

dti

**THE FUTURE VALUE OF
STORAGE IN THE UK
WITH GENERATOR
INTERMITTENCY**

CONTRACT NUMBER: DG/DTI/00040/00/00

URN NUMBER: 04/1877

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The Future Value of Storage in the UK with Generator Intermittency

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DG/DTI/00040/00/00
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Contractor

**MANCHESTER CENTRE FOR ELECTRICAL ENERGY
UMIST**

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Executive Summary

Although penetration of intermittent renewable resources and other forms of distributed generation by 2020 and beyond may displace significant amounts of energy produced by large conventional plant, concerns over system costs are focussed on the questions as to whether these new generation technologies will be able to replace the capacity and flexibility of conventional generating plant. Meeting a variable load with intermittent and uncontrolled generation (such as wind, wave and pv) will be a challenge for secure operation of the sustainable electricity systems of the future.

The purpose of this work was to provide magnitude of order estimates of the potential value of storage in managing intermittency of wind generation in the context of the future UK electricity system. In order to manage the balance between demand and supply under increased uncertainty due to penetration of wind generation, the system will need to hold increased amounts of reserve. This reserve will be generally supplied by a combination of synchronised reserve, provided by part-loaded generating plant and standing reserve, in the form of storage and/or flexible generation, such as OCGTs. In this context, OCGT technology is a prime competitor to storage.

In order for synchronised conventional 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%. Application of standing reserve would reduce the amount synchronised reserved committed. This has two positive effects: (i) an increase in efficiency of system operation by reducing the number of part loaded generators and (ii) an increase in the amount of wind power that can be absorbed as fewer generating units are scheduled to operate leaving more room for wind to supply demand, which is particularly relevant when high wind conditions coincide with low demand.

The inherent advantage of storage over OCGTs lies in its ability to exploit (store) excesses in generation during periods of high wind and low demand, and subsequently make a part of this energy available, and hence reduce the fuel cost and CO₂ emissions. The actual magnitude of this benefit will be primarily driven by the amount of wind installed and the flexibility of the generation system. In systems characterised by low flexibility generation and with large wind capacity installed, the benefits of storage based standing reserve over OCGT solution will be most significant.

In this work we evaluated the benefits of using storage for providing a part of the reserve needs in the form of standing reserve, against the reserve being provided by part loaded synchronised plant only (no standing reserve) and part of the reserve being provided by standing OCGT plant. The benefits were evaluated in terms of (i) savings in fuel cost associated with system balancing, (ii)

corresponding reduction in CO₂ emissions and (iii) indirectly, additional amount of wind energy that can be absorbed.

Assuming a system with 26 GW of wind capacity installed, producing about 80TWh per year, the key factor affecting the value of storage was found to be the flexibility of conventional generation mix. Other factors, such as amount of storage installed, cost of fuel of OCGTs, are found to have potentially significant impact on the value of storage. The impact of storage efficiency was also analysed and shown to have relatively modest impact.

Given the assumption that storage facilities will be capable of providing system backup, to cover the situations with failures of conventional plant (similar to OCGT technology), this work focuses on the additional benefits that storage can create when assisting with balancing task. It shown that the application of storage in managing intermittency in the operational time horizons will reduce fuel consumption and hence reduce corresponding fuel cost and CO₂ emissions. In this context, the additional value of storage that storage brings over and above that from OCGT was quantified.

Given the assumptions adopted, the analysis suggests that in generation systems of limited flexibility, with 3GW of storage installed, the additional value of storage, manifested through a reduction in fuel cost associated with balancing, was found to be between 470£/kW to 800£/kW (capitalised value of fuel cost reduction). However, the value of storage over OCGT plant, in such systems was found to be between 60£/kW and 120£/kW. Application of storage, rather than OCGTs, for providing standing reserve reduced energy produced by conventional plant (associated with system balancing) from 0.45TWh to 2.5TWh. This could be interpreted as an increase in wind generation that can be absorbed. Furthermore, application of storage reduced CO₂ emissions in the range of 0.2 and 1.3 million tonnes of CO₂ per annum, when compared with OCGT based standing reserve.

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1. Report summary

Background

- 1.1 Although penetration of intermittent renewable resources and other forms of distributed generation by 2020 and beyond may displace significant amounts of energy produced by large conventional plant, concerns over system costs are focussed on the questions as to 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. Clearly, meeting a variable load with intermittent, and/or uncontrolled and/or inflexible generation (such as wind, wave and pv) will be a challenge for secure operation of the sustainable electricity systems of the future.
- 1.2 The recently completed SCAR project¹ investigated a number of possible scenarios showing that extending renewable generation to 20% or 30% of demand by 2020 would increase system costs associated with integration of this generation in the UK power systems. The extent of the additional system costs was found to vary considerably, depending on the technology and location of renewable plant. An analysis of the breakdown of the total costs, between the three elements examined – balancing and capacity, transmission, and distribution, demonstrated that balancing and capacity costs, principally the cost of maintaining system security, dominate all other costs. These costs arise because of the intermittency of many renewable technologies, in particular wind, which represents a large proportion of Great Britain's (GB) renewable resource. Large-scale pumped storage was shown in the SCAR report to be beneficial but the question of its value was not specifically addressed.
- 1.3 Bulk energy storage systems 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 this work is to provide magnitude of order estimates of the potential value of storage in managing intermittency of wind generation in the context of the future UK electricity system². We studied a number of generation systems

¹ ILEX, UMIST, System Cost of Additional Renewables, study for DTI, October, 2002.

² In principle, this analysis applies to any form of storage that possesses assumed flexibility. Hence, the exact storage technology is not specified and could take any form, from dedicated large scale bulk storage facilities (such as pump-storage) to highly distributed smaller scale storage technologies.

characterised by different mixes of generation technologies, representative of the size of the GB system with some 26 GW³ of wind capacity installed.

Managing intermittency: synchronised and standing reserve

- 1.4 In order to deal with the increased uncertainty due to penetration of wind generation, the system will need to apply increased amounts of reserve. This will be generally provided by a combination of synchronised and standing reserve.
- 1.5 In order for synchronised conventional 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%. Since some of the generators will run part loaded to provide reserve (in case the output of wind generation reduces), some other units will need to be brought onto the system to supply energy that was originally allocated to the plant that is now running at reduced output. This usually means that plant with higher marginal cost will need to run, and this is another source of cost.
- 1.6 In addition to synchronised reserve, which is provided by part-loaded plant, the balancing task will also be supported by standing reserve, which is supplied by higher fuel cost plant, such as OCGTs and storage facilities.
- 1.7 Application of standing reserve could improve the system performance through reduction of the fuel cost associated with system balancing. This can be achieved by reducing the amount of synchronised reserved committed. This has two positive effects: (i) an increase in efficiency of system operation by reducing the number of part loaded generators and (ii) an increase in the amount of wind power that can be absorbed as fewer generating units are scheduled to operate, which is particularly relevant when high wind conditions coincide with low demand. Both of these effects lead to a reduction of the amount of fuel used. The cost of using OCGTs to provide standing reserve will be driven by their efficiency and fuel used while the cost of using energy storage facilities for this task will be influenced by their efficiency and the fuel cost of CCGT plant (used to charge the storage).
- 1.8 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. The balance between

³ This amount of wind capacity installed is expected to produce 80TWh of total electrical energy demanded.

synchronised and standing reserve could be optimised to achieve a minimum overall reserve cost of balancing.

- 1.9 The *value* of standing reserve (both storage and OCGT based) is quantified as the *difference* in the performance of the system (fuel cost and CO2 emissions) when system balancing is managed via synchronised reserve only, against the performance of the system with combined synchronous and standing reserves are used to balance the system.

Methodology

- 1.10 In contrast to SCAR, this analysis is not based on the high level statistical assessment of system operation based on an analytical (closed form) solution technique, but on a more detailed simulation of the operation of the system. We simulated, hour by hour, year round operation of the system (including 26 GW of wind capacity) taking into consideration daily and seasonal demand variations and variations in wind output. One of the key advantages of this approach is the ability to optimise more precisely the amount of synchronised reserve required (in each hour) as a function of wind output forecast and the amount of standing reserve available, while taking into account characteristics of generating plant and storage. This was shown to be an important advantage of the simulation approach over the analytical assessment employed in earlier studies, particularly in the context of the accuracy of quantified cost of operation and hence the value of storage.
- 1.11 This analysis is concerned with the evaluation of additional fuel costs associated with balancing the system with considerable contribution of intermittent generation and it does not deal with market arrangements and mechanisms for cost recovery (e.g. value of storage in short term energy markets with dual cash out price, such as NETA, capacity payments etc, are not part of this work). It is important to stress that this analysis excludes purposely the assessment of the value of arbitrage activities and the application of flexible storage in managing TV pickups and focuses only on the question of additional fuel cost associated with system balancing.

Generation systems considered

- 1.12 This analysis demonstrated that one of the key factors determining the additional value of storage when involved in system balancing is the flexibility of conventional generation mix. We have therefore 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 role⁴. The characteristics of the systems studied are presented in Table 1.1.

- 1.13 The so-called base load segment of the generation mix considered generally consists of inflexible plant that runs at full output and cannot be turned on and off frequently (such as nuclear). We have also incorporated a segment of the generation mix that includes plant that is moderately flexible, that can be turned on and off but with somewhat limited ability to run part loaded (with relatively high minimum stable generation) and a segment of relatively flexible plant.

Table 1.1 Characteristics of generation systems considered

Generation System	Parameters	Inflexible Generation	Generation of moderate flexibility	Flexible Generation
Low Flexibility (LF) Generation System	MSG ⁵	100%	77%	50%
	Capacity installed	8.4GW	26GW	>25.6GW
Medium Flexibility (MF) Generation System	MSG	100%	62%	50%
	Capacity installed	8.4GW	26GW	>25.6GW
High Flexibility (HF) Generation System	MSG	N/A	N/A	45%
	Capacity installed	0 GW	0GW	>60GW

- 1.14 In the subsequent analysis we will assume that the amount of conventional plant on the system is adequate for supplying the demand while maintaining the historical levels of security (24% capacity margin). Hence, given a specific generation system, both capital cost of the generation system and the corresponding fuel cost associated with meeting the demand are specified. In addition to these capital and fuel cost associated with supplying the demand, there will be *additional fuel* costs associated to *balancing* of the system in real time. These costs are effectively fuel cost associated with holding and exercising reserve necessary to manage fluctuations of demand and generation.
- 1.15 As OCGT technology, we assume that storage would be used to provide some of the *system backup* (capacity margin) in situations with failures of conventional plant, particularly when coincide with low wind outputs. In addition to this capacity oriented function, storage will be used to assist with the balancing task, which is the subject of this work. In the context of this additional fuel cost incurred in the balancing task, the application of

⁴ Ramp rates were not found to be particularly important, as long as the maximum rate of change of output of plant that provides synchronised reserve was above 5MW/min, which is well within existing gas and coal technologies.

⁵ MSG stands for Minimum Stable Generation and is expressed as percentage of the maximum generator capacity

storage versus OCGT is examined and the value of storage over and above OCGT estimated.

Additional value of storage when providing standing reserve

- 1.16 In this analysis we concentrate on this *additional* value that storage creates when used for *balancing*, in addition to providing system backup.
- 1.17 The additional value created by storage is a result of reduced of fuel consumption associated with balancing. This reduced fuel consumption leads to reduce fuel cost and reduced CO2 emissions. This additional value is the largest in systems with generators of low flexibility (LF) and reduces as the flexibility of generation mix improves.
- 1.18 The additional value of storage when providing standing reserve for the balancing task is calculated by evaluating the *difference* in the performance of the system (fuel cost and CO2 emissions) when balancing is managed via synchronised reserve only, against the performance of the system with storage facilities used to provide standing reserve. The annual reduction of fuel balancing cost obtained from the application of storage is shown in Figure 1.1.

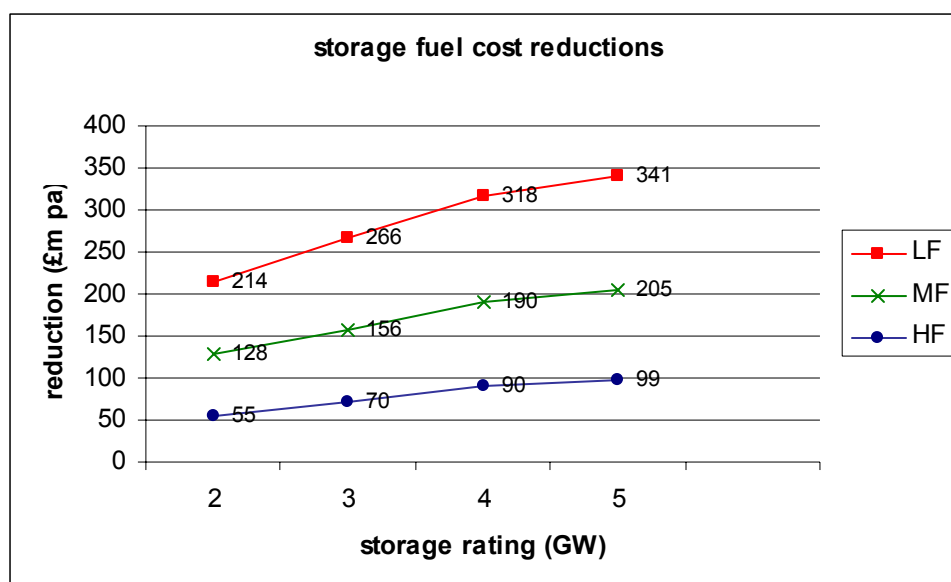


Figure 1.1 Reduction of fuel cost (balancing cost) with energy storage

- 1.19 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 is shown in Figure 1.2 that presents the *capitalised value of reduced fuel cost* as a function of the amount of installed capacity of storage. As expected the value of storage is higher in systems with less flexible generation and reduces with the increase in storage capacity installed.
- 1.20 These values present the additional value created by storage through assisting in the balancing task. The values in Figure 1.2 represent the net benefit that corresponds to fuel cost savings achieved by using storage in the balancing task, rather than balancing the system through part loaded synchronised plant only. This additional value is the largest in systems with generators of low flexibility (LF) and reduces as the flexibility of generation mix improves.

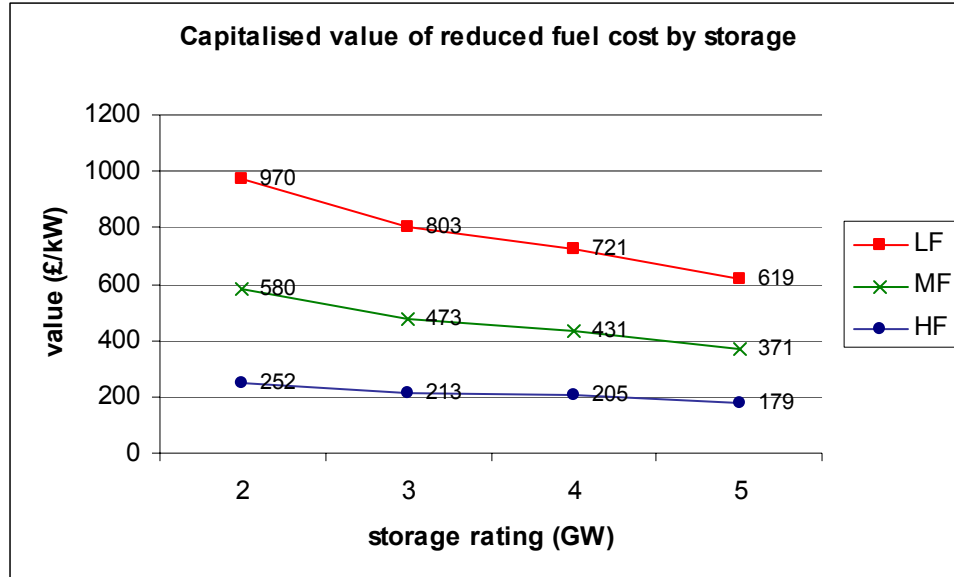


Figure 1.2 Capitalised value of reduction of fuel cost with energy storage

Value of OCGT plant when providing standing reserve

- 1.21 Standing reserve can also be provided by conventional flexible plant. In this context OCGT technology can be considered as a principal competitor to

storage⁶. We have therefore quantified the additional value of this type of standing reserve when applied to assist with system balancing. This was carried out for generation systems of various levels of flexibility. Savings in fuel cost associated with balancing cost when applying OCGT plant to supply reserve are presented in the form of capitalised cost as shown in Figure 1.3, assuming that cost of fuel used by OCGTs is 50£/MWh.

