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Business cases for energy storage with multiple service provision

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Abstract Energy storage (ES) has been considered as the key source of flexibility to support the integration of renewable energy. Previous studies have demonstrated the substantial system cost savings by the deployment of ES, including both investment and operation of generation, transmission and distribution infrastructure. However, this societal benefit may not be realized if industry actors do not have a viable business case to appropriately capture these multiple value streams. In this context, this paper investigates the value that ES may deliver to its owner over two specific business cases in a 2030 UK system. Firstly, the application of large-scale ES in the wholesale market is analysed. It is demonstrated that the optimal allocation of ES to provide multiple services is the key element for ES to become competitive in the electricity market. In the second business case, this paper analyses the value of kilowatt-scale ES combined with roof photovoltaic (PV) system in the household and community level. The study shows that multiple service provision of ES through advanced pricing schemes, for example time-of-use (ToU) tariff and dynamic distribution use of system (DUoS), lead to higher value and the coordination in the community level could further justify the application of domestic ES.

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1 Introduction

The electricity systems all over the world are undergoing significant changes to provide secure, affordable and low carbon electricity. As an emerging technology to support the cost-efficient integration of renewable energy, energy storage (ES) has attracted extensive research to investigate its role and value in the future low carbon electricity system. Previous studies analyse the value of ES in US [1], Europe [2] and Australia [3] to perform energy arbitrage by storing low-cost electricity during periods of low net demand and releasing back to the grid during periods of high net demand. While authors in [4, 5] demonstrate the increased value of ES by providing both energy arbitrage and ancillary services. Stochastic approach is applied in [6] to quantify the value of ES under wind uncertainty. The impact of the increased renewable energy on the volatility of the market prices and hence the value of ES is discussed in [7, 8]. Further, the application of ES in distribution network is reviewed in [9]. The analysis in [10, 11] shows the benefits of ES to increase the revenue for the non-firm distributed renewable generation.

Recent studies identify the need for combined analysis of various electricity sectors to adequately assess the value of ES from multiple revenue streams. In particular, the studies carried out in [12, 13] suggest a substantial system cost reduction driven by ES covering both investment and operation over generation, transmission network and distribution network. However, this societal benefit may not be realised if industry actors do not have a viable business case to appropriately capture these multiple value streams. The authors in [14] propose a novel business model for ES to simultaneously participate in week-ahead, day-ahead and hour-ahead auctions. While the study in [15] quantify the value of distributed ES in providing energy arbitrage, reserve, response and DNO service. Both of these studies demonstrate the enhanced value proposition of ES when optimally allocating ES among multiple functions. However, these studies do not consider either the impact of renewable energy on the market prices or recently established capacity market.

In this context, this paper further analyses the value of ES with simultaneous provision of multiple services and informs the design of market and regulatory framework to align the commercial incentives in investing ES with the societal benefits that ES may deliver. Two business cases for both MW-scale centralized ES and kW-scale domestic ES are considered. Firstly, as the increased price volatility and balancing challenges driven by the integration of renewable energy, the application of MW-scale centralized ES in wholesale market may become particularly attractive. Secondly, as the rapid growth in roof PV installation in UK, there is significant potential of combined application of kW-scale domestic ES and PV to maximise the feed-in-tariff (FiT) revenue. Furthermore, the introduction of ToU tariff and dynamic DUoS charge may further support the application of kW-scale ES in the household and community level. The key contributions of this paper can be summarised as:

1) This paper analyses a wide range of services that ES could potentially provide. Energy arbitrage, balancing service, wind support, network support, frequency response (FR) provision and capacity market are considered for bulk ES, while energy arbitrage, PV support, distribution network support and FR provision are considered for domestic ES. The results demonstrate that it is critical for ES to simultaneously provide multiple services in order to make a profitable business case. Furthermore, the optimised multiple service provision from ES may also reduce the lift-time degradation.
2) This paper also analyses the impacts of different market arrangements (e.g. FR market) and tariff designs (e.g. ToU) on the value of ES. The results suggest that appropriately designed market and tariff need to be in place to facilitate ES to capture its multiple value streams.
3) To enable the analysis, this paper extends our previous modelling framework to include co-locating ES with wind farm (WF) to provide balancing/network support, flexible FR market and capacity market. Furthermore, a wide range of measured demand profiles in UK is collected, categorized and analysed in this paper.

