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Short communication

# Value of storage in providing balancing services for electricity generation systems with high wind penetration

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**Abstract**

In an electricity grid with large wind penetration additional system balancing costs are incurred due to the intermittent nature of wind. In this work, we evaluated the benefits of using storage for providing standing reserve as part of the overall reserve needs, in terms of savings in fuel cost and $CO_2$ emissions associated with system balancing, compared to other solutions. We found that providing a greater part of the increased reserves needed from standing reserve in the form of pumped hydro storage increases efficiency of system operation and reduces the amount of wind power that cannot be absorbed.

*Keywords:* Pumped; Storage; Balancing; Intermittent; Wind; Reserve

## 1. Background

Due to environmental concern over $CO_2$ emissions it is expected that penetration of intermittent renewable resources into the electricity grid will increase in future years. This has raised concerns over system costs, focussed on whether these new generation technologies will be able to replace the capacity and flexibility of conventional generating plant. As intermittency and non-controllability are inherent characteristics of renewable energy based electricity generation systems, the ability to maintain the balance between demand and supply has been a major concern.

An analysis of the breakdown of the total additional system costs incurred when extending renewable generation to 20 or 30% of demand, between costs of balancing and capacity, transmission, and distribution, demonstrated that balancing and capacity costs, principally the cost of maintaining system security, dominate all other costs [1]. These costs arise because of the intermittency of wind; principally because of wind forecast error leading to imbalances between the scheduled generation supply and the electricity demand, which needs to be met in real time.

Bulk energy storage systems such as large-scale pumped storage appear to be an obvious solution to dealing with the intermittency of renewable sources and the unpredictability of their output: during the periods when intermittent generation exceeds the demand, the surplus could be stored and then used to cover periods when the load is greater than the generation.

The purpose of the work presented in this paper is to provide quantified estimates of the potential value of storage in managing intermittency of wind generation in the context of the future UK electricity system. We studied a number of generation systems characterised by different mixes of generation technologies, representative of the size of the GB system with some 26 GW of wind capacity installed.

## 2. Wind forecast uncertainty

The magnitude of changes in wind output will strongly depend on the time horizon considered. Statistical analysis of

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Table 1
Fluctuation of wind output for 26 GW of installed capacity of wind generation

| Lead time (h) | S.D. (MW) | Likely max change (MW) | Extreme change (MW) |
|---|---|---|---|
| 0.5 | 360 | 1090–1450 | 2600 |
| 1 | 700 | 2100–2800 | 3950 |
| 2 | 1350 | 4050–5400 | 6550 |
| 4 | 2400 | 7200–9650 | 13500 |

the changes in wind output (forecast error) over various time horizons can be performed to characterise the uncertainty of wind output. The fluctuations of wind power output are usually described in term of standard deviation of changes of wind output over various time horizons. Table 1 presents the standard deviations of wind output for a system with 26 GW of installed wind generation capacity for time horizons from 0.5 to 4 h. The likely maximum changes covering 3–4 standard deviations are also presented in the table. These would indicate the amount of reserve required to cover more than 99% of fluctuations.

For 26 GW installed capacity of wind, the single most extreme changes observed in the model data are given in Table 1 and as expected, these variations in wind output will increase with the time horizon considered. It is expected that it would not be appropriate to carry out reserve to cover for very infrequent events and that some other measures (such as load shedding) would be used to deal with these extremes.

It is important to bear in mind that balancing requirements are not assigned to back up a particular plant type such as wind, but to deal with the overall uncertainty in the balance between demand and generation. The uncertainty to be managed is driven by the combined effect of the demand forecasting error in demand and conventional and renewable generation. The individual forecasting errors are generally not correlated, which has an overall smoothing effect with a consequent beneficial impact on cost of balancing. A key factor in the case of wind is diversity—the phenomenon of natural aggregation of individual wind farm outputs. The output of individual wind turbines is generally not highly correlated, particularly when wind farms are located in different regions [2].

The predictability of wind variations for managing the demand and generation balance is important. Cleary, if the fluctuations of wind were perfectly predictable, the cost of operation of the system with a large penetration of wind power would be relatively small provided that there is sufficient flexibility in conventional plant to manage the changes.

## 3. Managing intermittency: synchronised and standing reserves

Traditionally, conventional generating plant is used for balancing purposes. In order for synchronised plant to provide reserve it must run part-loaded. Thermal units operate less efficiently when part-loaded, with an efficiency loss of between 10 and 20%, although losses in efficiency could be even higher, particularly for new gas plant. The consequence of carrying large amounts of spinning reserve, is that significant number of part loaded CCGT plant need to run reducing the amount of wind generation that can be absorbed, particularly when low demand conditions coincide with high wind power conditions.

