

Opportunities for

Assessing Whole-System Economic Benefits of Energy Storage in Future Electricity Systems

ANY COST-EFFECTIVE TRANSITION TOWARD LOW-CARBON ELECTRICITY SUPPLY will necessitate improved system flexibility to address the challenges of increased balancing requirements and degradation in asset use. Energy storage (ES) represents a flexible option that can bring significant, fundamental economic benefits to various areas in the electric power sector, including reduced investment requirements for generation, transmission, and distribution infrastructure as well as reduced system operation and balancing costs. The additional flexibility offered by ES could also significantly reduce the requirement for investment in low-carbon generation capacity while achieving the established carbon intensity targets. Moreover, ES may present significant option value, as it can provide flexibility for dealing with uncertainty in future system development.

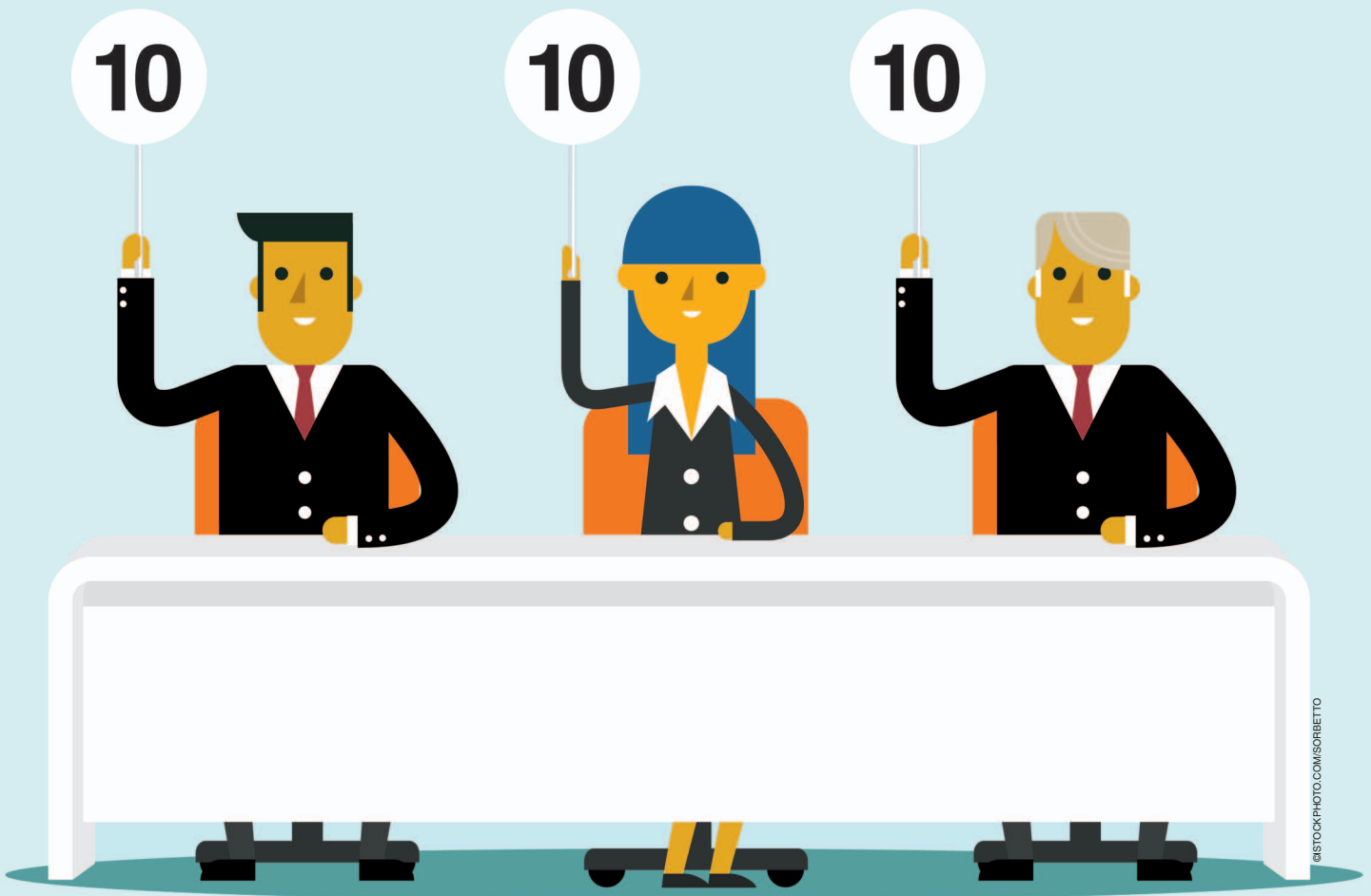
However, market and regulatory barriers may prevent the realization of quantifiable system value in cases where an ES asset cannot access the entire range of system services. Developing fully cost-reflective markets and effective regulatory frameworks—achieved by establishing a level playing field between investment in traditional network/generation solutions and investment in ES—is therefore necessary to ensure that commercial incentives for investing in and operating ES are aligned with its societal benefits.

Overview

Transforming the electricity sector in the United Kingdom over the coming decades toward a low-carbon system poses significant challenges. According to government plans, significant carbon reductions expected by 2030 will be based on deploying renewable and nuclear generation technologies combined with electrifying segments of the heat and transport sectors. Traditional business-as-usual infrastructure planning along with a high penetration of variable and inflexible low-carbon generation may result in prohibitive system integration costs, curtailment of low-carbon generation (potentially exceeding 25% in 2030), and significant degradation in infrastructure asset utilization (from 55% today to less than 30% in 2030). In this context, technology options such as ES, demand-side response (DSR), and flexible power generation could provide the versatility to reverse these trends.