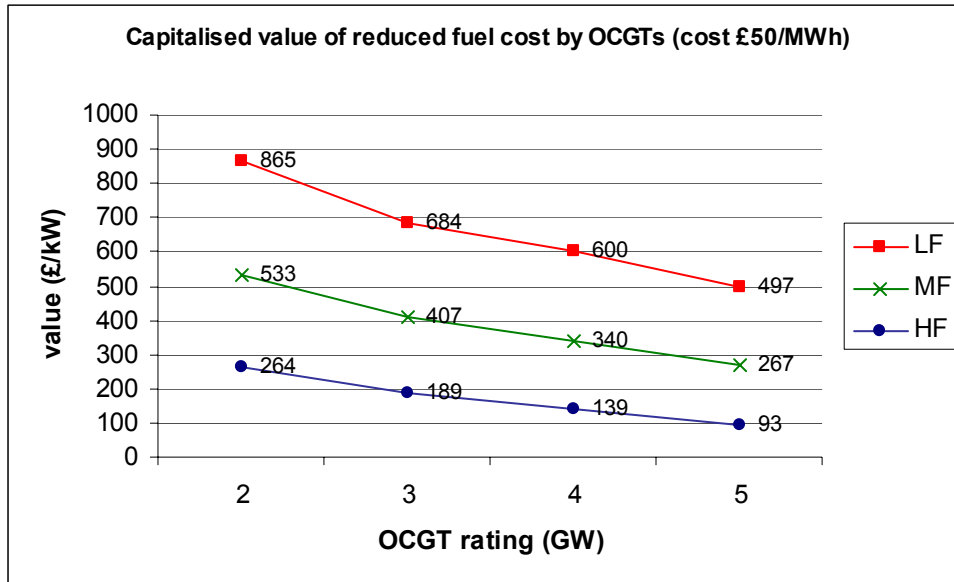


Figure 1.3 Capitalised value of reduction of fuel cost with OCGTs

Storage versus OCGT

- 1.22 By subtracting the values in Figures 1.3 from the corresponding values in Figure 1.2 we can assess the comparative advantage of using storage over OCGT plant for providing standing reserve. This is shown in Figure 1.4. The values in the figure present the *additional capital expenditure* that could be spent on storage over and above that of OCGTs. Consider for example, a case of 3GW of standing reserve employed in system balancing in a medium flexibility (MF) generation system. If the investment cost of storage facilities is greater than the cost of OCGT technology for less than 66£/kW, it would be worthwhile to install storage rather than OCGTs.

⁶ In this analysis we assume that storage facilities and OCGT plant have similar flexibility and reliability characteristics.

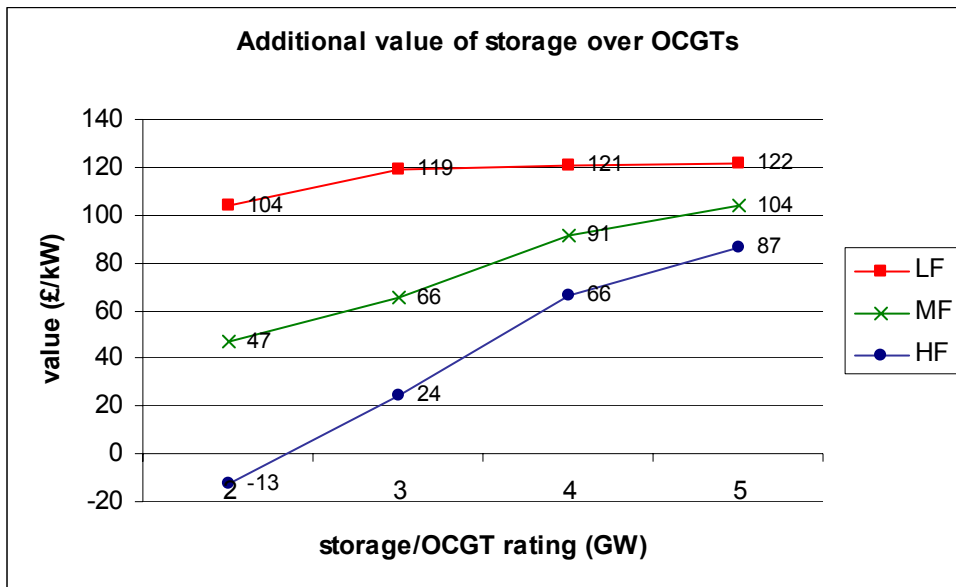


Figure 1.4 Additional value of storage over OCGT plant when providing standing reserve

1.23 In the majority of situations storage is more valuable than OCGT plant when providing standing reserve, particularly in low and medium flexibility systems (given the assumptions associated with input data)⁷. The three following factors will determine the relative competitiveness of storage and OCGT based standing reserves

- (i) The *inherent advantage* of storage over OCGTs lies in its ability to exploit (store) excesses in generation during periods of high wind and low demand, and subsequently make a part of this energy available, and hence reduce the fuel cost. Storage can provide both upward (“positive”) and downward (“negative”) reserve (while an OCGT plant can provide only upward regulation). Clearly, in the case that generation is lower than demand, we discharge storage, while in the case that demand is lower than generation we charge storage to balance the system. The ability of storage to provide this “negative” reserve will be of critical importance when low demand conditions coincide with a high level of output of wind generation (of course, some of the energy stored will be lost). The actual magnitude of this inherent benefit will be driven by the amount of wind installed and the flexibility of the generation system. In systems characterised by low flexibility generation and with large wind capacity installed, the benefits of storage based standing reserve over OCGT solution will be most significant.
- (ii) The *inherent disadvantage* of storage against OCGTs is that the amount of spinning reserve required in systems with storage providing standing reserve will always be greater than in systems

⁷ The only exception is the high flexibility case with 2 GW standing reserve use in the form storage or OCGT

with OCGTs providing standing reserve (assuming the same capacity employed for system balancing and the same reliability performance of both technologies). Clearly, when the system net demand to be met by synchronised plant exceeds the capacity of the synchronised plant running at that particular instant, OCGTs will be able to provide the support equal to their installed capacity, while the ability of storage to provide this output will be limited by the amount of energy stored at that particular point in time (and this will depend on the operation regime of storage facility in the periods before this discharge was required).

- (iii) The cost of running storage will be driven by its efficiency and the cost of CCGT generation, while the cost of running OCGTs will depend on fuel used and the efficiency of the technology employed. In this study, we adopted the marginal cost of CCGT plant to be 20£/MWh, assumed storage efficiency of 70%, against operating cost of OCGT assumed at 50£/MWh.

- 1.24 The overall effect of the above factors on the relative performance of storage against OCGT plant will be system specific and will depend on the amount of standing reserve utilised. Clearly, the impact of (i) will depend on the amount of wind installed and the flexibility of the generation system, while the importance of (iii) will be increasing with the increase in utilisation of standing reserve. In order to investigate the impact of these factors on the value of storage we have carried out a number of sensitivity studies analysing the impact of penetration of wind generation, efficiency of storage and OCGT fuel cost.

CO2 reductions – storage versus OCGT

- 1.25 In the context of the analysis of alternatives for balancing, it is important to consider the impact on CO2 emissions. As indicated above
- (i) In contrast to OCGT based standing reserve provision, the advantage of storage lies in its ability to exploit surpluses in generation during periods of high wind and low demand, and hence reduce fuel consumption and CO2 emissions; we assumed a CO2 emissions level of 0.4tonnes/MWh for CCGT plant when operated fully loaded.
 - (ii) Both storage and OCGT plant will reduce the need for spinning reserve provided by part-loaded plant, and hence reduce CO2 emissions as a result of higher efficiency of the system operation.
 - (iii) OCGTs, when used, will contribute to an increase in CO2 emissions and the level will depend on the efficiency of OCGT

plant and the actual fuel used. In this study we assumed a CO₂ emissions level of 0.6tonnes/MWh for OCGTs. The overall amount of CO₂ emissions produced by OCGTs will be directly proportional to their utilisation.

- 1.26 Again, the overall effect of using storage versus OCGT based standing reserve on CO₂ emissions will be system specific. We have compared the reductions in CO₂ emissions in different systems with storage and OCGTs providing standing reserve and the benefits of using storage over OCGTs are presented in Figure 1.5.
- 1.27 As expected, the comparative advantage of storage over OCGT plant in the context of reducing CO₂ emissions is most prominent in the low flexibility system and increases with the amount of storage installed.
- 1.28 Given the assumptions regarding the input data, we observe that storage will contribute more to CO₂ reductions than the application of OCGT plant in the majority of cases studied.

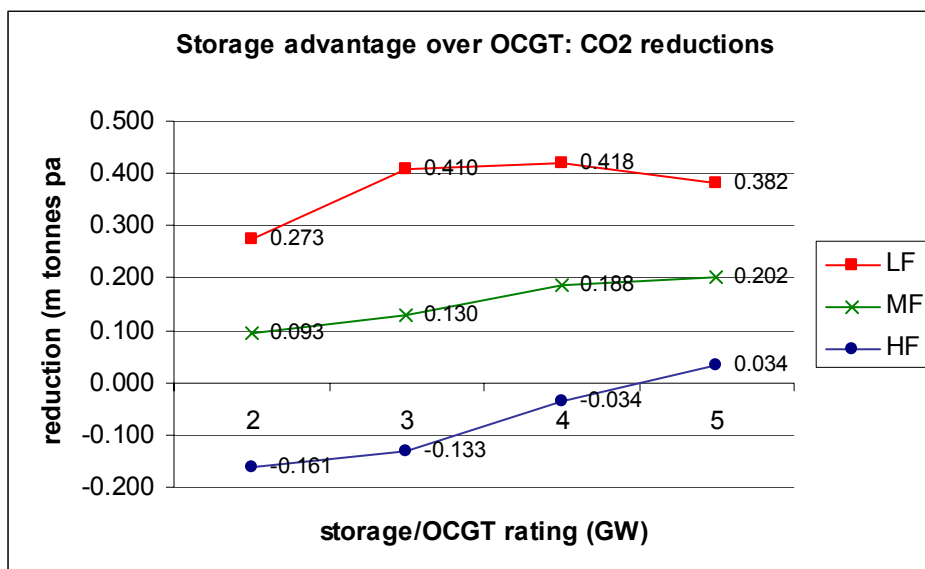


Figure 1.5 Benefits in reduction of annual CO₂ emissions of using storage rather than OCGT plant when providing standing reserve

- 1.29 For example, for the capacity of standing reserve of 3GW, in a medium flexibility system, using storage to provide standing reserve would generate 0.130million tonnes less CO₂ than the same system with OCGT plant providing standing reserve. To put this into context, this amount of emissions would be generated by a CCGT plant of 500MW capacity running at full output for more than 650 hours (27 days) per year and producing 325 GWh of energy.

1.30 Reductions in CO2 emitted could be used to measure the contribution that storage technology can make in the context of the Government’s targets.

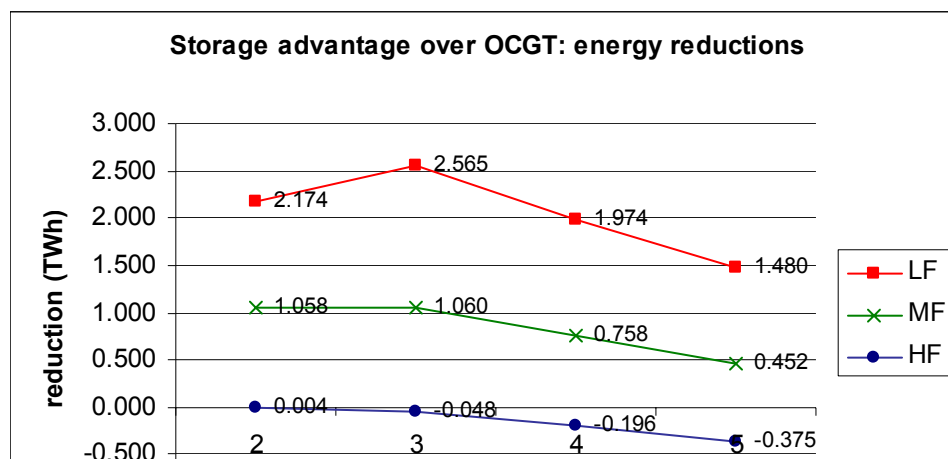
Wind energy saved and energy produced by conventional plant– storage versus OCGT

1.31 By applying storage or OCGT plant to provide standing reserve, the amount of synchronised reserved committed can be reduced and this will lead 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 the amount of wind that has to be rejected when high wind conditions coincide with low demand will be reduced. Any remaining surplus of wind could be partly or fully absorbed by charging the storage facilities. On the other hand, clearly, if standing reserve is provided by OCGT plant, this surplus of wind generation would be wasted. One of the results of the evaluation is the amount of wind that needs to be *curtailed* in order to maintain a stable operation of the system. We can hence quantify the savings in wind energy curtailed by using storage.

1.32 However, the value of wind saved (or curtailed) should not be used to directly measure the benefits of storage. This is because the storage efficiency will be a key factor here. At the extreme, 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 will be actually saved due to low efficiency of storage plant.

1.33 Therefore, we quantify instead the amount of energy produced by conventional generation and measure the benefits of storage and OCGT plant in terms of reducing this quantity. Clearly, the amount of energy produced by conventional plant can be used as a direct measure of the net effect of wind energy saved, as this already includes storage efficiency losses.

1.34 Application of storage and OCGT plant for providing reserve has the potential to reduce the amount of energy produced by conventional plant by increasing utilisation of wind power. The benefits of storage in reducing the energy produced by conventional over OCGT based standing reserve is shown in Figure 1.6



*Figure 1.6 Reducing energy produced by conventional plant:
benefits of storage in over OCGTs*

- 1.35 We observe that the application of storage will reduce significantly the total output of conventional plant for low and medium flexibility generation systems. For a system with 3GW of installed storage capacity, the energy output from conventional plant will reduce by 2.56TWh (in the LF case) and 1.06TWh (in the MF case) in comparison with the system in which standing reserve is provided by OCGT plant.
- 1.36 We could interpret this energy reduction as wind energy saved, given that the net effects are the same. Clearly, the total energy produced by conventional plant plus wind energy absorbed, equals demand plus losses in storage. Hence, we could say that additional 2.56 TWh (in the LF case) and 1.06 TWh (in the MF case) of wind energy will be absorbed (saved) in the system with storage providing standing reserve than in the system with OCGT providing it.
- 1.37 If we consider the HF system with 5 GW of storage or OCGT, we observe that the amount of energy produced by conventional plant is higher in the system with storage than in the system with OCGT plant providing standing reserve. A close inspection of the systems would reveal that the amount of wind curtailed is low, irrespective of whether storage or OCGT plant is used to provide standing reserve. Given that the utilisation of standing reserve in both cases is significant (as the amount of synchronised reserve is reduced) and given 70% efficiency, the conventional plant will need to produce more energy in the system with storage than in systems with OCGTs.
- 1.38 The increase in energy produced by conventional plant in the system with storage is not necessarily a consequence of wind curtailed but may be driven by the need to use storage as a standing plant. This application requires storage to be charged (and discharged), and hence it leads to losses of energy. From the energy balance perspective, this increase in the production of energy from conventional plant, could be interpreted as wind energy curtailed.

