind Turbine at a Glance.

[30] Hayes, B. P., Collin, A. J., Gil, I. H., Acosta, J. L., Hawkins, S., Harrison, G. P., Djokic, S. Z. (2012). All-scale modelling of wind generation and responsive demand in power system studies. IEEE PES General Meeting, San Diego, CA.

[31] Hayes, B. P., Ilie, I., Porpodas, A., Djokic, S. Z., Chicco, G. (2011). Equivalent power curve model of a wind farm based on field measurement data. IEEE PowerTech 2011 Conf.

[32] Hayes, B. P., Djokic, S. Z. (2013). Modelling of wind generation at all scales for transmission system analysis. IET Generation, Transmission & Distribution, 7 (10), pp. 1144-1154.

[33] Bayon, L., Grau, J. M., Ruiz, M. M., Suarez, P. M. (2012). Mathematical modelling of the combined optimization of a pumped-storage hydro-plant and a wind park. Mathematical and Computer Modelling. 57, pp. 2024-2028.

[34] APX Power UK Spot Exchange. (2014). ‘Daily UKPX Auction Index.’ [Online] http://www.apxgroup.com/trading-clearing/apx-power-uk/.

[35] Beaudin, M., Zareipour, H., Schellenberglabe, A., Rosehart, W. (2010). Energy storage for mitigating the variability of renewable electricity sources: An updated review. Energy for Sustainable Development. 14, pp. 302-314.

[36] IMECHE. (2014). Energy Storage- The missing link in the UK's Energy Commitments. [Online] http://www.imeche.org/knowledge/themes/energy/energy-storage.

[37] Baines, J. A., Newman, V. G., Hannah, I. W., Douglas, T. H. (1985). Dinorwig Pumped Storage Scheme. ICE Proceedings. 78 (4), pp. 919-957.

[38] Walawalkar R., Apt J. (2008). Market analysis of emerging electric energy storage systems. [Online] http://www.netl.doe.gov/energy-analyses/pubs/Final%20Report-Market%20Analysis%20of%20Emerging%20Electric%20Energy%20Sto.pdf.

[39] Poullikkas, A. (2013) A comparative overview of large-scale battery systems for electricity storage. Renewable and Sustainable Energy Reviews, 27, pp. 778-788.

[40] MWH. (2009). Technical Analysis of Pumped Storage and Integration with Wind Power in the Pacific Northwest. Final Report, Northwest Division, Hydroelectric Design Center.