2 Bulk energy storage in wholesale market

2.1 Modelling of wholesale market

This section implements an advance contracting market structure, where there is a short-term power exchange (STPX) with hourly energy prices available in a rolling basis. This market is assumed to be closed 4-hour ahead of real-time operation. Once STPX is closed, all market players submit their final positions to system operator (SO) as the contracted obligations. However, some participant may not be able to provide the contracted energy due to the plant outages or generation variation. Therefore, SO re-dispatches the system in real time to manage system imbalance. In particular, flexible resources would bid into the balancing market to balance the supply and demand. Any real-time energy imbalances are cleared at either the system buy price (SBP) for short positions or system sell price (SSP) for long positions. To avoid the risk of high imbalance charges, a market participant could buy a balancing contract with another party. In this case, if one party were short on its contracted position, the second party would increase output to keep the group position in balance and hence avoid paying high SBP in the balancing market. This is extremely relevant for WF due to the difficulties associated with accurate forecast of wind generation. In such situation, the combined operation of ES and WF may become attractive.

A similar market structure as [5] is applied in this section to assess the value of ES with multiple service provision. The annual value of ES is calculated by dividing the total profit of the storage in a targeted year with its rated capacity. As shown in Fig. 1, the study is carried out in 2 stages. The first stage is to derive the energy prices, imbalance prices and FR prices in a rolling basis by using the advanced stochastic unit commitment (ASUC) model in [16]. The ASUC model optimizes the operation of a given future system by simultaneously scheduling energy production, reserve services and FR under uncertainties assocted with wind generation and plant outages. After the commitment decisions are made, the model calculates the optimal dual variable of demand and generation balance constraint as the energy or imbalance price. The energy price is calculated in a single scenario which describes the most-likely value of stochastic variables in day-ahead, while the imbalance price is calculated in real-time operation with full consideration of stochastic variables in the scenario tree. Furthermore, the system scheduling model in [16] captures the impact of reduced system inertia on the