1.39 It is interesting to observe that for the high flexibility (HF) system a storage system of 5GW outperforms an OCGT based solution by 0.034 million tonnes of CO₂ per annum but underperforms it in terms of the reduction of the output of conventional plant. Note that for 5GW of standing reserve the amount of spinning reserve used is relatively small, so that both systems can absorb similar amounts of wind generation. However, the amount of electrical energy produced by OCGTs is smaller than that used to charge the storage (as storage is 70% efficient). On the other hand, OCGTs emit more CO₂ given that CCGTs are effectively used to charge the storage.

Sensitivity assessment

(i) *Impact of storage efficiency*

1.40 The key factor affecting the value of storage is found to be the flexibility of conventional generation mix (together with the amount of storage capacity present) and these are explicitly considered in all studies performed. The impact of other factors such as efficiency of storage, wind capacity installed and cost of fuel of OCGTs, is investigated within a specific sensitivity analysis task.

1.41 The impact of increasing efficiency of storage from 70% to 80% on its competitiveness over OCGT plant is shown in Figure 1.7, assuming 3GW of standing reserve used in system balancing (in the form of storage or OCGT).

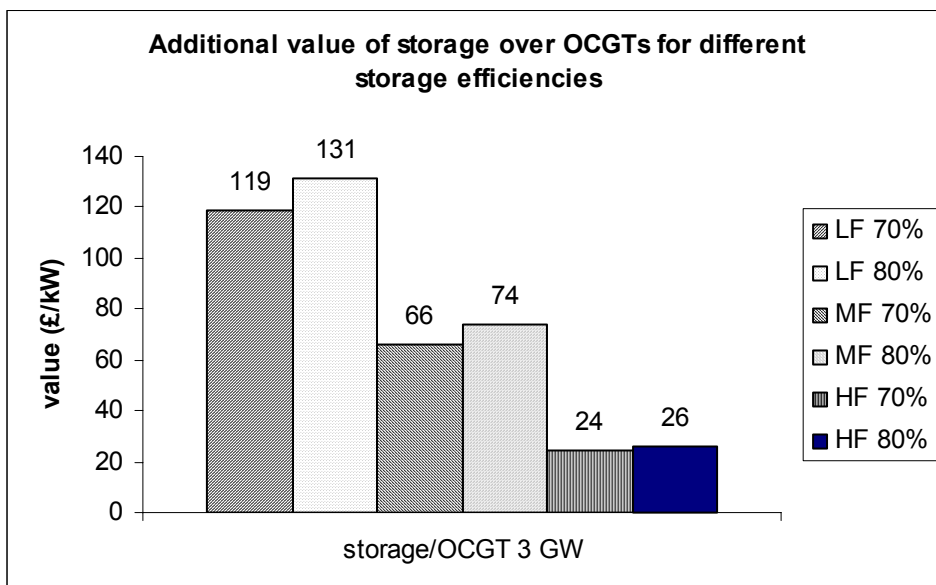


Figure 1.7 Impact of storage efficiency on its competitiveness over OCGT plant

1.42 We observe that increasing efficiency of storage from 70% to 80% will increase its competitiveness over OCGTs for about 10% across the three systems.

(ii) Impact of wind penetration

1.43 We have analysed the value of storage for increased wind capacity of 30GW. This is shown in Figure 1.8. We can observe that the relative value of storage increases in low and medium flexibility systems.

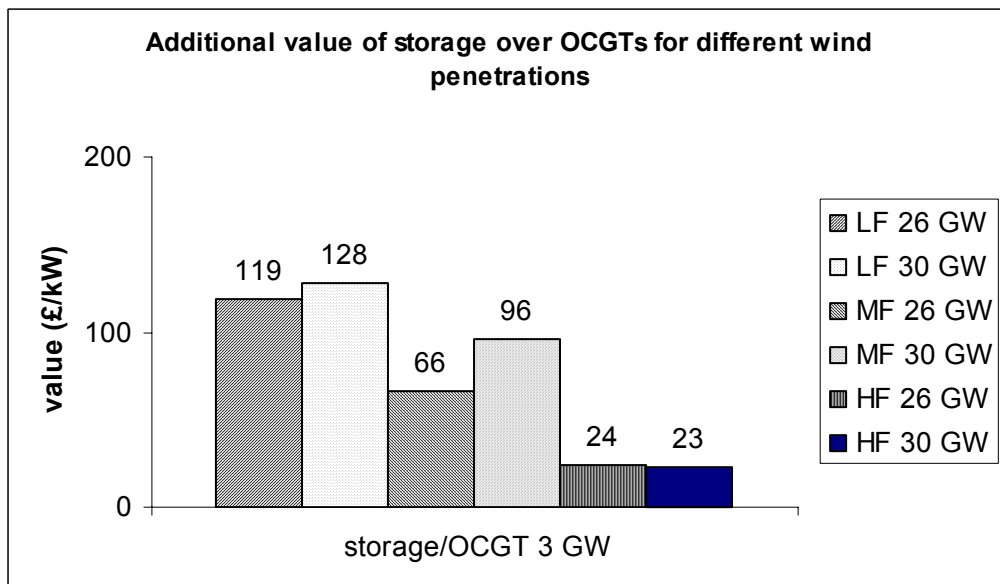


Figure 1.8 Impact of wind capacity installed on competitiveness of storage over OCGT plant

(iii) Impact of OCGT fuel cost

1.44 The impact of fuel cost of OCGTs has been found to have a significant impact on the value of storage. The full set of case studies was performed for fuel cost of OCGTs being 100£/MWh.

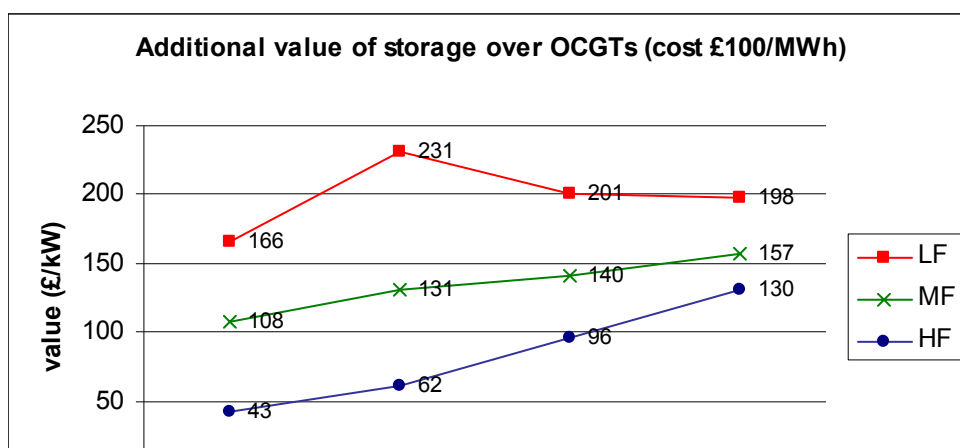


Figure 1.9 Impact of OCGT fuel cost on competitiveness of storage over OCGT plant

Conclusions

- 1.45 In this report the additional value of storage has been analysed in a GB like generation system with 26 GW of wind capacity installed. Storage is being used to manage intermittency: to reduce the cost of system balancing and increase the amount of wind power that can be absorbed, and hence increase the overall efficiency of the system operation and reduce CO2 emissions.
- 1.46 The prime competitor of storage technologies is OCGT generating plant and the relative competitiveness of these two technologies is assessed by evaluating performance of various systems with storage and with OCGT plant providing standing reserve.
- 1.47 The key factors affecting the value of storage in such system are found to be the flexibility of conventional generation mix. Other factors, such as amount of storage installed, wind capacity installed, cost of fuel of OCGTs, are found to have potentially significant impact on the value of storage. The impact of storage efficiency is also analysed and shown to have relatively smaller impact on the overall value of storage.
- 1.48 The analysis suggests that in generation systems of limited flexibility and with significant penetration of wind generation the additional value of storage was found to be about 800£/kW and 470£/kW for the low and medium flexibility systems with 3GW of storage installed. However, the additional value of storage over OCGT plant, was found to be 120£/kW and 66£/kW respectively.
- 1.49 Application of storage, rather than OCGTs, for providing standing reserve could significantly reduce the amount of wind curtailed and reduce the amount of energy produced by conventional plant. This will be 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 0.45TWh to 2.5TWh, by applying storage. This could be interpreted as savings in wind energy curtailments.

- 1.50 Consequently, by reducing wind generation curtailments, storage will reduce the amount of CO₂ emitted. This will be the case in 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.

2. Intermittency and balancing

- 2.1 Renewable and other low carbon energy sources will have to become a major part of the future UK electricity generation system if a significant reduction in CO₂ emission is to be achieved. Although penetration of intermittent renewable resources and other forms of distributed generation by 2020 and beyond may displace significant amounts of energy produced by large conventional plant, as described in the Energy White Paper, concerns over system costs are 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.
- 2.2 The total capacity of installed generation must be larger than the system maximum demand to ensure the security of supply in the face of variations in demand due to adverse weather, generation breakdowns and interruptions to primary fuel sources. The former Central Electricity Generating Board (CEGB), while planning their generation system, employed a generation security standard that required that demand disconnections were expected to occur in not more than “9 winters in hundred years”, or that the probability of peak demand exceeding available generation should not be greater than the 9%. This required about 24% plant margin⁸.
- 2.3 One interesting question is to examine the contribution that intermittent generation can make to system security or, in other words, to examine the amount of capacity of conventional plant that can be displaced by intermittent renewables whilst maintaining the same degree of security. In the SCAR study, such an analysis was carried out and the results are summarised here. The intermittent behaviour of wind was statistically assessed from the frequency distribution of GB wind generation, based on a sample of historic wind generation data. The behaviour of conventional units and wind generation were then statistically combined, enabling the risk of peak demand exceeding available generation to be assessed. This analysis was then employed to calculate the minimum capacity of conventional generation necessary to ensure that the risk of loss of supply is not greater than the 9% in the combined conventional and wind generation system.
- 2.4 We found that for a GB peak demand of between 57GW and 62GW, between 70.5 - 77.5 GW of conventional capacity will be required to supply demand at the required level of security (13 GW to 15.5 GW of backup capacity). By installing 26 GW of wind capacity the amount of conventional plant required could be reduced only by about 5GW. As a result, load factors of conventional plant will be reduced. It is expected that the average load

⁸ The current electricity market arrangements do not contain a statutory or formal generation security standard that would define the required capacity margin for a particular mix of generation types.

factors for the conventional generation will be reduced from 50% (with no wind) to about 40% (with 26GW of wind).

- 2.5 Further analysis, based on the assumption of a generic system composed of units of 500MW and a notional merit order, was carried out to determine the utilisation of individual plant in both of these two situations. This analysis demonstrated that the amount of conventional generation operating at load factors below 10% would increase from about 15GW (no wind) to about 20GW with (26GW of wind). Given the relative capital and fuel costs of various generation technologies, the majority of very low load factor plant in both systems (with and without wind) would probably be OCGT⁹.
- 2.6 One of the key issues in this context is the question of the ability of storage technologies to provide required backup, similar to that provided by OCGT. An analysis of frequency and duration of various possible deficits caused by plant failures¹⁰ shows that shortages that matter will be relatively modest, up to several GW. Furthermore, the expected duration of outages was found to be rather small, up to a few hours, decreasing with the increase in penetration of wind generation. This is clearly very promising for the application of energy storage in providing some of the backup capacity given that the size of shortage, both power and energy is relatively modest. From this we conclude that conventional bulk storage technologies and their modern equivalents could provide backup of the similar quality as conventional plant such as OCGT. The choice between OCGT and storage, in the context of the backup function, will be primarily driven by the capital cost of respective technologies.
- 2.7 In the subsequent analysis we will assume that the required amount of conventional plant is installed in order to supply the demand while maintaining the historical levels of security. Hence, given a specific generation system, both capital cost of the generation system and the fuel cost associated with meeting the demand can be calculated. In addition to these costs, there will be *additional fuel* costs attributable to *balancing* of the system. These costs are composed of fuel cost associated with holding and exercising reserve necessary to manage fluctuations of demand and generation. These three major cost components are schematically presented in Figure 2.1.
- 2.8 These additional balancing costs are the subject of this study. In the context of this additional fuel cost incurred in the balancing task, the application of storage versus OCGT is examined and the value of storage over and above OCGT estimated.

⁹ In practice, of course, NETA (or a successor market arrangement) may deliver a very different plant mix.

¹⁰ G Strbac, A Shakoor, M Black, "Integration of Large Scale Intermittent Renewable Generation in Electricity System: What is the Role of Energy Storage?", Institute of Mechanical Engineers, Conference on Storage of Renewable Energy Strategies & Technologies to meet the challenge.

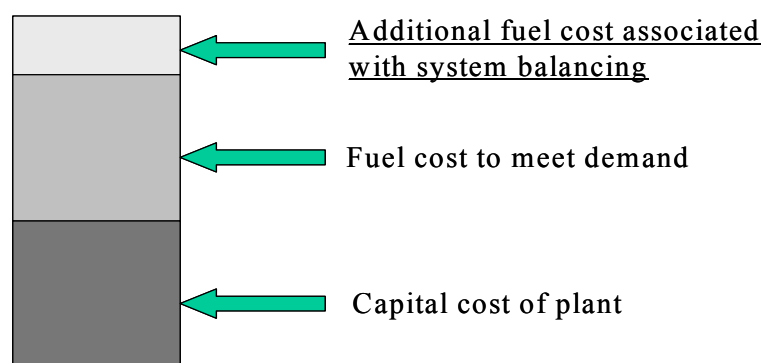


Figure 2.1 Three cost components of a generation system: this study quantifies the benefits that storage and OCGT plant can create by reducing the additional fuel cost incurred by balancing task.

- 2.9 Meeting a variable load with intermittent, and/or uncontrolled and/or inflexible generation (such as wind, wave and pv) will be a challenge for secure operation of the sustainable electricity systems of the future. Furthermore, the location of these new sources will be of considerable importance in assessing the impacts on the transmission network. Potentially, operational problems would arise from two principal causes, namely, the intermittent nature of the outputs of new generation (such as renewable generation) and the location and remoteness of this generation relative to centres of demand. In this work the application of storage is limited to dealing with system balancing, while the application to transmission and distribution network congestion management is beyond of the scope of this work.
- 2.10 As the amount of wind generation on an electricity network increases, and the uncertainties in wind output start to become evident some extra balancing costs will be incurred. This will require extra resources for frequency regulation to be scheduled and utilised. As discussed in the SCAR report, the amount of additional resource required to manage unscheduled wind generation will not be on a 'megawatt for megawatt' basis. The key factor here is the 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.
- 2.11 The magnitude of changes in wind output will strongly depend on the time horizon considered. Statistical analysis of 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 2.1 presents the standard deviations of wind output for a system with 26GW of installed wind generation capacity for time horizons from half hour to 4 hours. 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.

- 2.12 For the time scales from several seconds to a few minute time spans, the fluctuation of the overall output of wind generation will be small, given the considerable diversity in outputs of individual wind farms. In these very short time scales, the dominant variability factor is the potential loss of conventional plant, rather than fluctuations in wind power. Given that this work is concerned with the application of storage in the context of wind penetration, response requirements are not explicitly modelled. Furthermore, since the focus of the analysis is on comparing the benefits of various reserve policies, such detailed modelling would not be relevant.