In addition to synchronised reserve, which is provided by part-loaded synchronised plant, the balancing task can be supported by so called standing reserve, which is supplied by higher fuel cost plant, such as OCGTs and storage facilities. Application of standing reserve can improve the system performance through reduction of the fuel cost associated with system balancing. This reduction in the amount of synchronised reserve committed leads to: (i) an increase in the efficiency of system operation and (ii) an increase in the ability of the system to absorb wind power, and hence reduce the amount of fuel used.

The allocation of reserve between synchronised and standing plant is a trade-off between the cost of efficiency losses of part-loaded synchronised plant (plant with relatively low marginal cost) and the cost of running standing plant with relatively high marginal cost [3]. The cost of using energy storage facilities for this task is influenced by their efficiency. The balance between synchronised and standing reserve can be optimised to achieve a minimum overall reserve cost of system management.

## 4. Methodology

The analysis is based on a detailed simulation of the operation of the system. We simulated, hour by hour, year round optimal economic operation of the system (including 26 GW of wind capacity) taking into consideration daily and seasonal demand variations and variations in wind output, using Dash Xpress optimisation software. This analysis is concerned with the evaluation of underlying costs associated with operation of the system with considerable contribution of intermittent generation, and so focuses only on the question of the management of intermittency by providing standing reserve. It purposely excludes the assessment of the value of arbitrage activities, a traditional market for storage, and the application of flexible storage in managing TV pickups.

### 4.1. Generation systems considered

The analysis demonstrated that one of the key factors determining the value of storage is the flexibility of conventional generation mix; therefore, we studied the behaviour of three generating systems of distinctly different flexibilities. Among dynamic parameters of generating units considered, the ability of plant to be turned on and off and the ability to run at low levels of output (minimum stable generation) were found to play a critical role.

Table 2
Characteristics of generation systems considered

| Generation system | Inflexible generation | Moderately flexible generation | Flexible generation |
|---|---|---|---|
| Low flexibility (LF) | 8.4 GW installed, has to run at 100% of max capacity | 26 GW installed, minimum stable generation 77% of max capacity | >25.6 GW installed, minimum stable generation 50% of max capacity |
| Medium flexibility (MF) | 8.4 GW installed, has to run at 100% of max capacity | 26 GW installed, minimum stable generation 62% of max capacity | >25.6 GW installed, minimum stable generation 50% of max capacity |
| High flexibility (HF) | None | None | >60 GW installed, minimum stable generation 45% of max capacity |

The characteristics of the systems studied are presented in Table 2.

Peak demand is taken to be 57 GW while minimum demand is 18 GW. The annual hourly demand profile is built from considering 6 characteristic days that represent three seasons (winter, summer and spring/autumn) and two types of day (business and non-business day). Demand is assumed to be perfectly predictable and the impact of demand forecasting error is neglected. An annual hourly wind generation profile is used, taken from wind output data aggregated from a number of wind farms and scaled up to represent 26 GW of wind generation capacity installed. A randomisation of this profile is generated to represent the forecast wind on which day ahead unit commitment decisions are made, whilst the economic dispatch of conventional generation, wind and storage to meet demand in real time uses the historical profile.

### 4.2. Reserve requirements

For balancing load and generation in our study, synchronised reserve is used to accommodate relatively frequent but comparatively small imbalances between generation and demand whilst standing reserve is used for absorbing less frequent but relatively large imbalances. The value of storage based standing reserve is quantified as the difference in performance of the system (fuel cost and $CO_2$ emissions) when intermittency is managed via synchronised reserve only, against the performance of the system with standing reserve. The planning horizon for committing operational reserve is set at 4 h on the assumption that the time it takes to bring a large conventional plant (CCGT) on the system will be 4 h. The system is assumed to use reserves to cover possible fluctuations in this period.

Two main cases are considered: (i) entire reserve is provided by synchronised conventional plant only (spinning reserve) and (ii) part of the reserve is provided by conventional synchronised plant while the rest is supported by standing reserve, in the form of pumped hydro storage facilities. The amount of reserve for the base case (i) is set at 3.5 times the standard deviation of the wind output forecast error. Traditionally, reserve levels are set at about 3 standard deviations of the forecast error. A more detailed analysis of wind data suggests that wind fluctuations (changes in wind output) broadly follow a normal type distribution but with longer tales, indicating that more resources will be needed for system balancing than a normal distribution would suggest.

Table 3
Maximum spinning reserve for cases considered

| Storage capacity (GW) | Maximum spinning reserve (MW) |
|---|---|
| 2 | 5700 |
| 3 | 4700 |
| 4 | 3700 |
| 5 | 2700 |

Given the amount of installed standing reserve, the maximum amount of synchronised reserve scheduled is presented in Table 3.