Our recent studies suggest that ES technologies may have a significant role to play in facilitating the cost-efficient transition to a low-carbon power system. ES could deliver cost savings across the electricity system by offsetting the need for generation and network investment while at the same time contributing to operating cost savings. In this context, the pioneering demonstration project Smarter Network Storage, led by UK Power Networks, explored the capabilities of a grid-scale battery storage device in deferring traditional network reinforcement, while also providing national-level balancing services. Figure 1 shows the battery storage facility (6 MW, 10 MWh) installed as a key part of this project in the U.K.'s Leighton Buzzard substation.

Energy Storage



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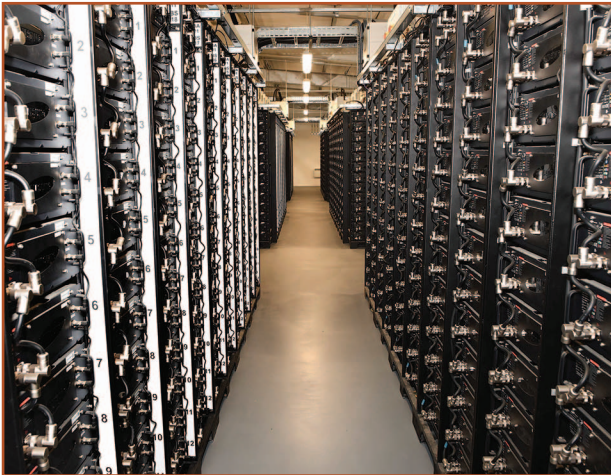


figure 1. The battery storage facility in the U.K.'s Leighton Buzzard substation. (Used with permission from UK Power Networks.)

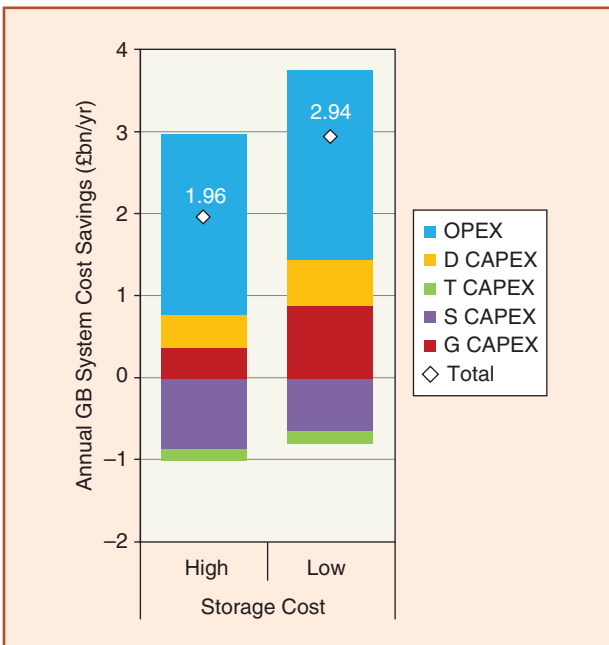


figure 2. The annual GB system cost savings resulting from deployment of distributed ES.

However, traditional regulatory regime and electricity market arrangements could represent a barrier to providing some services, possibly undermining the business case for ES. In this context, the specific objectives of this article are to

- ✓ demonstrate the economic benefits of deploying ES over multiple sectors in the future U.K. electric power system
- ✓ identify the value of ES in reducing carbon emissions at lower cost
- ✓ assess the potential competition between ES and other flexible options (DSR, flexible generation, and interconnectors)

- ✓ demonstrate the impact of future market arrangements on the business case for ES
- ✓ present a concept for quantifying the contribution of ES to security of supply
- ✓ demonstrate ES's option value under uncertainty.

Whole-System Benefits of Storage in the Future U.K. Electricity System

Economic Benefits of Storage Deployment

In this section, we discuss the whole-system value of ES for the Great Britain (GB) electricity system in 2030. The WeSIM model, developed at Imperial College London, was applied to add cost-optimal ES capacity to the GB electricity generation mix in the National Grid's "Gone Green" scenario, which features a high penetration of variable renewables. The model could adjust only conventional generation capacity—combined-cycle gas turbines (CCGTs) and open-cycle gas turbines (OCGTs)—while investing in ES; the low-carbon generation portfolio was kept the same as in the original scenario. Assumptions regarding the cost of distributed ES technologies in 2030 were taken from the report by the Carbon Trust and Imperial College (see the "For Further Reading" section), with a high ES cost scenario of £1,160/kW and a low ES cost scenario of £360/kW. To annualize the ES investment cost, a 20-year lifetime and 7% cost of capital are assumed.

System optimization results show that the model finds it cost optimal to add 8–19 GW of additional ES, depending on its cost. The option to build ES, therefore, represents the opportunity to reduce overall system cost. Figure 2 presents the total annual system cost savings per component, comparing the case without new ES and cases where new ES is available at either a high or a low cost.

The total net cost savings resulting from ES deployment vary between about £2 billion and £3 billion per year; higher savings are associated with lower cost of ES and vice versa. The net system cost savings consist of several key components.

- ✓ *System operating expense (OPEX) savings.* The deployment of ES results in the higher use of low-carbon generation, characterized by lower operating costs (reduced curtailment) and reduced production over a conventional gas-fired plant. This also includes provision of balancing and frequency regulation (FR) services, now growing in importance in GB given the reduction of system inertia.
- ✓ *Distribution capital expense (D CAPEX).* Distributed ES could support the management of power flows in distribution networks, leading to lower requirements for distribution network investment that may reinforce the grid to cope with increasing demand and/or increasing deployment of distributed generation, e.g., photovoltaic (PV) generation.
- ✓ *Generation capital expense (G CAPEX).* ES displaces peaking capacity (e.g., OCGT) as the conventional provider of adequate generation capacity required to

meet the security of supply criterion. This is reflected in lower capacity and, consequently, in reduced investment cost in peaking capacity units.