Table 2.1 Characterising fluctuation of wind output for 26GW of installed capacity of wind generation

Lead Time [Hours]	Standard Deviation [MW]	Likely maximum change [MW]	Extreme change [MW]
0.5	360	1,090 – 1,450	2,600
1	700	2,100 – 2,800	3,950
2	1,350	4,050 – 5,400	6,550
4	2,400	7,200 – 9,650	13,500

- 2.13 For examining extreme variations in wind generation outputs the largest changes in wind output are analysed¹¹. For 26 GW installed capacity of wind, the single most extreme changes observed in the model data are given in Table 2.1 and as expected, these variations in wind output will increase with the time horizon considered¹². 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.
- 2.14 It is important to bear in mind that balancing requirements are not assigned to back up a particular plant type (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.

¹¹ This is based on the analysis of annual model wind output profile and modelling assumptions adopted in SCAR.

¹² The analysis of extreme fluctuations in wind output model data covering one year is used.

- 2.15 Given the prediction that the mix of conventional plant post 2020 is likely to be dominated by gas, the fluctuations in time horizons larger than 3-4 hours are assumed to be managed by starting up additional units, which should be within dynamic capabilities of modern gas fired technologies.
- 2.16 The predictability of wind variations for managing the demand and generation balance is important. Clearly, 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. For short-term forecasts, up to several hours ahead, persistence-based techniques are generally used, while for longer horizons, forecasts based on meteorological information will considerably reduce wind forecast error and outperform persistence techniques. There is considerable activity in this area and further improvements in the accuracy of wind prediction are expected.

3. Managing intermittency: synchronised and standing reserves

- 3.1 Traditionally, conventional generating plant is used for balancing purposes. In order for synchronised plant to provide reserve (and response) 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. Since some of the generating units will be part-loaded to provide the balancing service, other units will need to be brought on the system to supply energy that was originally allocated to flexible plant. This usually means that plant with higher marginal cost will need to run, and this is another source of the cost associated with balancing.
- 3.2 The consequence of carrying large amount of spinning reserve, would be that significant number of generators would need to run (part loaded CCGT plant) reducing the amount of wind generation that can be absorbed, particularly when low demand conditions coincide with high wind power conditions.
- 3.3 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.
- 3.4 Application of standing reserve could improve the system performance through reduction of the fuel cost associated with system balancing. This reduction in the amount of synchronised reserved 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.
- 3.5 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. The cost of using energy storage facilities for this task will be influenced by their efficiency. The balance between synchronised and standing reserve could be optimised to achieve a minimum overall reserve cost of system management.
- 3.6 For balancing load and generation synchronised and standing reserve are used as follows. Synchronised reserve will be used to accommodate relatively frequent but comparatively small imbalances between generation and demand while standing reserve will be used for absorbing less frequent but relatively large imbalances. This is illustrated in Figure 3.1.

Reserve allocation

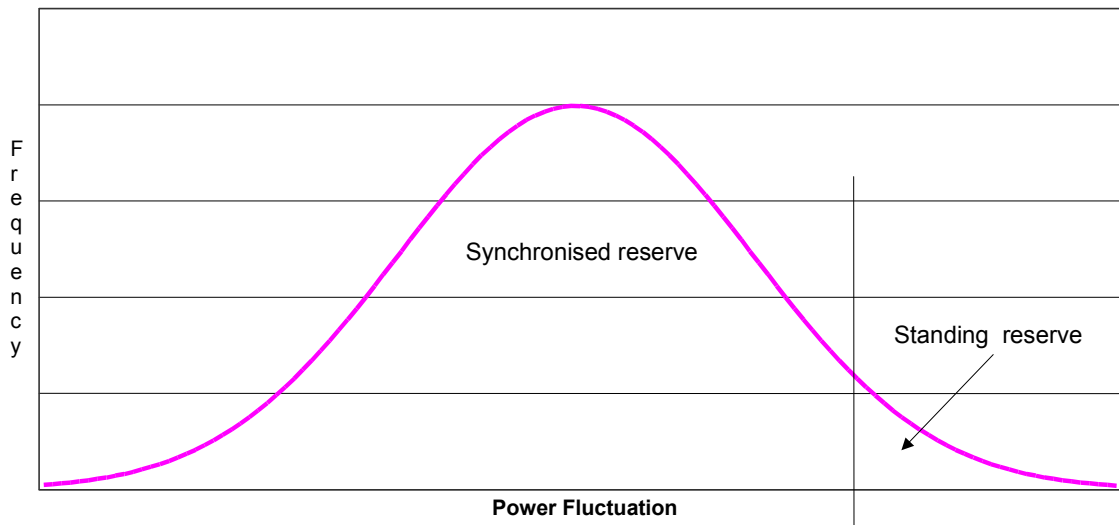


Figure 3.1 Allocation of reserve between synchronised and standing

- 3.7 The value of standing reserve (both storage and OCGT based) will be quantified as the *difference* in performance of the system (fuel cost and CO2 emissions) when intermittency is managed via synchronised reserve only, against the performance of the system with standing reserve.
- 3.8 Note that storage can provide both upward (“positive”) and downward (“negative”) reserve

4. Benefits of storage over OCGT based standing reserve

4.1 Standing reserve can be provided by storage or conventional flexible plant. In this context OCGT technology is the prime competitor to storage technologies¹³.

4.2 The three following factors will determine the relative competitiveness of storage and OCGT based standing reserves.

- (iv) The *inherent advantage* of storage over OCGTs lies in its ability to exploit (store) excesses in generation during periods of high wind and low demand, and subsequently make a part of this energy available, and hence reduce the fuel cost. Storage can provide both upward (“positive”) and downward (“negative”) reserve (while an OCGT plant can provide only upward regulation). Clearly, in the case that generation is lower than demand, we discharge storage, while in the case that demand is lower than generation we charge storage to balance the system. The ability of storage to provide this “negative” reserve will be of critical importance when low demand conditions coincide with a high level of output of wind generation (of course, some of the energy stored will be lost). The actual magnitude of this inherent benefit will be driven by the amount of wind installed and the flexibility of the generation system. In systems characterised by low flexibility generation and with large wind capacity installed, the benefits of storage based standing reserve over an OCGT solution will be most significant.
- (v) The *inherent disadvantage* of storage against OCGTs is that the amount of spinning reserve required in systems with storage providing standing reserve will always be greater than in systems with OCGTs providing standing reserve (assuming the same capacity installed and the same reliability of both technologies). Clearly, when the system net demand to be met by synchronised plant exceeds the capacity of the synchronised plant running at that particular instant, OCGTs will be able to provide the support equal to their installed capacity, while the ability of storage to provide this output will be limited by the amount of energy stored at that particular point in time (and this will depend on the operation regime of storage facility in the periods before this discharge was required).

¹³ In this analysis we assume that storage facilities and OCGT plant have similar flexibility and reliability characteristics.

(vi) The cost of running storage will be driven by its efficiency and the cost of CCGT generation, while the cost of running OCGTs will depend on fuel used and the efficiency of the technology employed. In this study, we adopted the marginal cost of CCGT plant to be 20£/MWh, assumed storage efficiency of 70%, against operating cost of OCGT assumed at 50£/MWh.

4.3 The overall effect of the above factors on the relative performance of storage against OCGT plant will be system specific and will depend on the amount of standing reserve utilised. Clearly, the impact of (i) will depend on the amount of wind installed and the flexibility of the generation system, while the importance of (iii) will be increasing with the increase in utilisation of standing reserve. In order to investigate the impact of these factors on the value of storage we have carried out a number of sensitivity studies analysing the impact of penetration of wind generation, efficiency of storage and OCGT fuel cost.

4.4 The overall effect of the above factors on the performance of storage will be system specific and will depend on the amount of standing reserve utilised. Clearly, the impact of (i) will depend on the amount of wind installed and the flexibility of the generation system, while the importance of (iii) will be increasing with the increase in utilisation of standing reserve. In order to form a view regarding the overall impact of these factors we have carried out sensitivity studies analysing the impact of penetration of wind generation, efficiency of storage and OCGT fuel cost.

5. Key inputs and assumptions¹⁴

Generation systems

- 5.1 In addition to the question of loss of efficiency of running part loaded plant when it provides reserve, a key factor for determining the value of storage in this context will be the flexibility of conventional plant.
- 5.2 We have therefore studied the behaviour of three generating systems of 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. On the other hand, ramp rates were not found to be particularly important, as long as the maximum rate of change of output of plant that provides synchronised reserve was above 5MW/min, which is well within existing gas and coal technologies. The characteristics of the systems studied are presented in Table 5.1.
- 5.3 The so-called base load segment of the generation mix considered consists of generally inflexible plant that runs at full output and cannot be turned on and off frequently (such as nuclear). We have also incorporated a segment of the generation mix that includes plant that is only moderately flexible, that can be turned on and off but with somewhat limited ability to run part loaded, i.e. with relatively high minimum stable generation, and a segment of very flexible plant.
- 5.4 Due to its inability to substantially reduce the output from synchronised conventional generation, the low flexibility system will not be able to absorb the entire production of wind generation and the excess of wind power will be wasted if some form of storage is not used.
- 5.5. We have assumed the fuel cost of moderately flexible and flexible generation to be 20£/MWh. The cost of inflexible generation has no impact on the value of storage given that it must run in both systems with and without storage.
- 5.6. The drop in efficiency when running at 50% of the maximum output is taken to be on average 16%. The efficiency at any other output level is calculated by assuming the efficiency drops linearly between the maximum and the minimum output. Although the drop in efficiency is nonlinear this assumption is found to be acceptable given that the vast majority of generators would run either at their minimum stable generation or at their maximum output.

¹⁴ Experts from several generating companies were consulted to create a reasonably representative set of input parameters and data used in the analysis.

Table 5.1 Characteristics of generation systems considered

Generation System	Parameters	Inflexible Generation	Generation of moderate flexibility	Flexible Generation
Low Flexibility (LF) Generation System	MSG ¹⁵	100%	77%	50%
	Capacity installed	8.4GW	26GW	>25.6GW
Medium Flexibility (MF) Generation System	MSG	100%	62%	50%
	Capacity installed	8.4GW	26GW	>25.6GW
High Flexibility (HF) Generation System	MSG	N/A	N/A	45%
	Capacity installed	0 GW	0GW	>60GW

Demand

- 5.7. Peak demand is taken to be 57GW while minimum demand is 18GW. 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).
- 5.8. Demand is assumed to be perfectly predictable and the impact of demand forecasting error is neglected.

Wind generation

- 5.9 An annual hourly wind generation profile, similar to that used in SCAR, is developed to represent 26 GW of wind generation capacity installed.

Reserve requirements

- 5.10 The planning horizon for committing operational reserve is adopted to be 4 hours given the assumption that the time it takes to bring a large

¹⁵ MSG stands for Minimum Stable Generation and is expressed as percentage of the maximum generator capacity

conventional plant (CCGT) on the system will be 4 hours. The system is assumed to use reserves to cover possible fluctuations in this period.

- 5.11 Two main cases are considered:
- (i) Entire reserve is provided by synchronised conventional plant only (spinning reserve).
 - (ii) Part of the reserve is provided by conventional synchronised plant while the rest is supported by standing reserve, in the form
 - (a) OCGTs or
 - (b) Storage facilities

5.12 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 tails, indicating that more resources will be needed for system balancing than a normal distribution would suggest. In order to cater for this we have carried out the analysis with reserve requirements being 3.5 and 4 standard deviations, instead of 3. Although this has an impact on the absolute value of system balancing cost, it has relatively little impact on the relative competitiveness of storage against OCGT technology.

5.13 Given the amount of standing reserve used for balancing, the maximum amount of synchronised reserve required is presented in Table 5.2

Table 5.2 Maximum spinning reserve for cases considered

OCGT / Storage capacity used for balancing	Maximum spinning reserve
2 GW	5700 MW
3 GW	4700 MW
4 GW	3700 MW
5 GW	2700 MW

5.14 The actual amount of synchronised reserve committed in each hour was determined by taking into account the predicted output of wind generation. For example, in the case of 2GW of standing reserve (provided by OCGTs) the maximum amount of 5.7GW of synchronised reserve would be required only if the predicted wind output is above 7.7GW (5.7 GW spinning reserve plus 2GW standing reserve). Otherwise the amount of spinning reserve could be reduced.

- 5.15 In the case of storage providing standing reserve, it would not normally be possible to achieve similar reductions in spinning reserve, as the ability of storage to provide reserve will depend on the energy stored at that point and the duration of support required. The ability of storage to reduce the amount of spinning reserve was analysed in off line studies and then incorporated in the simulation process.
- 5.16 Given that wind output is relatively low for a significant proportion of time, modelling of the synchronised reserve commitment taking into account specific wind condition was found to be important for both the absolute value of storage in providing standing reserve and for its competitive advantage over OCGT plant.

Storage and OCGT plant characteristics

- 5.17 Both OCGTs and storage plant are assumed to be very flexible (i) no minimum output constraints and (ii) high ramp rates.
- 5.18 In this analysis we have also assumed that storage facilities and OCGT plant have similar reliability characteristics. Analysis of the impact and the value of reliability on relative competitiveness of storage is beyond the scope of this work.
- 5.19 Given the flat marginal generation cost of 20£/MWh, storage is *prevented* from energy arbitrage, and is used only to provide standing reserve (and hence reduce generation costs associated with provision of synchronised reserve) and absorb excesses in wind generation that would otherwise be wasted.
- 5.20 Storage efficiency is assumed to be 70%.
- 5.21 Cost of fuel of standing reserve provided by OCGTs is 50£/MWh.

Modelling and evaluations

- 5.22 In contrast to SCAR, this analysis is not based on the high level statistical assessment of system operation but on a more detailed simulation of the operation of the system. We simulated, hour by hour, a year round operation of the system with 26 GW of wind capacity, taking into consideration daily and seasonal demand variations and variations in wind output. One of the key advantages of this approach is the ability to optimise more precisely the amount of synchronised reserve required (in each hour) as a function of wind output forecasts and the amount of standing reserve available. This was shown to be an important advantage of the simulation approach over the statistical assessment employed in earlier studies, particularly in the context of the accuracy of the quantification of the cost of

operation, the value of storage and its additional value when compared with OCGT plant.

- 5.23 The model employed does not explicitly consider start up cost and hence the potential benefits arising from reducing the number of start-ups of generating units as a result of the application of flexible storage or OCGTs are not included. We however do not expect this approximation to make any significant impact on the *relative* competitiveness of storage over OCGT plant, given that the number of start ups is expected to be broadly similar irrespective of which form of standing reserve is used.
- 5.24 Similarly to SCAR this analysis is concerned with the evaluation of underlying *costs* associated with the operating the system and not with electricity market rules and mechanisms of cost recovery.
- 5.25 Network effects are not considered. However, in cases of congested transmission and distribution networks location the specific value of (distributed) storage may be significant.
- 5.26 The simulation model is run for a time horizon of one year and the following information is obtained
- annual energy produced by conventional plant
 - annual generation cost including cost associated with carrying spinning reserve
 - annual energy not supplied (due to insufficient reserves and constraints on ramp rates)
 - annual wind generation curtailed (due to minimum stable generation constraints and constraints on ramp rates)
 - annual charge and discharge energies (when a storage system is used)
 - annual energy produced by OCGTs (when OCGT plant is used)
 - annual CO2 emissions
- 5.27 Comparing the results of the individual studies the following key outputs are obtained:
- (i) The *value of standing reserve* (for *both* forms - storage and OCGT plant) is quantified by evaluating the *difference* in the fuel cost and CO2 emissions when intermittency is managed via synchronised reserve only, against the performance of the system with various amounts of standing reserve.
 - (ii) The *relative competitiveness* of storage against OCGT technology is then evaluated as the *difference in savings* in fuel cost delivered by storage versus OCGT plant. The same methodology is applied to CO2 emissions and to reductions in energy produced by conventional plant.