The actual amount of synchronised reserve committed in each hour is determined by taking into account the predicted output of wind generation. For example, in the case of 2 GW of standing reserve the maximum amount of 5.7 GW of synchronised reserve would be required only if the predicted wind output is above 7.7 GW (5.7 GW spinning reserve plus 2 GW standing reserve). Otherwise the amount of spinning reserve could be reduced. Note though that in the case of storage providing standing reserve, it is not normally possible to achieve the maximum reductions in spinning reserve but rather a fraction of this, as the ability of storage to provide reserve depends on the energy stored at that point and the duration of support required. Storage plant is assumed to be very flexible and storage efficiency is assumed to be 70%.

## 5. Results

The value of storage in providing standing reserve is calculated by evaluating the difference in the performance of the system when intermittency is managed via synchronised reserve only, against the performance of the system with storage facilities used to provide standing reserve. We have calculated the total annual reductions in fuel cost attributable to storage. We have also calculated equivalent capital values of these reductions in annual operating cost using a rate of 10% over a 25-year time period. This tells us the capital value of storage capacity as a function of the amount of installed capacity meaning enabling us to decide which systems it is worth installing storage in, given the capital cost of storage as it stands today. Reductions in fuel utilisation in the system with storage are directly reflected in the improvement of $CO_2$ performance of the system and are system specific. Therefore, we have also calculated the amount of $CO_2$ that can be saved by storage.

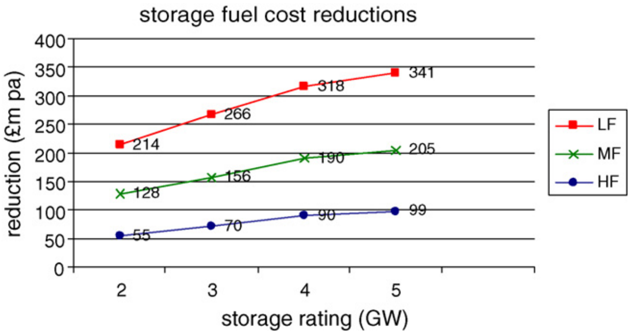

Fig. 1. Reduction of fuel cost with energy storage.

Finally, we also quantify the savings in wind energy curtailed by using storage. By applying storage, the amount of synchronised reserved committed can be reduced and this leads to an increase in the amount of wind power that can be absorbed. This is a consequence of operating fewer conventional generating units and hence reducing the amount of wind that has to be rejected when high wind conditions coincide with low demand. Any remaining surplus of wind can be absorbed by charging the storage facilities. Within our methodology we calculate the amount of wind that would need to be curtailed in order to maintain a stable operation of the system. However, the value of wind curtailed cannot be used to directly measure the benefits of storage because the storage efficiency is a key factor here. For example, having a very large but very inefficient storage facility could reduce the amount of wind curtailed (as all surplus can be stored) but very little of the wind stored would be actually saved. Therefore, reductions by storage in the amount of energy produced by conventional plant are used to measure the net effect of wind energy saved. In effect this reduction in energy comprises the utilisation of wind, as shown by the reduction in wind curtailment, but with the deduction of energy lost due to storage efficiency losses.

The annual reduction of fuel cost obtained from the application of storage is shown in Fig. 1. The value of storage is higher in the system with less flexible generation and reduces with the increase in storage capacity installed.

Fig. 2 presents the capital value of storage capacity as a function of installed capacity.

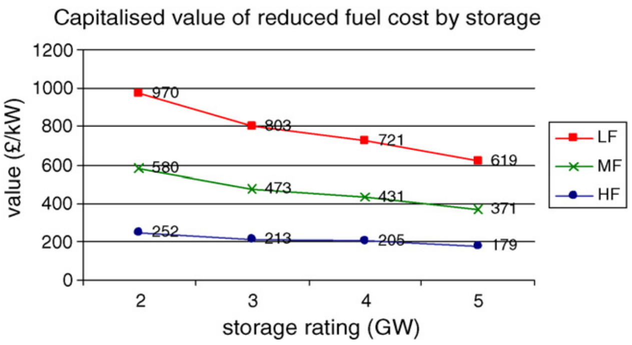

Fig. 2. Capitalised value of reduction of fuel cost with energy storage.