✓ *Transmission capital expense (T CAPEX)*. This component represents the investment cost associated with the reinforcement of key GB transmission corridors. Improved use of wind resources in the north of GB enabled by ES capacity in other parts of the country makes it more economical to reinforce north–south transmission capacity.

✓ *Storage capital expense (S CAPEX)*. This component appears negative in total net savings, as this is the additional cost required to build new ES assets; hence, it is offset against gross system savings.

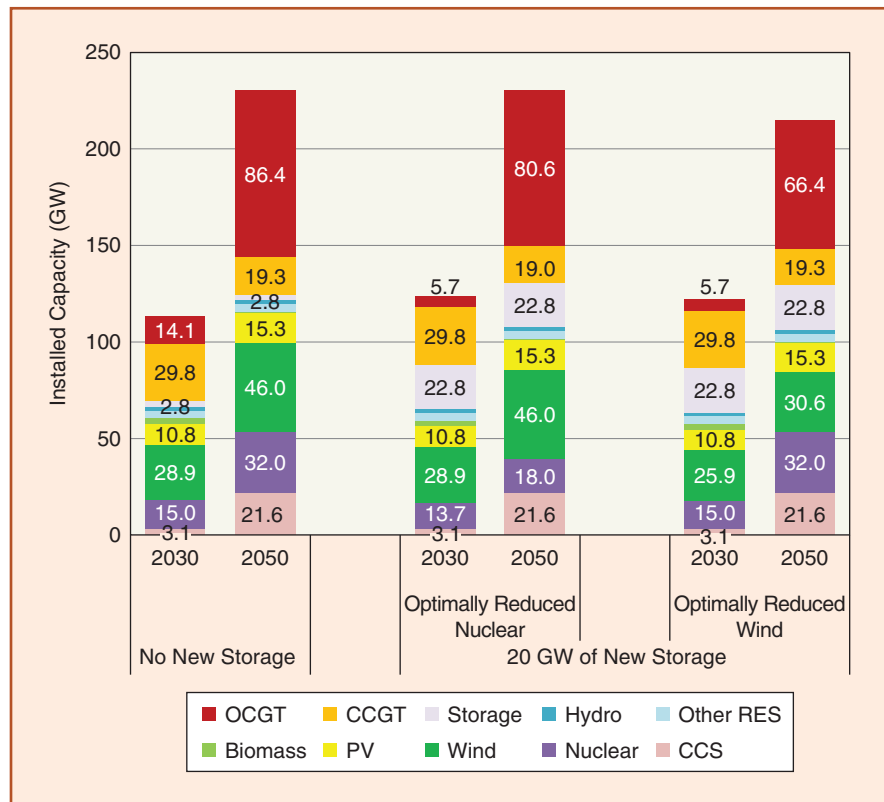


figure 3. The generation capacity mix in 2030 and 2050 before and after adding 20 GW of ES.

Value of Storage in Achieving Carbon Targets at a Lower Cost

ES can deliver carbon savings through improved operational efficiency of conventional plants and enhanced use of low-carbon generation. As a direct consequence, the deployment of ES may enable a given carbon reduction target to be achieved with lower capacity of low-carbon generation, bringing corresponding savings in investment cost.

To demonstrate the magnitude of this impact, a set of studies was carried out given the carbon intensity target of 100 g/kWh in 2030 and 25 g/kWh in 2050. The base case assumed no new ES added to the system. As shown in Figure 3, this scenario is characterized by 61 GW of combined wind and PV capacity and 32 GW of nuclear capacity in 2050.

Two additional sets of studies were then carried out with 20 GW of additional ES present in the system: 1) with optimally reduced nuclear and conventional capacity, while maintaining the 2030 and 2050 carbon targets, and 2) with reduced wind capacity. In both cases, the 20 GW of new ES made it possible to avoid building a significant amount of low-carbon generation capacity, while still meeting the same carbon emission targets.

The changes in the generation mix enabled by additional ES capacity are presented in Figure 4. In 2030, the new ES eliminates the need to install 1.2 GW of nuclear or 2.9 GW of wind capacity as part of the mix delivering a carbon intensity of 100 g/kWh. In 2050, on the other hand, as much

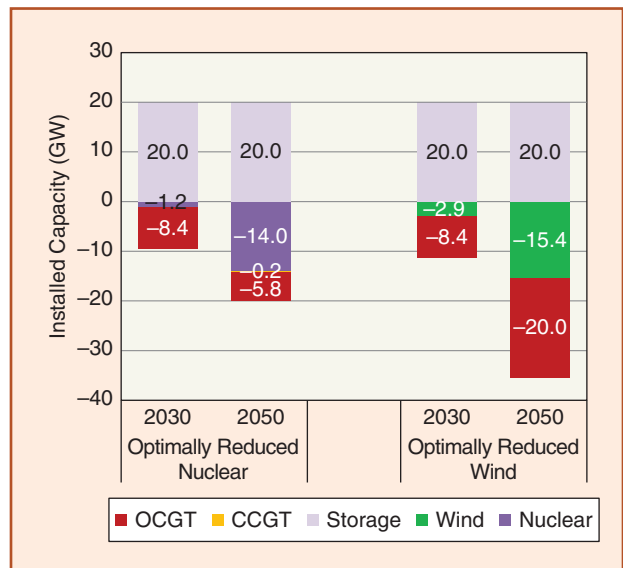


figure 4. The changes in the generation capacity mix in 2030 and 2050, driven by deployment of 20 GW of ES.

as 14 GW of nuclear capacity could be removed from the system if a sufficient volume of ES is installed. Similarly, ES would reduce the need for 15 GW of offshore wind generation, while still meeting the carbon emission target of 25 g/kWh.