6. Results of case studies

6.1 Here we present full results of the case studies performed. This covers the following:

- (a) Value of standing reserve provided by storage
- (b) Value of standing reserve provided by OCGTs
- (c) Value of storage versus OCGT technology
- (d) Sensitivity studies

(a) Value of standing reserve provided by storage

6.2 In each of the Tables below (and in the corresponding Figures) the *benefits* of using energy storage as the standing reserve provider are presented, in each of the three generation systems with various degree of flexibility (LF, MF, HF), in terms of the three key indicators:

- reduction in fuel cost (Tables and Figures 6.1a and 6.1b),
- reduction in CO₂ emissions (Table and Figure 6.1c) and
- reduction in energy produced by conventional plant (Table and Figure 6.1d).

Reduction in fuel cost

6.3 As discussed above, the application of storage improves the system performance through reduction of fuel cost associated with system balancing. This is achieved by reducing the amount of synchronised reserved committed, which in turn has two positive effects:

- increase in efficiency of system operation by reducing the number of part loaded generators and
- increase in the amount of wind power that can be absorbed and hence reduction in the amount of fuel burnt. This comes from the fact that when operating fewer generating units the amount of wind that has to be rejected when high wind conditions coincide with low demand reduces. Furthermore, surpluses of wind could be absorbed by charging the storage facilities and subsequently used to supply demand and hence reduce the amount of energy produced by conventional plant¹⁶.

Table 6.1a: Benefits of storage: Reduction in fuel cost associated with balancing

	Reduction in fuel cost in £m/pa
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¹⁶ Of course, the net amount of wind saved will depend on the efficiency of storage.

Storage Capacity (GW)	LF	MF	HF
2	214	128	55
3	266	156	70
4	318	190	90
5	341	205	99

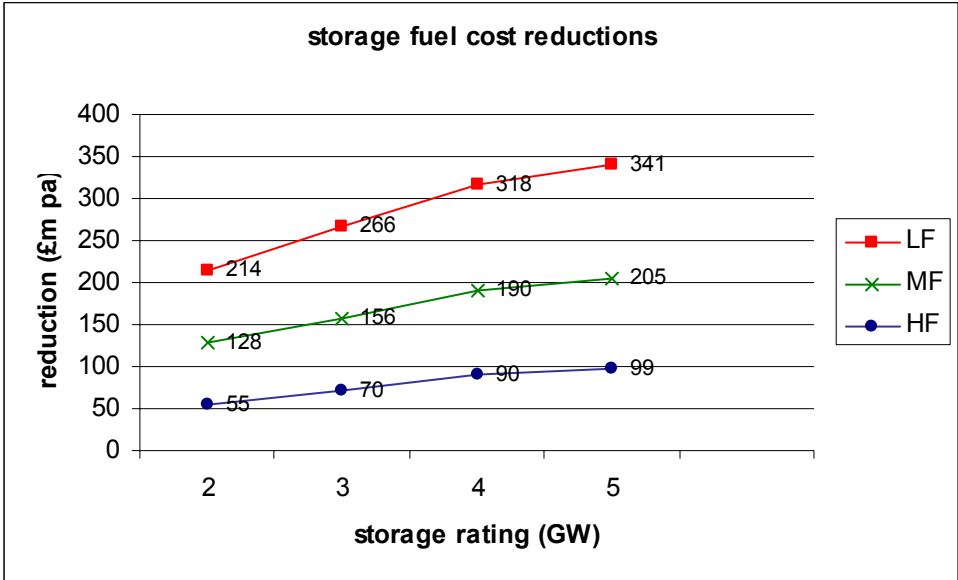


Figure 6.1a: Benefits of storage: Reduction in fuel cost associated with balancing

- 6.4 The figures in Table 6.1a and Figure 6.1a present annual reduction in fuel costs. Note that the range of savings is quite large. As expected, the fuel savings are higher in systems with less flexible generation and increase with the increase in storage capacity installed. For example, a storage system of 3GW installed in a generation system of medium flexibility (MF case), would save an amount of fuel worth £156m every year. Given the marginal generation cost at 20£/MWh, this would correspond to the amount of fuel used by running a 890MW plant at maximum output for one year.
- 6.5 We have also capitalised the fuel savings using a rate of 10% over a 25 year time period. The capitalised value of reduced fuel cost, enabled by storage providing standing reserve, as a function of the amount of capacity used is given in Table and Figure 6.1b. As expected, the value of storage per kW reduces with the increase in storage capacity installed. These values present the additional value created by storage in performing balancing task. The values in Figure 6.1b represent the net benefit that corresponds to fuel cost savings achieved by using storage in the balancing task, rather than balancing the system through synchronised plant only. This additional value is the largest in systems with generators of low flexibility (LF) and reduces as the flexibility of generation mix improves.

Table 6.1b: Benefits of storage: Capitalised value of reduced fuel cost associated with balancing

Storage Capacity (GW)	capital value of storage capacity (£/kW)		
	LF	MF	HF
2	970	580	252
3	803	473	213
4	721	431	205
5	619	371	179

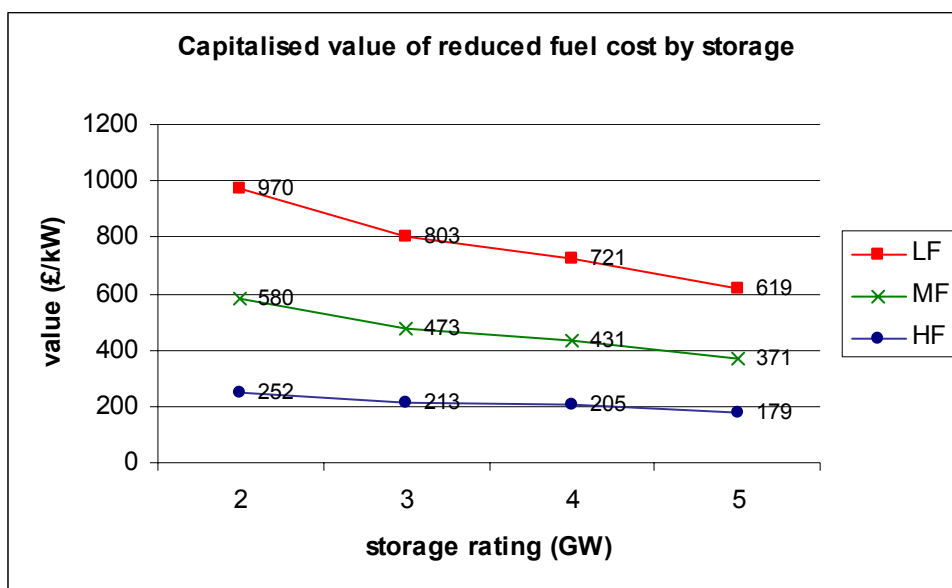


Figure 6.1b: Benefits of storage: Capitalised value of reduced fuel cost associated with balancing

Reduction in CO2 emissions

6.6 Reductions in fuel utilisation in the system with storage will be directly reflected in the improvement of CO2 performance of the system. The amount of CO2 that can be saved by storage applications will be system specific, as shown in Table 6.1c and Figure 6.1c. As expected, the CO2 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).

Table 6.1c: Benefits of storage: reduction in CO2 emissions

Storage Capacity (GW)	Reduction in CO2 emissions in million tonnes/pa		
	LF	MF	HF
2	4.480	2.620	1.110
3	5.560	3.200	1.410
4	6.680	3.880	1.810
5	7.170	4.180	1.980

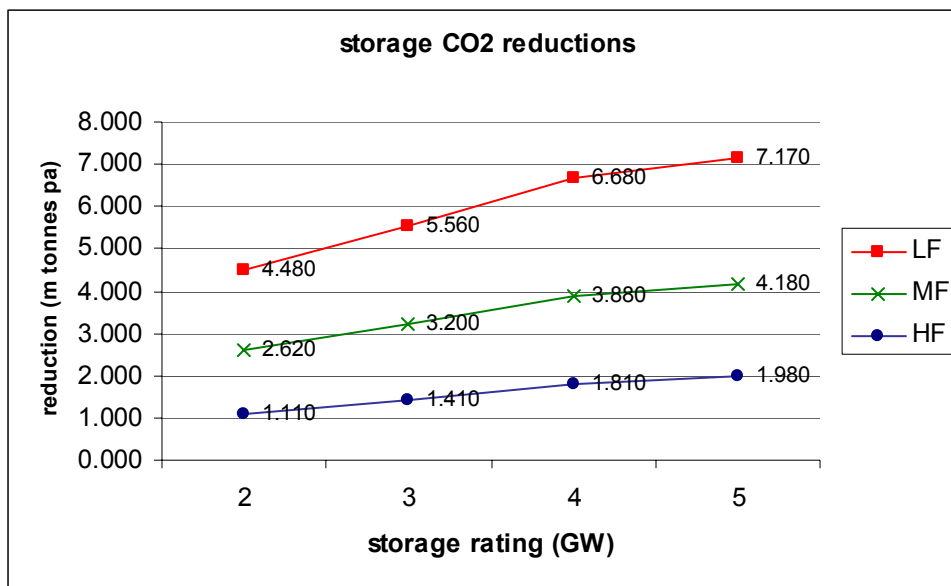


Figure 6.1c: Benefits of storage: reduction in CO2 emissions

- 6.7 For example, a storage system of 3GW installed in a generation system of medium flexibility (MF case), would save 3.2 million tonnes of CO2 per annum. This amount of CO2 saved, would be emitted by a conventional plant of more than 900MW running at full output for a year.
- 6.8 Reductions in CO2 emitted could be used to measure the contribution that storage technology can make in the context of Government's targets.

Reduction in energy produced by conventional plant

- 6.9 By applying storage, the amount of synchronised reserved committed can be reduced and this will lead 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 the amount of wind that has to be

rejected when high wind conditions coincide with low demand will be reduced. Any remaining surplus of wind could be absorbed by charging the storage facilities. Within our methodology we calculate the amount of wind that need to be *curtailed* in order to maintain a stable operation of the system. We can hence quantify the savings in wind energy curtailed by using storage.

- 6.10 However, the value of wind saved (or curtailed) should not be used to directly measure the benefits of storage. This is because the storage efficiency will be a key factor here. At the extreme, 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 will be actually saved due to low efficiency storage plant.
- 6.11 On the other hand, we could quantify the amount of energy produced by conventional generation and measure the benefits of storage in terms of reducing this quantity. Clearly, the amount of energy produced by conventional plant can be used as a direct measure of the net effect of wind energy saved, taking into account storage efficiency losses. This is shown in Tables 6.1d, 6.1e and 6.1f.

Table 6.1d: Benefits of storage: reduction in energy provided by conventional generation

Storage Capacity (GW)	Reduction in energy produced by conventional plant in TWh/pa		
	LF	MF	HF
2	8.897	3.679	0.125
3	10.730	4.173	0.085
4	11.913	4.472	-0.047
5	12.275	4.463	-0.219

- 6.12 We observe that the reduction in energy produced by conventional plant (given in Table 6.1d) is equal to the difference between reduction in wind energy curtailed (Table 6.1e) and the energy lost in storage (Table 6.1f). In other words, the reduction in energy provided by conventional generation is effectively the utilisation of wind as shown by the reduction in wind curtailment in Table 6.1e, but with the deduction of energy lost in storage (efficiency losses) as shown in Table 6.1f.

Table 6.1e: Benefits of storage: reduction in wind curtailment

Storage Capacity (GW)	Reduction in wind curtailment in GWh/pa		
	LF	MF	HF
2	10,018	4,188	166
3	12,071	4,737	170
4	13,055	5,043	170
5	13,339	5,113	170

Table 6.1f: Corresponding storage efficiency losses

Storage Capacity (GW)	Energy lost in storage (efficiency losses) in GWh/pa		
	LF	MF	HF
2	1,123	509	42
3	1,341	564	85
4	1,143	570	218
5	1,065	650	390

- 6.13 The net reduction in energy produced by conventional plant is also shown in Figure 6.1d. For the LF case, benefits of storage are significant. The reduction of the output of conventional plant is between 8.9 TWh/pa to 12.3 TWh/pa, 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.
- 6.14 For the HF case however, the total output of the conventional plant does not change substantially with the presence of storage, and in fact becomes negative for utilisation of large storage capacities. For the HF system 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.

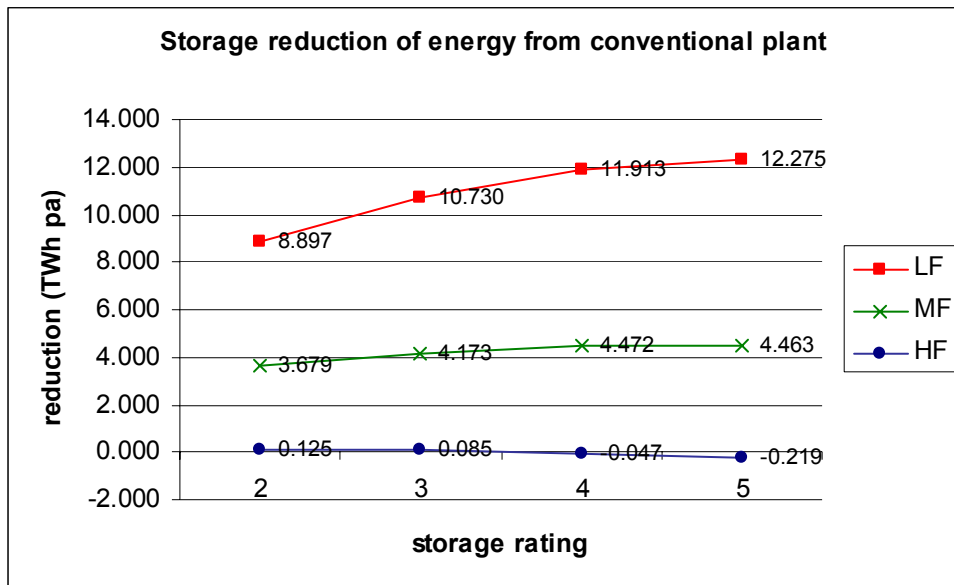


Figure 6.1d: Benefits of storage: reduction in energy provided by conventional generation

- 6.15 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 overall production cost is lower. For 5GW of storage, the total amount of energy produced by conventional plant is increased by 219GW/pa (Figure 6.1d), while simultaneously, the cost of production has reduced by £99m/pa (Figure 6.1a), and the amount of CO₂ emitted is reduced by 1.9 million tonnes (Figure 6.1c). The system with storage can clearly run more efficiently, because storage, as a standing reserve provider, reduces the amount of part loaded plant.
- 6.16 Observe that setting a particular energy output of conventional plant does not uniquely define the corresponding fuel cost (and CO₂ emissions). For example, an energy output of 500MWh (achieved over 1 hour) can be realised by running one unit of 500MW at full output for one hour, or alternatively, by having two units of 500MW capacity operated part-loaded at 250MW (to meet reserve requirement). Assuming a marginal cost of 20£/MWh, the cost in the former case is 500MWh x 20£/MWh = 10,000£. In the latter case, however, assuming a loss in efficiency of 16%, the marginal generation cost will be 23.2£/MWh and hence the production cost will be 2 x 250MWh x 23.2£/MWh = 11,600£.

Value of standing reserve provided by OCGTs

- 6.17 In each of the Tables below (and in the corresponding Figures) the *additional benefits* of using OCGT plant as the standing reserve provider are presented, in each of the three generation systems with various degree of flexibility (LF, MF, HF), in terms of the three key indicators:
- reduction in fuel cost associated with balancing (Tables and Figures 6.2a and 6.2b),
 - reduction in CO2 emissions (Table and Figure 6.2c) and
 - reduction in energy produced by conventional plant (Table and Figure 6.2d).