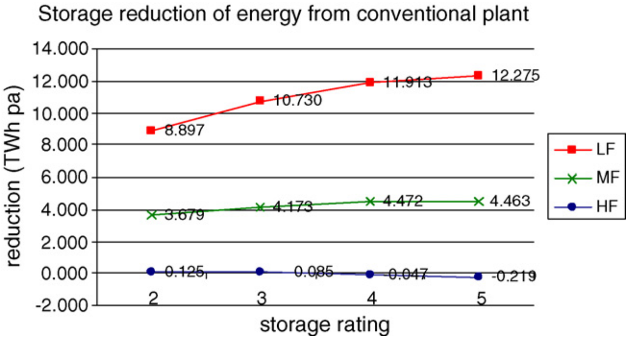

Fig. 3. Benefits of storage: reduction in energy provided by conventional generation.

The $CO_2$ savings are higher in systems with less flexible generation and increase with the increase in storage capacity installed (the latter is specific to the system studied and the range of capacities applied in this work). For example, a storage system of 3 GW installed in a generation system of medium flexibility (MF case) would save 3.2 million tonnes of $CO_2$ per annum. This amount of $CO_2$ saved, would be emitted by a conventional plant of more than 900 MW running at full output for a year.

The net reduction in energy produced by conventional plant show that for the LF case, benefits of storage are significant. The reduction of the output of conventional plant is between 8.9 and 12.3 TWh per annum, depending on the size of storage capacity installed. The contribution to savings of wind energy is significant as the reduction in output from conventional plant is more than 10% of the total wind contribution. More flexible systems can absorb more wind and the benefits in terms of reduction in output from conventional plant reduce. For the HF case however the reduction in wind curtailment due to the presence of storage is relatively small, as the system is highly flexible. For large storage capacity, a significant amount of reserve is provided by storage and the increased utilisation of storage will lead to an increase in energy produced by conventional plant necessary to charge storage.

However, note that although in the HF system supported by storage, more energy is produced by conventional plant (to cover losses in storage plant), the production cost is lower.

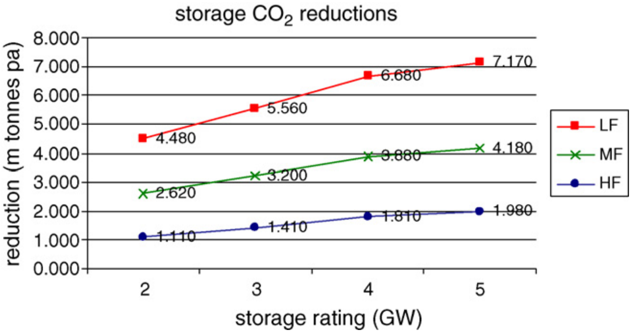

Fig. 4. Benefits of storage: reduction in $CO_2$ emissions.

For 5 GW of storage, the total amount of energy produced by conventional plant is increased by 219 GW per annum (Fig. 3), while simultaneously, the cost of production has reduced by £99 million per annum (Fig. 1), and the amount of $CO_2$ emitted is reduced by 1.9 million tonnes (Fig. 4). The system with storage can clearly run more efficiently, because storage, as a standing reserve provider, reduces the amount of part loaded plant.

## 6. Conclusions

The key factor found to affect the value of storage was the flexibility of the conventional generation mix. Other factors, such as the amount of storage installed, and wind capacity installed were also found to have potentially large impact on the value of storage. The impact of storage efficiency was also analysed in sensitivity studies and shown to have relatively small impact on the overall value of storage. The analysis suggests that in generation systems of limited flexibility and with significant penetration of wind generation the value of storage was found to be about £800 and 470 $kW^{-1}$ for the low and medium flexibility systems with 3 GW of storage installed.

We found that the application of storage for providing standing reserve could significantly reduce the amount of wind curtailed and reduce the amount of energy produced by conventional plant. This was particularly prominent in generating systems with limited flexibility. In the particular systems analysed, it was possible to reduce the amount of energy produced by conventional generation from 0.45 to 2.5 TWh, by applying storage. This could be interpreted as savings in wind energy curtailments. Consequently, by reducing wind generation curtailments, storage reduced the amount of $CO_2$ emitted in the generating systems with limited flexibility. In the particular systems analysed, these reductions were between 0.2 and 1.3 million tonnes per annum, depending on the system and the rating of storage facilities.

We conclude also that storage is unique compared to other plant providing standing reserve services, such as OCGT plant, because of its ability to store excesses in generation during periods of high wind and low demand, and subsequently make a part of this energy available (bearing in mind though that the ability of storage to provide this energy is limited by the amount of energy stored at the particular point in time that discharge is required) [4]. Generally, the value of storage based standing reserve is driven by the amount of wind installed and the flexibility of the generation system. The benefits are more significant in systems characterised by low flexibility generation and with large wind capacity installed.

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