Clearly, there is a massive scope for the application of ES and other flexible options in the context of future decarbonization of the U.K. power system. The flexibility provided by ES has the potential to enable the system to achieve ambitious future decarbonization targets at a far lower cost than with a low-flexibility system.

Competition Among ES and Other Flexible Solutions

In addition to ES, there are other competing flexible technological solutions that can have a positive effect on the ability of a system to achieve cost-effective integration of low-carbon generation. Some of the most studied solutions include DSR and flexible generation. In this section, we consider the potential competition among ES and other flexible options and quantify their impact on optimal deployment levels of ES as well as the resulting system benefits. Figure 5

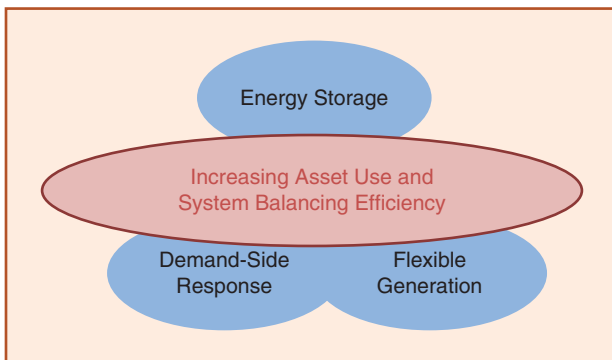


figure 5. Flexibility options in future electricity systems.

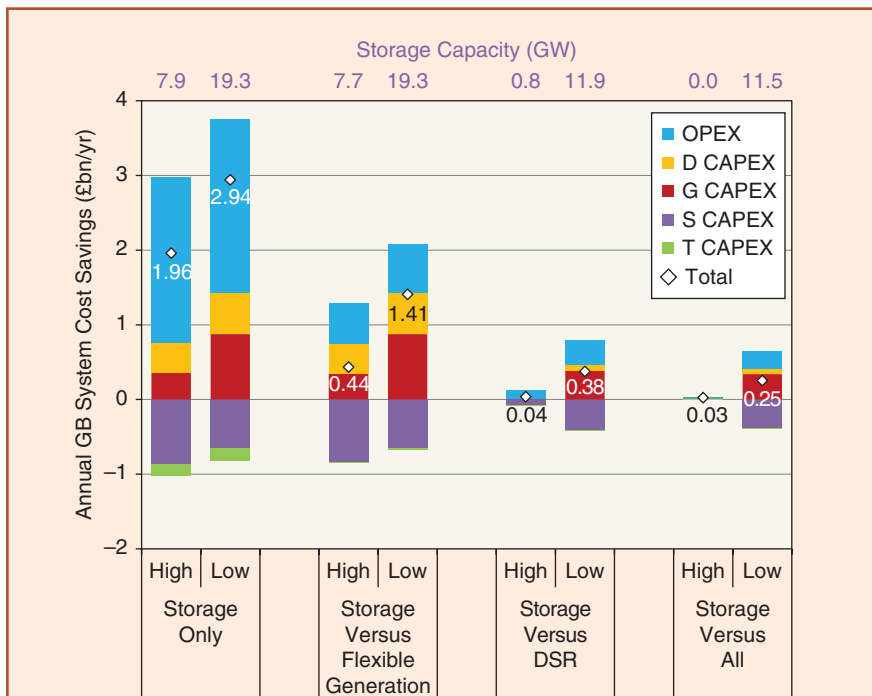


figure 6. Changes in deployed ES capacity when it is exposed to competition from other flexible options.

illustrates the interaction and competition among these flexible options in delivering a cost-efficient, low-carbon power system. Although no two options will be direct substitutes, there will be a degree of competition among them.

As in the storage-only studies presented in the “Economic Benefits of Storage Deployment” section, the system optimization model adds ES only if it results in a net system benefit. Figure 6 illustrates how the net benefits of ES deployment change as a consequence of having other flexible options present in the system and also indicates the cost-optimal volumes of ES for the same scenarios along the top axis.

The availability of flexible generation reduces the opportunities for new ES to generate operating cost savings due to more efficient operation and lower curtailment of renewables. Conversely, the system cost savings for generation and distribution CAPEX are not affected. Compared to the storage-only scenario, the total annual net benefits of ES drop to the range of £0.4–1.4 billion/year—although it is interesting to note that the volume of ES being deployed does not change significantly. This occurs because it is cost-effective to add storage as long as its marginal benefit is above its cost, and this break-even point is observed at similar volumes in cases with and without flexible generation. On the other hand, in the case without flexible generation, the marginal system benefits for first gigawatts of storage capacity are higher; hence, the total cumulative benefit up to the break-even point is also greater.

Under full penetration of DSR, the net benefits ES can provide are even further reduced. With low ES cost, the net benefits materialize at £0.38 billion/year (significantly lower than with storage only); in the case of high storage cost, the system net benefits are virtually zero. The cost-optimal amount of ES to add in a high-cost scenario with DSR is lower than 1 GW; in a low-cost scenario, the optimal volume is 7 GW lower than in the storage-only case, as DSR takes advantage of the same cost-saving opportunities as ES. Unlike flexible generators, DSR could also affect the distribution network loading, thus reducing the associated reinforcement cost. At the same time, DSR can support system balancing, provide reserve and response services, and reduce backup generation capacity requirements.