Reduction in fuel cost

- 6.18 As discussed in section 2, a considerable amount of the overall generation capacity in future systems is likely to be provided by OCGT type technology (low capital cost) given low utilisation factors. Some of this plant could be used to provide not only backup but also used for system balancing. The application of OCGT can improve system performance through reduction of the fuel cost associated with system balancing. This is achieved by reducing the amount of synchronised reserved committed, which increases the efficiency of system operation by reducing the number of part loaded generators and hence increases the amount of wind power that can be absorbed and hence reduction in the amount of fuel burnt. As in the case with storage, this comes from the fact that when operating fewer generating units the amount of wind that has to be rejected when high wind conditions coincide with low demand reduces. However, in contrast to systems with storage, remaining surpluses of wind will be wasted in systems with OCGTs providing standing reserve.

Table 6.2a: Benefits of OCGT plant: Reduction in fuel cost associated with balancing

OCGT Capacity (GW)	Reduction in fuel cost in £m/pa		
	LF	MF	HF
2	191	117	58
3	226	134	62
4	264	150	61
5	274	147	51

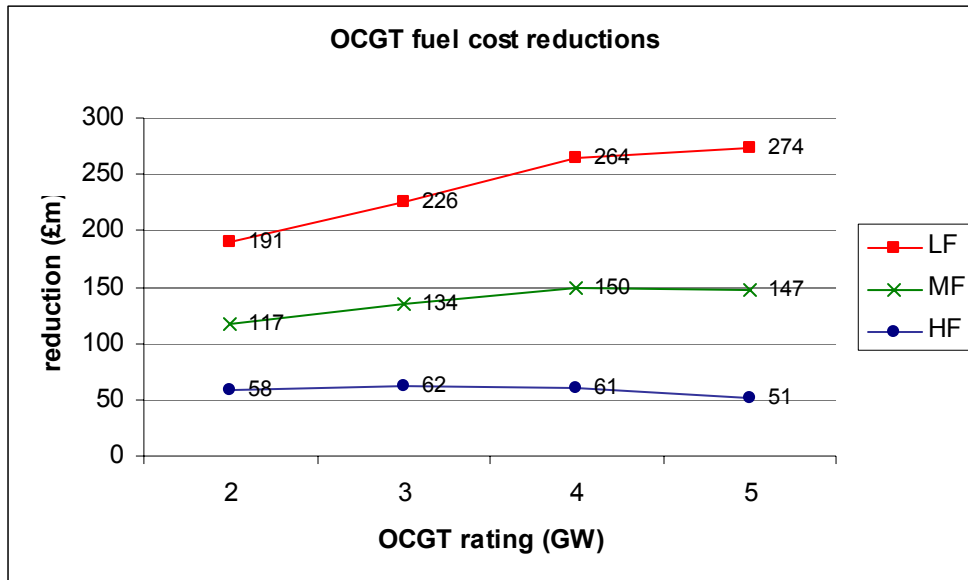


Figure 6.2a: Benefits of OCGT plant: Reduction of fuel cost associated with balancing

- 6.19 The figures in Table 6.2a and Figure 6.2a present annual reduction in fuel costs. Note that the range of savings is quite large. As expected, the fuel savings are higher in system with less flexible generation and generally increase with the increase in OCGT capacity used for system balancing¹⁷.
- 6.20 As in the case with storage, we have also capitalised the fuel savings using a rate of 10% over a 25 year time period. The *capitalised value* of the additional benefit created by OCGT through reducing cost of fuel associated with system balancing, as a function of the capacity of OCGT employed in the balancing task, is given in Table and Figure 6.2b.

Table 6.2b: Benefits of OCGT plant: Capitalised value of reduced fuel cost associated with balancing

OCGT Capacity	capitalised value of OCGT (£/kW)		
	LF	MF	HF

¹⁷ The slight reduction in benefits of OCGT with increase in capacity used for balancing in MF and HF cases indicates that standing reserve is being utilised more than necessary and that the allocation between spinning and standing reserve could be optimised further.

used for balancing (GW)			
2	865	533	264
3	684	407	189
4	600	340	139
5	497	267	93

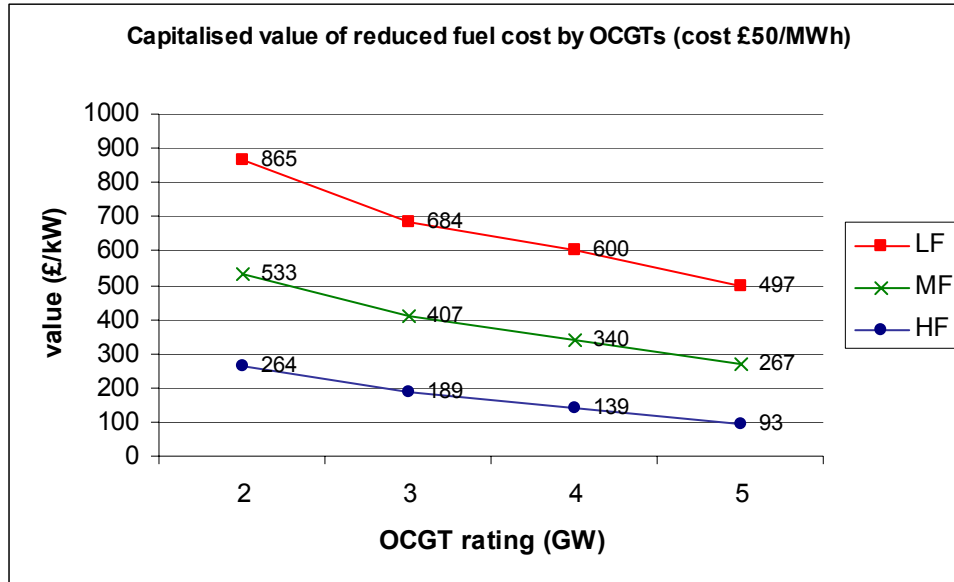


Figure 6.2b: Benefits of OCGT plant: Capitalised value of reduced fuel cost associated with balancing

6.21 The values in Figure 6.2b represent the net benefit that corresponds to fuel cost savings achieved by using OCGT in the balancing task, rather than balancing the system through synchronised plant only. This additional value is the largest in systems with generators of low flexibility (LF) and reduces as the flexibility of generation mix improves.

Reduction in CO2 emissions

6.22 Reductions in fuel utilisation in the system with OCGTs will be reflected in the improvement of CO2 performance of the system. The amount of CO2 that can be saved by OCGT applications will be system specific, as shown in Table 61c and Figure 6.1c. As expected, the CO2 savings are higher in the system with less flexible generation and increase with the increase in storage capacity installed.

6.23 Although we observed a slight reduction in benefits of OCGT plant with the increase in capacity in MF and HF (from 4 GW to 5 GW) in terms of fuel cost, the benefits in terms of CO2 continue to increase. Clearly, the net effect of reducing the amount of part loaded plant and increasing utilisation of standing reserve has environmental benefits, given the assumption that

standing plant emits 0.6tonnes/MWh (in contrast to the emission level of synchronised plant being set at 0.4tonnes/MWh). On the other hand the net effect on cost would not be beneficial given the assumption that cost of running of OCGT is set at 50£/MWh (in contrast to marginal cost of synchronised plant being 20£/MWh)

Table 6.2c: Benefits of OCGT plant: reduction in CO2 emissions

OCGT Capacity (GW)	Reduction in CO2 emissions in million tonnes/pa		
	LF	MF	HF
2	4.207	2.527	1.271
3	5.150	3.070	1.543
4	6.262	3.692	1.844
5	6.788	3.978	1.946

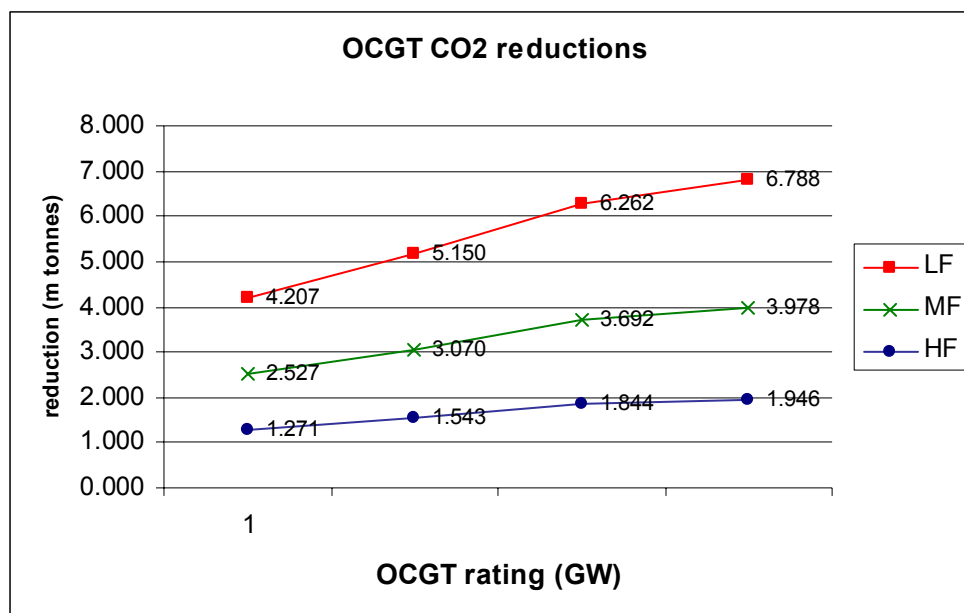


Figure 6.2c: Benefits of OCGT plant: reduction in CO2 emissions

6.24 Clearly, the benefits of reducing spinning reserve by employing standing reserve in the form of OCGT could significantly reduce CO2 emissions. For example, a portfolio of OCGT plant of 3GW installed capacity in a generation system of medium flexibility (MF case), would save 3.07 million tonnes of CO2 per annum, only marginally below the storage based system (see Figure 6.1c).

Reduction in energy produced by conventional plant

6.25 By using OCGT plant for providing standing reserve, the amount of synchronised reserve committed can be reduced and this will lead to an increase in the amount of wind power that can be absorbed. As in the case of storage, this is a consequence of operating fewer conventional generating units and hence the amount of wind that has to be rejected when high wind conditions coincide with low demand will be reduced.

6.26 One of the outputs of the evaluation is the amount of wind that needs to be curtailed in order to maintain a stable operation of the system. We can hence quantify the savings in wind energy curtailed by using OCGT based standing reserve provision.

6.27 Table 6.2d and Figure 6.2d present the reduction in the output of conventional plant as a result of using standing reserve in the form of OCGT. This reduction is a direct consequence of the increased ability of the system to accommodate more wind.

Table 6.2d: Benefits of OCGT plant: reduction in energy provided by conventional generation

OCGT Capacity (GW)	Reduction in energy produced by conventional plant in TWh/pa		
	LF	MF	HF
2	6.723	2.527	0.121
3	8.165	3.113	0.133
4	9.939	3.714	0.149
5	10.795	4.011	0.156

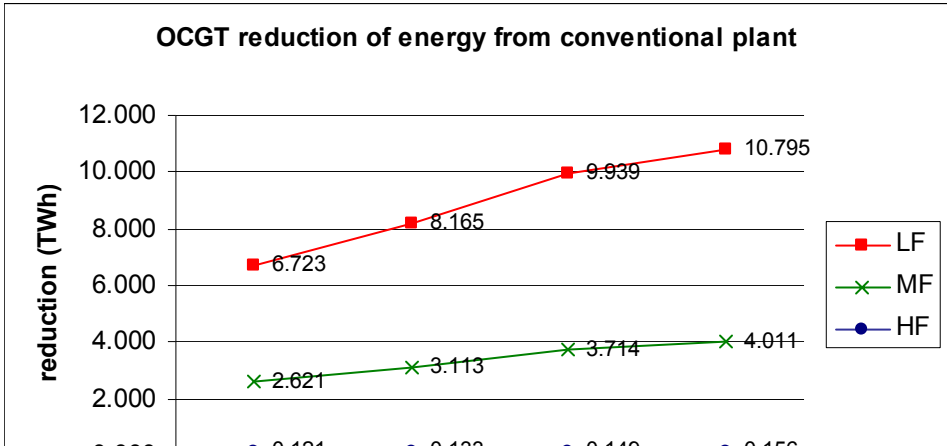


Figure 6.2d: Benefits of OCGT plant: reduction in energy provided by conventional generation

Value of storage versus OCGT

- 6.28 In each of the Tables below (and in the corresponding Figures) the *benefits* of using storage versus OCGT plant as the standing reserve provider are presented, in each of the three generation systems with various degree of flexibility (LF, MF, HF), in terms of the three key indicators:
- reduction in fuel cost (Tables and Figures 6.3a and 6.3b),
 - reduction in CO2 emissions (Table and Figure 6.3c) and
 - reduction in energy produced by conventional plant (Table and Figure 6.3d).

Reduction in fuel cost

- 6.29 By subtracting the values in Table 6.2a (Figure 6.2a) from the corresponding values in Table 6.1a (Figure 6.1a) we can assess the comparative advantage of using storage over OCGT plant for providing standing reserve in the context of reduction of operation costs. This is presented in Table 6.3a and Figure 6.3a.

Table 6.3a: Benefits of storage over OCGT plant: Reduction of fuel cost

Storage/ OCGT Capacity (GW)	Reduction in fuel cost in £m/pa		
	LF	MF	HF
2	23	10	-3
3	39	22	8
4	53	40	29
5	67	57	48

- 6.30 In the majority of situations storage is more valuable than OCGT plant when providing standing reserve, particularly in low and medium flexibility systems (given the assumptions associated with input data)¹⁸. We observe that the benefits of storage over OCGT increase with the capacity installed.

¹⁸ The only exception is the high flexibility case with installed capacity of storage or OCGT of 2 GW.

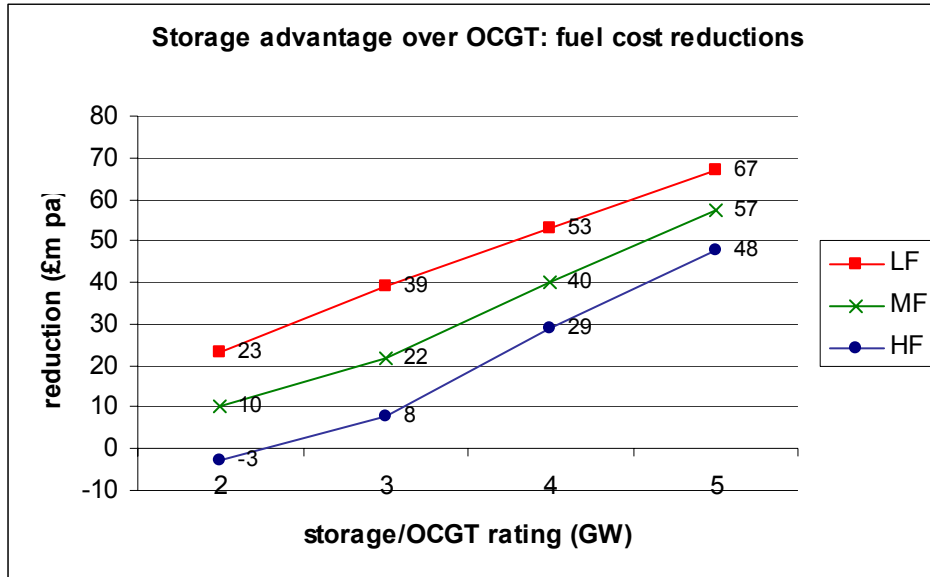


Figure 6.3a: Benefits of storage over OCGT plant: Reduction of fuel cost

6.31 As in previous cases we have capitalised the fuel savings using a rate of 10% over a 25 year time period. The capital value of the benefits of storage over OCGT plant as a function of the amount of installed capacity is given in Table 6.3b and Figure 6.3b.

6.32 As expected, the value of the benefit of storage over OCGT increases with the amount of storage capacity utilised for balancing purposes. The values in Table 6.3b and Figure 6.3b present the additional amount of capital expenditure that could be spent on storage over that of OCGTs. For example, in case of 3GW of standing reserve and a medium flexibility (MF) generation system, if the cost of storage facilities is 66£/kW greater than the cost of OCGT technology, it would be worthwhile to install storage rather than OCGTs.

Table 6.3b: Benefits of storage over OCGT plant: Capitalised value of reduced fuel cost

Storage/ OCGT Capacity (GW)	additional value of storage over OCGTs (£/kW)		
	LF	MF	HF

2	104	47	-13
3	119	66	24
4	121	91	66
5	122	104	87

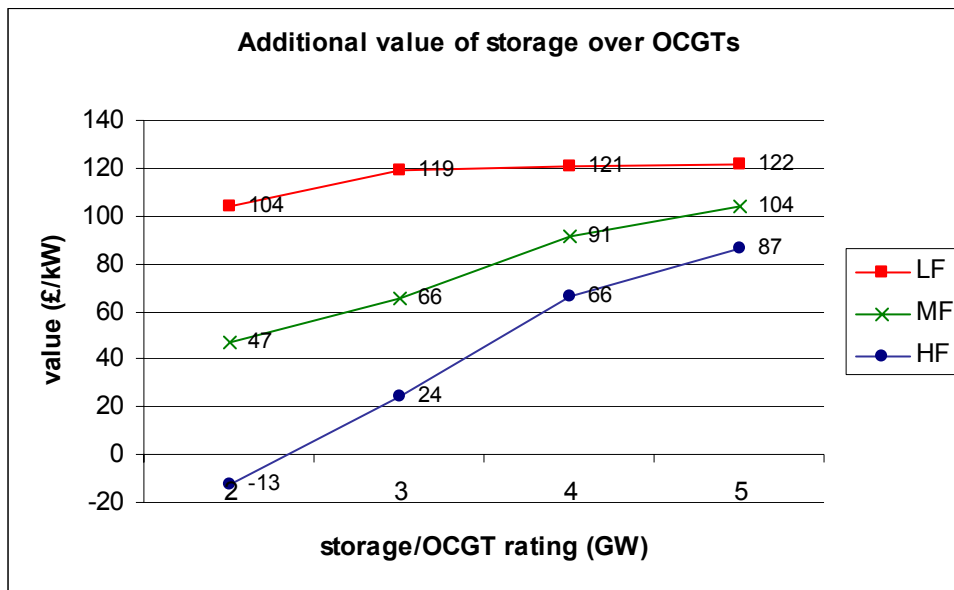


Table 6.3b: Benefits of storage over OCGT plant: Capitalised value of reduced fuel cost

Reduction in CO2 emissions

- 6.33 As indicated above, in contrast to OCGT based standing reserve provision, the advantage of storage lies in its ability to store surpluses in generation during periods of high wind and low demand, and make it subsequently available and hence reduce fuel consumption and CO2 emissions. Furthermore, OCGTs, when used, will contribute to an increase in CO2 emissions and the level of emission will depend on the efficiency of OCGT plant and the actual fuel used.
- 6.34 Again, the overall effect of using storage versus OCGT based standing reserve on CO2 emissions will be system specific. We have compared the reductions in CO2 emissions in different systems with storage and OCGTs providing standing reserve and the benefits of using storage over OCGTs are presented in Table 6.3c and Figure 6.3c.

- 6.35 Given the assumptions regarding the input data, we observe that storage will contribute more to CO2 reductions than the application of OCGT plant in the majority of cases studied. As expected, the comparative advantage of storage over OCGT plant in the context of reducing CO2 emissions is higher in low flexibility systems and increases with the amount of storage installed.
- 6.36 For example, for the capacity of standing reserve of 3GW, in a medium flexibility system, using storage to provide standing reserve would generate 0.130million tonnes less CO2 than the same system with OCGT plant providing standing reserve. To put this into context, this amount of emissions is equivalent to those produced by a CCGT plant of 500MW capacity running at full output for more than 650 hours (27 days) per year and producing 325 GWh of energy.

Table 6.3c: Benefits of storage over OCGT plant: reduction in CO2 emissions

Storage/ OCGT Capacity (GW)	Reduction in CO2 emissions in million tonnes/pa		
	LF	MF	HF
2	0.273	0.093	-0.161
3	0.410	0.130	-0.133
4	0.418	0.188	-0.034
5	0.382	0.202	0.034

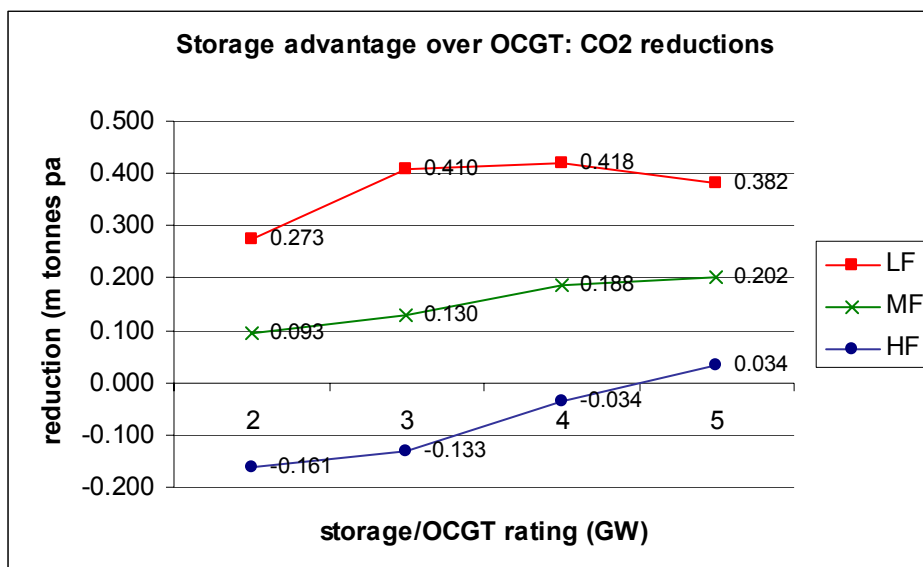


Figure 6.3c: Benefits of storage over OCGT plant: reduction in CO2 emissions

Reduction in energy produced by conventional plant

- 6.37 As discussed above, using storage or OCGT plant for providing standing reserve will reduce the amount of synchronised reserved committed and this will lead to an increase in the amount of wind power that can be absorbed. One of the measures of the benefits of storage over OCGT plant is in reduced energy produced by conventional plant. This is shown in Table 6.3d and Figure 6.4d.
- 6.38 Given the assumptions regarding the input data, we observe that storage will contribute more reduction in conventional energy than the application of OCGT plant in the majority of cases studied. The comparative advantage of storage over OCGT plant in this context is higher in low flexibility systems and generally reduces with the amount of storage installed.

Table 6.3d: Benefits of OCGT plant: reduction in energy provided by conventional generation

Storage/ OCGT Capacity (GW)	Reduction in energy produced by conventional plant in TWh/pa		
	LF	MF	HF
2	2.174	23.515	0.004
3	2.565	1.060	-0.048
4	1.974	0.758	-0.196
5	1.480	0.452	-0.375

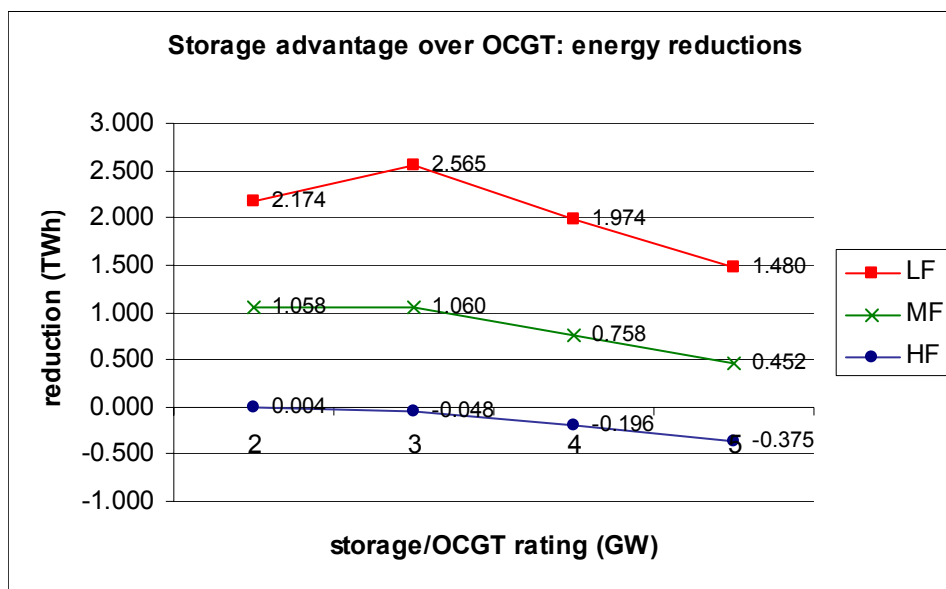


Figure 6.3d: Benefits of storage over OCGT plant: reduction in energy provided by conventional generation

Sensitivity studies

6.39 In order to form a view regarding the overall impact of the factors affecting the performance of storage and its competitiveness we have carried out a set of sensitivity studies. In particular we analysed the impact of storage efficiency, penetration of wind generation, and OCGT fuel cost.

Impact of storage efficiency

6.40 Sensitivity studies are carried out to investigate the impact of storage efficiency on the performance characteristics of the systems with storage. In each of the Figures below the benefits increasing storage efficiency from 70% to 80% are presented in each of the three generation systems with various degree of flexibility (LF, MF, HF), in terms of the three key indicators: (i) reduction in fuel cost over OCGT plant (Figure 6.4a and 6.4b), (ii) reduction in CO2 emissions over OCGT plant (Figure 6.4c) and (iii) reduction in energy produced by conventional plant over OCGT plant (Figure 6.4d). The sensitivity studies are carried out for the installed capacity of storage of 3GW.

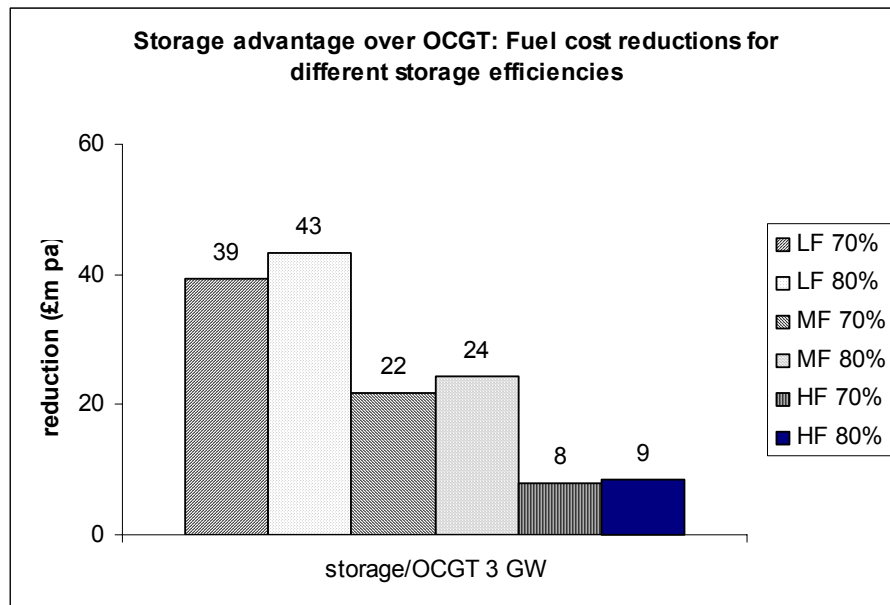


Figure 6.4a: Benefits of storage over OCGT plant: Reduction of fuel cost for 70% and 80% efficient storage

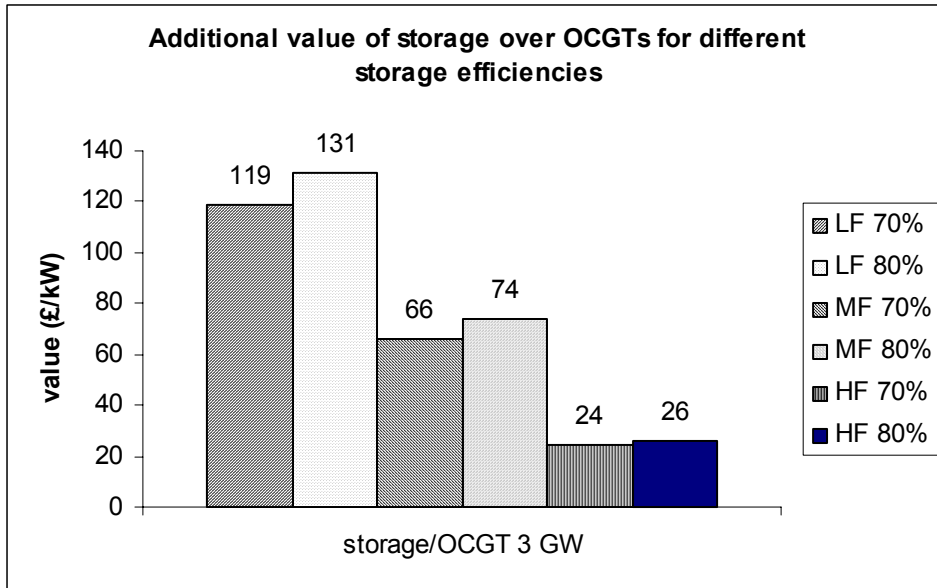


Figure 6.4b: Benefits of storage over OCGT plant: Capitalised value of the reduction of fuel cost for 70% and 80% efficient storage

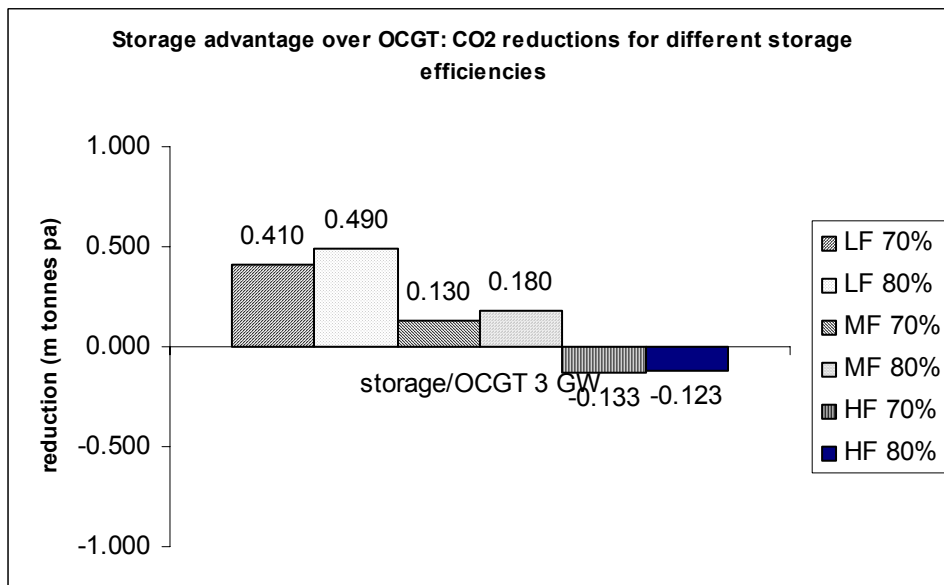


Figure 6.4c: Benefits of storage over OCGT plant: Reduction in CO2 emissions for 70% and 80% efficient storage