In the situation where ES competes against both flexible generation and DSR simultaneously, the results are similar to the case where only DSR competes against ES, confirming that DSR represents the key competitor to distributed ES. Additionally, the integration

of electric power and heat sectors may provide further sources of cost-effective flexibility to the electric power system and thus significantly reduce the need for electricity-based ES solutions.

Market Arrangements and the Business Case for ES

Deploying ES can result in significant system cost savings as well as carbon benefits. However, this societal benefit may not be realized if prospective investors in ES are not presented with a viable business case that adequately rewards them for creating these multiple sources of value. The following list describes the key services in which ES can be a primary contributor.

- ✓ *Energy arbitrage.* Participating in day-ahead energy markets, ES can take advantage of electricity price differentials by charging during lower-price periods and discharging during higher-price periods.
- ✓ *Balancing services.* Participating in real-time balancing markets, ES can provide short-term operating reserves to the system operator.
- ✓ *FR services.* Providing primary, secondary, and tertiary FR services to the system operator requires rapid response times and would be particularly well suited for battery storage technologies (the National Grid has recently introduced a new FR product, enhanced frequency response, that requires a response time of up to 1 s and is particularly well suited for lithium-ion battery applications).
- ✓ *Network support.* Placing ES at strategic locations in the distribution or transmission network may reduce the need to reinforce the network to cope with peak loading conditions.
- ✓ *Capacity market.* The participation of ES in contributing to firm supply capacity during critical peak hours of high system demand may reduce the need to keep low-utilization peaking plants on the system.
- ✓ *Carbon savings.* Improved operational efficiency of conventional plants and higher use of low-carbon generation capacity can contribute to carbon reduction. This contribution should be rewarded in the same way that low-carbon generation is rewarded.
- ✓ *Option value.* Option value refers to the ability of ES to defer and/or avoid premature commitment to capital investments.

Current market arrangements do not universally support the provision of many of these services and so may undermine the business case for ES. In several jurisdictions, ES is currently excluded from the capacity mechanism and cannot compete with conventional generation on a level playing field. Some markets that do consider ES as a resource may regard it as similar to gas turbines and other quick-start resources that may have limited run times but can defer traditional transmission improvements when the market design triggers the appropriate response. In these cases, ES is usually not considered part of transmission and distribution

tariffs. To achieve system-efficient levels of ES deployment, it is imperative that a level playing field be established that facilitates competition between traditional network reinforcement and ES, as discussed in the section “Assessing the Security of ES Supply Contribution.”

In the following, we demonstrate how an ES asset can maximize its revenues and achieve a positive business case by layering multiple services and securing multiple revenue streams (assuming a fully cost-reflective market design). If some of these revenue streams are not available to ES, the revenue may be insufficient to justify investment in ES, thus undermining its commercial viability. We further demonstrate how storage can be effectively used as one of the options for network planning alongside traditional assets, although this is currently not common in transmission and distribution planning. We also highlight the option value of storage, i.e., the additional benefit network planners could realize when faced with uncertain evolution of demand.

Commercial Value Derived from ES Providing Multiple Services

Here, we assess the revenues ES could potentially earn by providing a portfolio of services to various sectors. In this example, it is assumed that ES is connected to local PV generation, allowing management of its imbalances as well as any local network constraints. It is also assumed that markets for different services are fully cost-reflective; clearly, any inefficiencies in actual market arrangements may restrict the revenue opportunities for ES assets.

Conflicts and synergies among services may exist that need to be taken into account as part of the strategy for maximizing ES revenues. For instance, considering energy arbitrage and distribution network support services, if periods of high market prices coincide with periods of high demand at the distribution network level, it is obvious that both services will drive storage to discharge during the same time period, presenting a clear synergy between the two services. However, if peak demand conditions in the local distribution grid do not coincide with high system demand, these two services would be conflicting. The assessment of market revenues of ES carried out here ensures that any contracted services can be delivered when requested.

Figure 7 summarizes the results for the commercial value of ES from layered service provision. The capitalized value of annual revenues varies between £460/kW and £5,540/kW, depending on the range of services ES provides simultaneously. The ES value is capitalized assuming a 20-year life of the asset and the cost of capital of 7%.

The analysis assumes that the market design (including network charging) is fully cost-reflective and that the storage resource is then allocated to provide different services, maximizing the total revenue for ES while also delivering all commitments. In other words, this approach optimally balances synergies and conflicts among the provision of different services while maximizing income for the ES owner.

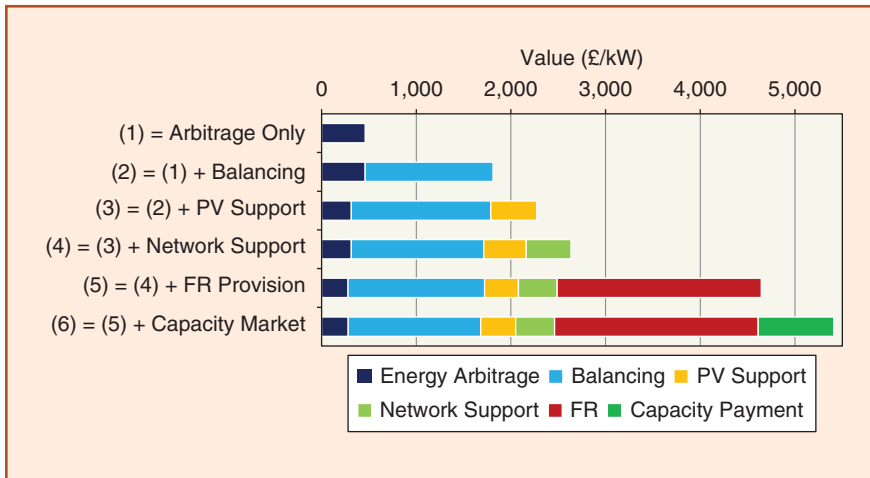


figure 7. The value of ES for providing multiple services.