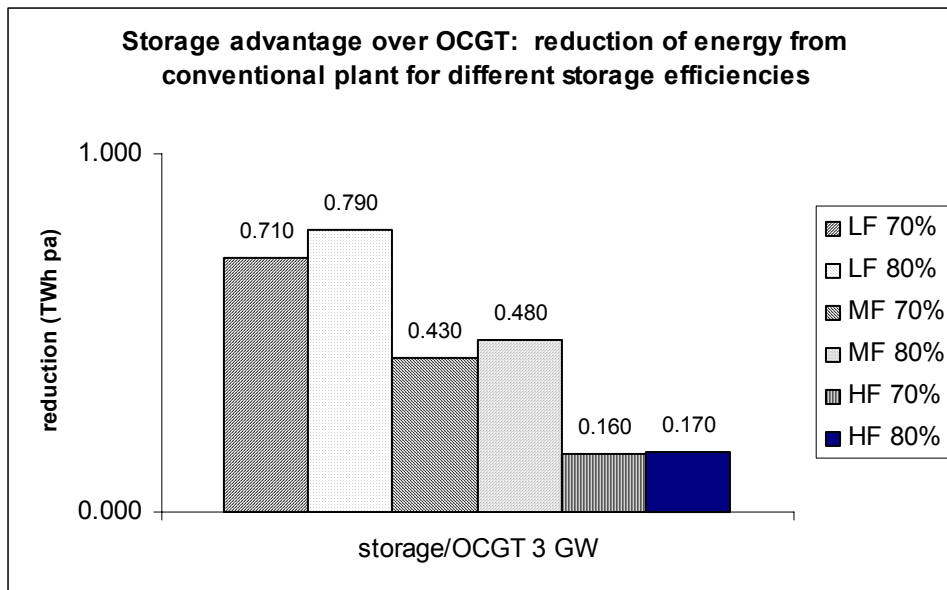


Figure 6.4d: Benefits of storage over OCGT plant: reduction in energy provided by conventional generation for efficiency of 70% and 80%

- 6.41 As expected, increasing the efficiency of storage improves its performance and increases the benefits over OCGT plant.
- 6.42 In the LF case, the value of storage over OCGT plant increases from 119£/kW to 131£/kW, for 12£/kW (just below 10%). This indicates the amount available for improving efficiency of storage from 70% to 80%. In the MF and HF systems the additional value of the improved efficiency, expressed in percentage, remains approximately constant, while the absolute value reduces. We could conclude that, given the base case assumptions, the improvement in efficiency of storage would have relatively modest impact on the competitiveness of storage.
- 6.43 The increase in storage efficiency from 70% to 80% will increase the benefits of storage over OCGTs for more than 20% (Figure 6.4c). For the LF case, the benefit in reducing CO2 emissions will increase from 0.41 to 0.49 million tonnes per annum.
- 6.44 Similarly, the increase in storage efficiency from 70% to 80% will increase the benefits of storage over OCGTs for about 10%.

Increase in wind penetration

- 6.45 Sensitivity studies are carried out to investigate the impact of wind generation penetrations on the performance characteristics of systems with storage. In each of the Figures below the benefits obtained when wind installed capacity increases from 26GW to 30GW is evaluated for each of

the three generation systems with various degrees of flexibility (LF, MF, HF), in terms of the three key indicators: (i) reduction in fuel cost over OCGT plant (Figure 6.5a and 6.5b), (ii) reduction in CO2 emissions over OCGT plant (Figure 6.5c) and (iii) reduction in energy produced by conventional plant over OCGT plant (Figure 6.5d). The sensitivity studies are carried out for the installed capacity of storage of 3GW.

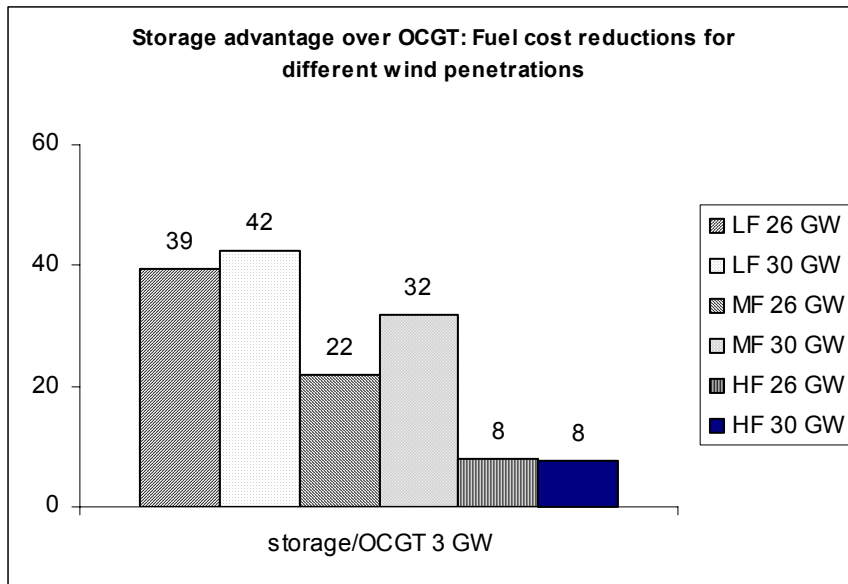


Figure 6.5a: Benefits of storage over OCGT plant: Reduction of fuel cost for 26GW and 30GW of wind power

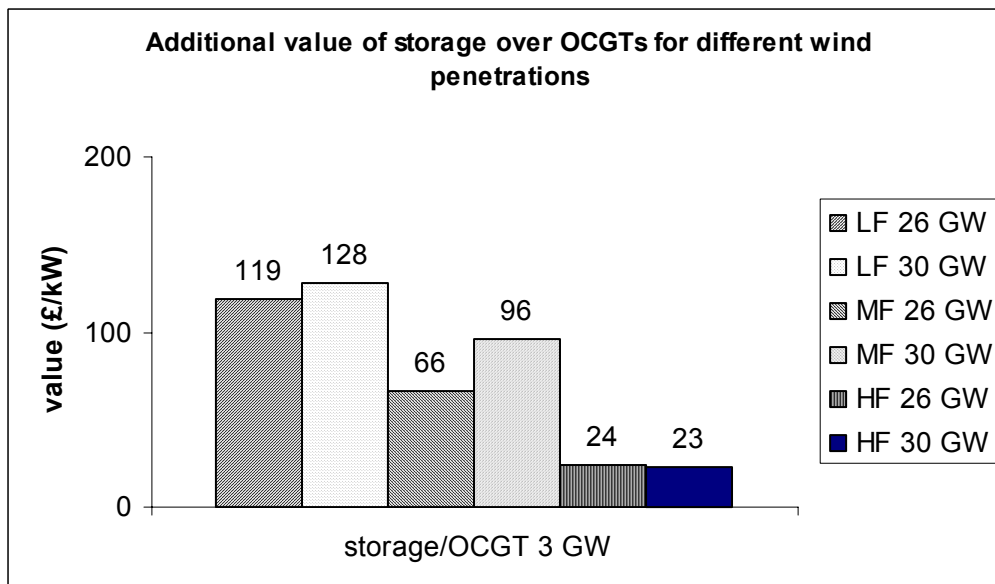


Figure 6.5b: Benefits of storage over OCGT plant: Capitalised value of the reduction of fuel cost for 26GW and 30GW of wind power

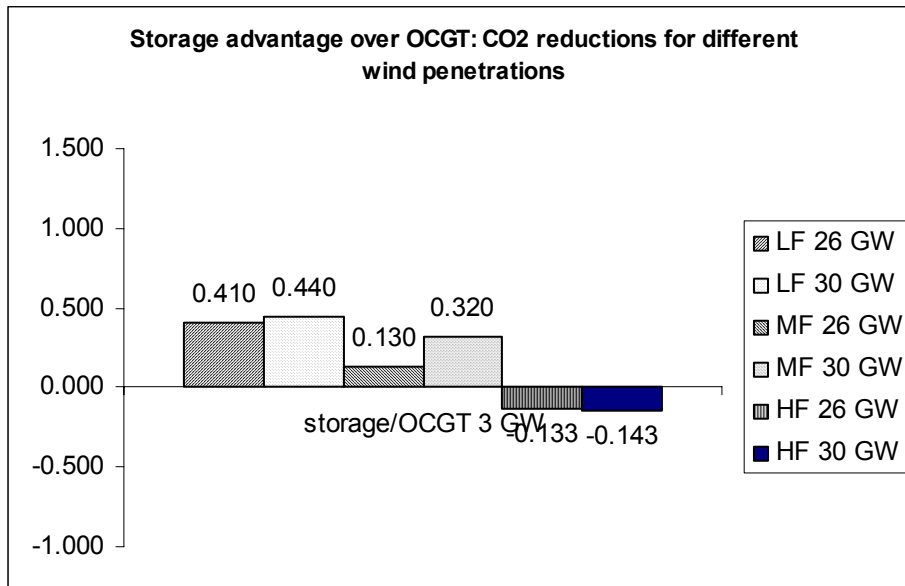


Figure 6.5c: Benefits of storage over OCGT plant: Reduction in CO2 emissions for 26GW and 30GW of wind power

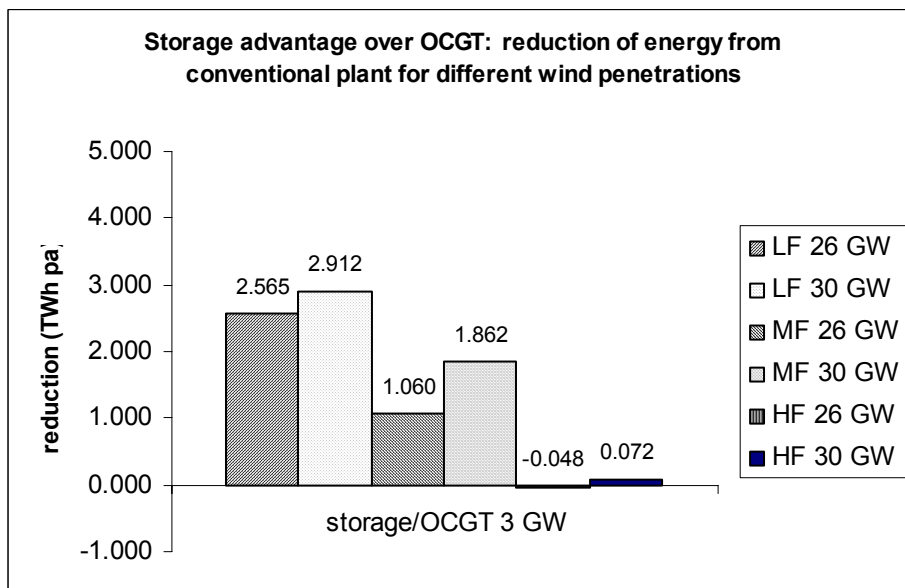


Figure 6.5d: Benefits of storage over OCGT plant: reduction in energy provided by conventional generation for 26GW and 30GW of wind power

6.46 The analysis demonstrates that increase in wind capacity installed will generally increase the value of storage over OCGT plant Figure 6.5a and Figure 6.5b, with the exception of the HF case (this case is however not very interesting as storage is not expected to be competitive in this system). Particularly significant increase in the value of storage over OCGT is achieved in the MF case.

- 6.47 Similarly, the benefits of storage over OCGT plant in the context of CO2 emission reduction, will increase for the LF and MF cases (Figure 6.5c)
- 6.48 Finally, the benefits of storage over OCGT plant in the context of the reduction of the energy produced by conventional plant will increase in all systems.

Impact of OCGT fuel cost

- 6.49 Sensitivity studies are carried out to investigate the impact of OCGT fuel cost on the relative performance of storage versus OCGT plant. In Figure 6.6a below the consequences of the fuel cost increase from 50£/MWh to 100£/MWh are evaluated for each of the three generation systems with various degree of flexibility (LF, MF, HF).
- 6.50 Comparing Figures 6.3b and 6.6.a, we observe that the impact of fuel cost of OCGT plant will have a significant impact on the competitiveness of storage (or OCGT technology). For example, in case of 3GW of standing reserve and a medium flexibility (MF) generation system, the value of storage above OCGT increases from 66£/kW to 131£/kW.

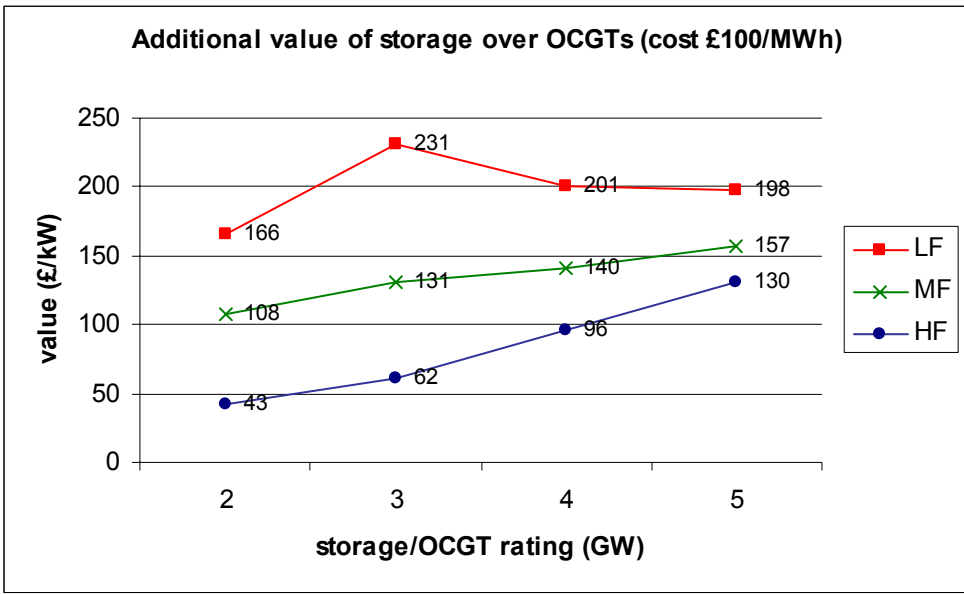


Figure 6.6a: Additional value storage over OCGT plant @100£/MWh: Capitalised value of the reduction of fuel cost

7. Conclusions

- 7.1 In this report the value of storage has been analysed in a GB like generation system with 26 GW of wind capacity installed. Storage is being used to manage intermittency: reduce cost of system balancing and increase the amount of wind power that can be absorbed, and hence increase the overall efficiency of the system operation and reduce CO₂ emissions.
- 7.2 In contrast to previous studies, this work is based on year round simulation of the operation of the system taking into consideration daily and seasonal demand variations and variations in wind output, allowing a more precise allocation of reserve between synchronised standing.
- 7.3 Given that the prime competitor of storage technologies is OCGT generating plant, the relative competitiveness of these two technologies is assessed by evaluating performance of various systems with storage and with OCGT plant providing standing reserve.
- 7.4 The key factor found to affect the value of storage is the flexibility of conventional generation mix. We have therefore studied the performance of storage in three generating systems of distinctly different flexibilities. Other factors, such as amount of storage installed, wind capacity installed, cost of fuel of OCGTs, are found to have potentially large impact on the value of storage. The impact of storage efficiency is also analysed and shown to have relatively small impact on the overall value of storage.
- 7.5 Given the assumptions adopted, the analysis suggests that in generation systems of limited flexibility, with 3GW of storage installed, the additional value of storage, manifested through a reduction in fuel cost associated with balancing, was found to be between 470£/kW to 800£/kW (capitalised value of fuel cost reduction). However, the value of storage over OCGT plant, in such systems was found to be between 60£/kW and 120£/kW. Application of storage, rather than OCGTs, for providing standing reserve reduced the additional energy produced by conventional plant (associated with system balancing) from 0.45TWh to 2.5TWh. This could be interpreted as an increase in wind generation that can be absorbed. Furthermore, application of storage reduced CO₂ emissions in the range of 0.2 and 1.3 million tonnes of CO₂ per annum, when compared with OCGT based standing reserve.