It is clear that the revenues from any single service would not justify the investment in ES. Optimized provision of multiple services is, therefore, the key route for ES to make a profitable business case.

The results suggest considerable added value from storage being colocated and operated together with a PV farm (or, potentially, a wind farm), particularly when there is an active network constraint. Participation in the capacity market could secure additional up-front payment for ES while only slightly reducing its profit from other markets.

Provision of FR from ES would significantly enhance its value proposition, although this would greatly depend on the FR market arrangements. Clearly, the present long-term, contract-based ancillary service framework—rather than a real-time market for ancillary services—would prevent ES from simultaneously accessing the revenues associated with providing FR and distribution network management services or energy arbitrage. Also, the system requirements for FR (and hence its value) vary significantly with actual system conditions, i.e., the level of demand and production of renewable generation (this is associated with the issue of inertia available in the system, provided by rotating synchronous generators).

When low-demand conditions coincide with high renewable output, the value of FR can be very high due to reduced

including operational planning needs and the human-machine interface.

Assessing the Security of ES Supply Contribution

ES plants, as well as other flexible solutions such as DSR and distributed generation, could play a role in enhancing the security of electrical systems; they can provide peak shaving services, as well as maintain supply during network contingencies, and may thus represent a viable alternative to conventional network reinforcement. The emergence of new technologies is creating the need to review historical network planning standards to establish a level playing field that will allow both conventional network solutions and new technologies to be considered when determining the most cost-effective solutions for dealing with demand growth.

To determine the capacity credit of an ES plant connected to a distribution network, we adopt the concept of effective load-carrying capability (ELCC), a standard metric defined as the amount by which the demand can increase while maintaining the same reliability of supply, measured through expected energy not served (EENS). As such, ELCC represents the amount of demand that can be added to the network supported by ES resulting in the same EENS as the original network (referred to as the “base case”); this equivalence is shown in Figure 8.

A continuous-time chronological Monte Carlo simulation framework is used to generate populations of fault histories, which are combined with a discrete-time steady-state model of ES operation to quantify the EENS across a large number of years. A simple $N-1$ system is assumed, as shown in Figure 8, with two transformers of 1 MW each and peak demand of 1 MW. It is further assumed that an ES plant is fully dedicated to security provision. The ES security contribution is then quantified based on the ES plant’s power and energy capability but also on network characteristics such as network outage times and demand shape.

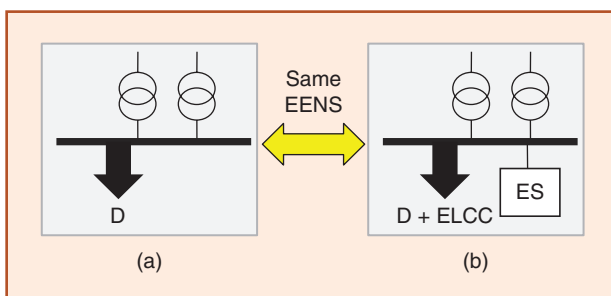


figure 8. The equivalence between (a) the base case system and (b) the system with ES. D: demand.

The first key finding is that the higher energy capacity of ES increases the ability to sustain operation during outage conditions. In Figure 9, normalized ELCC values are presented for six different ES plant sizes, characterized by a power rating normalized over peak demand and energy capacity expressed in hours at the maximum output. For instance, a 50%/5-h plant refers to an ES plant with 0.5 MW of power and 2.5 MWh of energy. Its normalized ELCC value is 72%, meaning that upon connecting the ES asset, 0.36 MW of demand can be added to the system with no increase to the original EENS. In this illustrative case study, the network's reliability parameters were assumed as follows: mean time between failures (MTBF) of one year and mean time outage duration (MTOD) of 3 h.

The second key finding is that network outage duration (which is a function of MTOD) is one of the most important drivers for the contribution of ES to security of supply: the longer the outage duration, the more energy is required from ES to supply the extra demand. This relationship is shown in Figure 10 by plotting normalized ELCC values across four different MTOD scenarios: 3, 12, 24, and 240 h. It is evident that the same ES plant will have a significantly reduced security contribution as the duration of network outage increases: for extremely long restoration times (240 h), the ELCC drops below 5% across all plant sizes; in a fast-restoration scenario, the ELCC of ES can reach close to 100% for a low normalized power rating.

Finally, the analysis suggests that, unlike the security contribution of conventional network and generation assets (determined based simply on the instantaneous peak demand level), with ES the shape of demand may also have a major impact on its security contribution. A flatter demand shape (i.e., increased minimum demand level) means that less energy is available for charging during single-outage events. For example, if the normalized minimum load in the network increases from 0.4 to 0.8, the ELCC of a 100%/5-h ES plant is reduced from about 50% to 30%.

In summary, for a full understanding of the security contribution of an ES asset, additional information regarding the shape of the network demand profile and network outage duration will be needed. The approach presented here has been used to inform the fundamental review of distribution network design standards in the United Kingdom aimed at establishing a level playing field that will allow both conventional network technologies and non-network technologies, such as ES, to be considered as cost-effective alternatives for meeting security requirements in case of demand growth.

Option Value of Storage

Besides the widely discussed benefits of ES in terms of enhancing operational flexibility, it can also play a key role in deferring capital investments. This ability is less recognized, although it can have strategic value when uncertainty is present. Historically, transmission and distribution planning has involved little uncertainty regarding future system evolution;

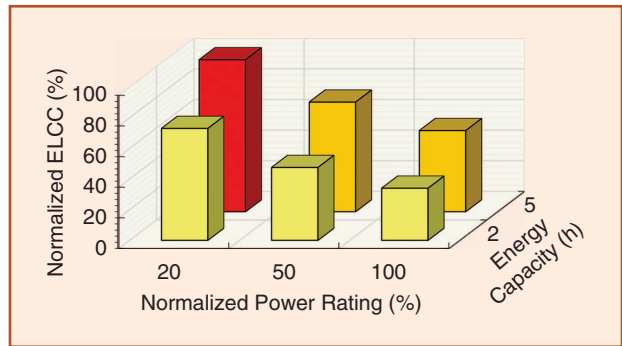


figure 9. The contribution of ES to security (ELCC) for different ES plant sizes.

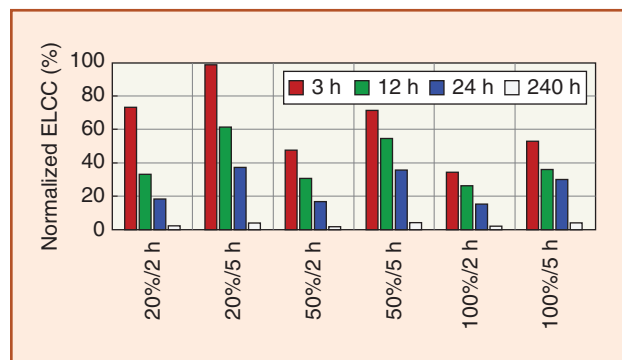


figure 10. The normalized ELCC for ES of different sizes across four MTODs with MTBF of one year.

however, planners today often have to approve projects ahead of need due to anticipation of rapid demand and/or generation growth and lengthy permitting and asset delivery procedures.

ES entails lower stranding risks because, even if the envisaged scenario that warranted its deployment does not materialize, it can still contribute to operation by providing other support services. In addition, the operational flexibility of ES can have broader nonlocalized effects, providing a natural hedge when future developments are characterized by locational uncertainty. Furthermore, it has recently been shown that flexible assets such as ES can grant planners the ability to react to unfolding uncertainty while deferring the commitment to investments until they are fully justified. In other words, interim solutions such as ES can “buy time” until uncertainty is resolved. Several forms of ES, such as batteries, can also be rapidly redeployed if network needs change.

The case presented here illustrates the option value of ES and demonstrates its significance to tip the decision in favor of strategic ES investments when uncertainty is formally considered in the planning process. Our study focuses on a transmission system comprised of two regions; the north region exports power to the demand in the south region through two 200-MW lines. We assume that the network is currently at its $N-1$ secure operating limit, i.e., facing a total group peak demand of 200 MW. Four scenarios spanning four stages of four years each have

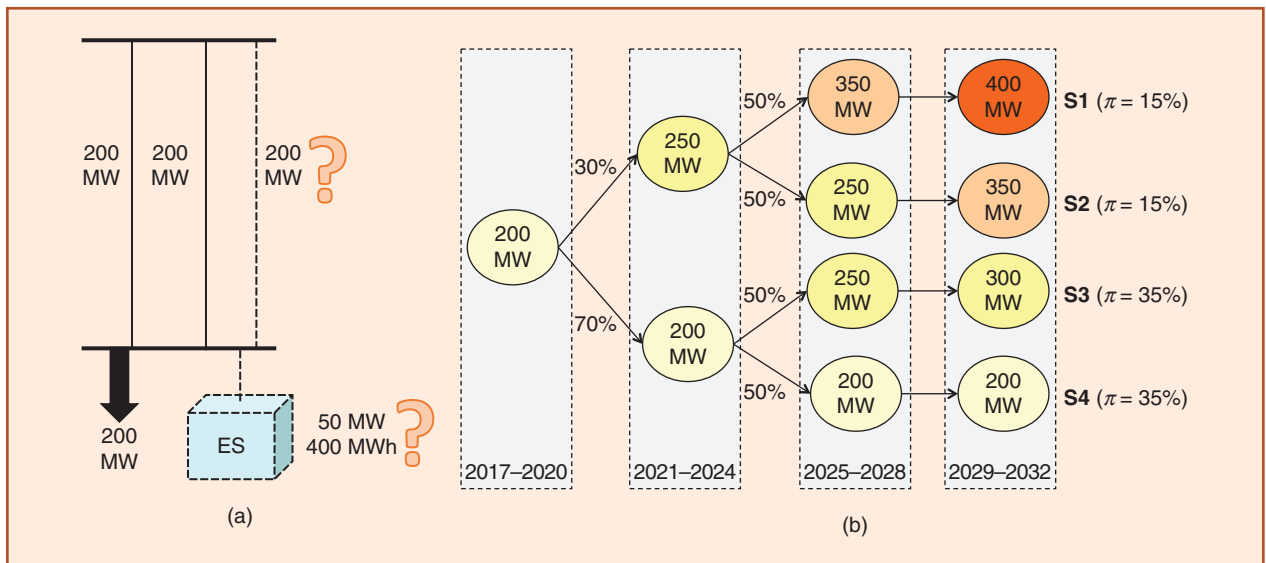


figure 11. (a) The system under study showing candidate assets. (b) A scenario tree showing the evolution of peak demand across four scenarios (S1–S4) over four-year periods.

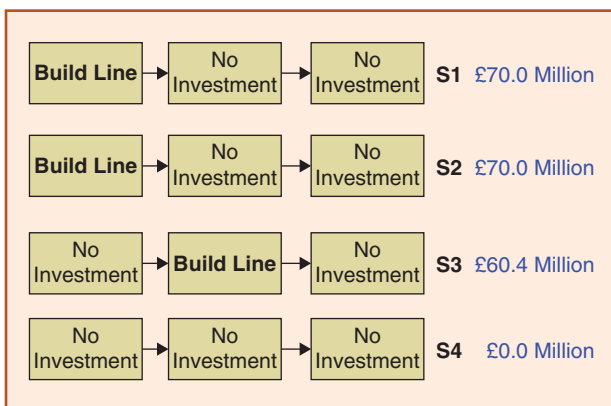


figure 12. The optimal investment plan for each of the four scenarios shown in Figure 11 when examined in isolation.

been developed to describe potential trajectories of the system’s demand evolution, as shown in Figure 11.

Scenario 1 represents a high-growth situation and is assigned 15% probability. Scenarios 2 and 3 capture more moderate growth cases, while scenario 4 describes the case in which no additional load is added to the system, occurring with 35% probability. The planner has the following two options for reinforcing the system:

- ✓ Install a new 200-MW line at a present capital cost of £70 million. We assume that the commissioning of the new line takes four years to complete due to permitting and other asset deployment constraints.
- ✓ Immediately deploy an ES plant with a 50-MW power rating and 125-MWh energy capacity; this plant has a present capital cost of £30 million.

Figure 12 presents the optimal investment plans obtained with a deterministic approach, in which the planner considers

each of the individual scenarios in isolation. In scenarios 1 and 2, the optimal strategy is to build a new line from the start, while in scenario 3 the investment is deferred to the second stage. Scenario 4 entails no demand increase and hence no investment is required.

It is of paramount importance to note that in Figure 12, although the option to build ES is available, it is not used in any individual scenario as it does not present additional benefit under perfect foresight. Figure 13, on the other hand, shows the optimal investment strategy when the planner does not know which of the four scenarios will actually materialize and hence needs to consider uncertainty in making investment decisions.

Two cases are shown, one in which investment decisions are limited to new lines only [Figure 13(a)] and the other that also allows the possibility of investing in ES [Figure 13(b)]. In the first version, it is necessary to build a line immediately to ensure that scenarios 1 and 2 do not lead to demand curtailment. However, when investment in ES is possible, a different strategy emerges: the first-stage investment decision is deferred to later stages and is made conditionally based on the scenario’s realization. The planner adopts a “wait-and-see” approach in the beginning and subsequently deploys both an ES plant and a line if demand begins to increase. The ES plant is used to enable interim operation until the line is commissioned. The expected net present values of the total investment cost for the two versions are £70 million and £50.85 million, respectively, making the option value of ES £19.15 million. This value arises from the ability of ES to allow the decision to invest in a new line to be deferred until later stages, if demand increases sufficiently; this case also ensures that, under scenario 4, no unnecessary investment is undertaken.

Energy storage can deliver carbon savings through improved operational efficiency of conventional plants and enhanced use of low-carbon generation.

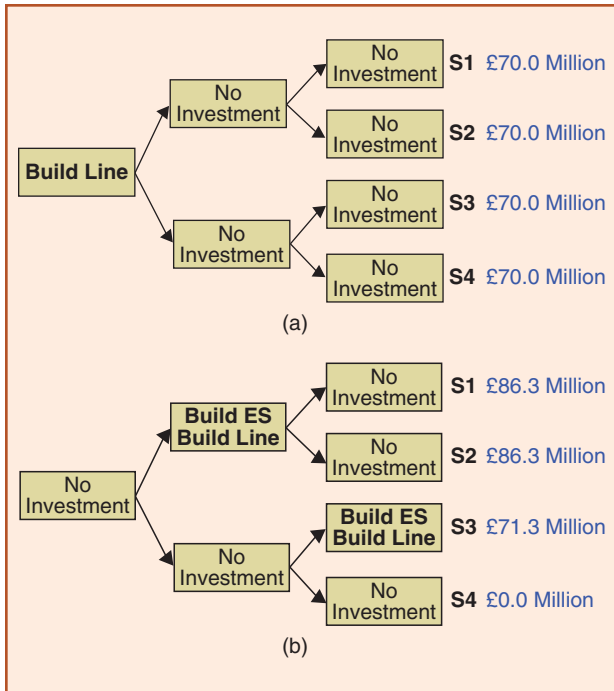


figure 13. The optimal investment strategy under uncertainty (a) limited to new lines and (b) considering ES investments.

Looking Forward

The cost-effective evolution toward low-carbon electricity supply will require improved system flexibility to address the challenges of increased balancing requirements and degradation in asset utilization. As we have shown here, the additional flexibility offered by ES could significantly reduce the requirement for low-carbon capacity.

Cost-efficient deployment of new ES in the United Kingdom in 2030 can reach up to 19 GW, depending on the cost of ES. However, DSR represents a key flexible competitor that could limit the business case for ES.

In an actual market environment, ES has the potential to provide a range of system services, such as energy arbitrage, balancing, network management, and capacity market adaptability. Moreover, ES presents significant option value, as it can provide flexibility to deal with uncertainty in future system development and be a key contributor to firm capacity during critical peak hours. However, present market and regulatory barriers may prevent the realization of the quantified system value and thus weaken the business case for ES. Developing fully cost-reflective markets and effective regulatory frameworks is therefore necessary to ensure that the commercial

incentives for investing and operating ES are aligned with the societal benefits. To unlock the full potential of ES, establishing a level playing field is fundamental to incorporating ES in network planning standards and market frameworks.

For Further Reading

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