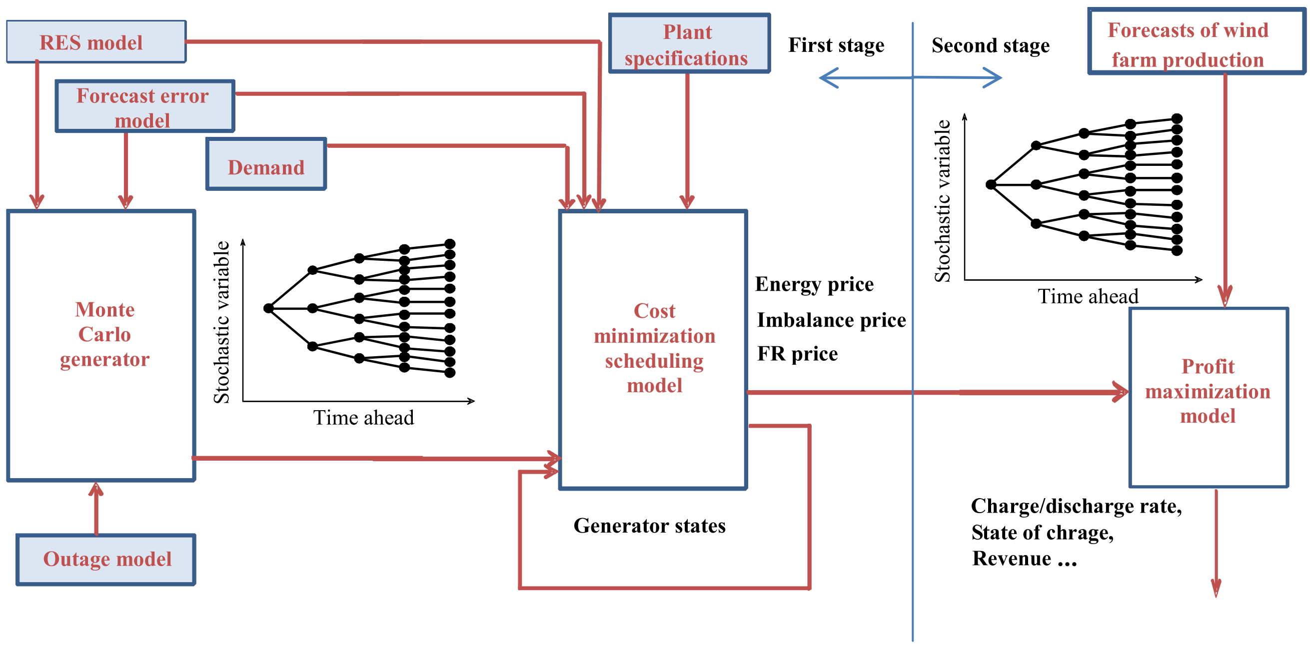

Fig. 1 Assessment framework to evaluate ES

FR requirements. The marginal cost of FR provision during each time interval is used as the FR price. This is calculated by comparing system operation costs with and without 100 MW freely-available FR.

In the second stage, with the assumption that the capacity of ES under investigation is small enough to be modelled as price-taker, the stochastic storage scheduling model determines the operation of ES to maximize the expected revenue of ES, based on the price information passed by the system scheduling model and a scenario tree that describes the possible realizations for wind production. WF is assumed to submit the persistent forecasts as the final position at the close of STPX. ES could therefore support WF by reducing the penalty charge on the mismatch between contracted and realized wind production, while still participating in other markets to maximize the overall profit. Furthermore, due to the intermittent nature of wind generation, the optimal capacity of network connection between WF and grid is normally lower than the total installed capacity of WF, which inevitably leads to wind curtailment during high wind conditions. Under this situation, ES could be applied to support network management by storing the excessive wind generation and selling it when the network capacity becomes available.

To provide FR in certain hour, ES is required to have spare headroom to deliver the increased active power as well as enough stored energy to sustain the increased power supply for 30 min. Under the present UK electricity market arrangements, FR is contracted for the duration of a month or a week, at long time ahead of real-time operation. The FR service is required to be available across the day or during chosen hours for the whole contracted period, which may prevent ES from providing other services. Furthermore, our analysis has clearly demonstrated that the value of FR provision varies significantly over time depending on the level of net demand. As shown in Fig. 2, the system cost saving from FR provision over a week varies from almost zero in the high net demand conditions to more than 200 £/MW/h in the low net demand conditions. These issues raise questions over the efficiency of present FR market arrangement. Therefore, the value of FR provision by ES is investigated under two different market arrangements:

1) Advanced contract of FR

   This is the same as the present electricity market arrangement, where the amount of FR is contracted at long time ahead of real-time operation and required to be available across the day (FR at all time) or during

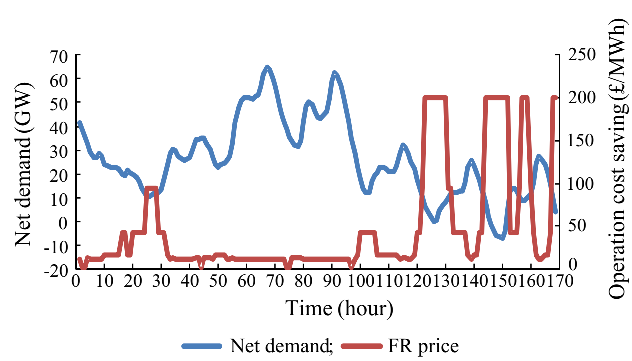

Fig. 2 Operation cost saving from FR provision

peak demand hours 07:00–09:00 and 17:00–21:00 (FR at selected hours).

2) Optimal FR
This is a more flexible arrangement for FR market, which allows the provision of FR to be determined at the close of STPX. Under this market arrangement, ES could actually optimize the provision of FR based on FR prices and prices of other services.

Moreover, capacity markets are recently developed in both Europe and US to ensure capacity adequacy in the future low carbon systems. To be quantified in the capacity market and obtain capacity payment, participates need to commit to provide a certain amount of energy production or demand reduction during peak hours determined by the system operator in a targeted year. ES could potentially participate in the capacity market by holding certain power headroom and stored energy available for these pre-determined hours. In this paper, it is assumed that participates in capacity market need to be available to produce 4 hours during peak time in 10 days with highest peak demand over the year, which are incorporated into ES profit maximization model as constraints if ES participating in this market. In addition to the extra payment, another attractive point of capacity market is that the payment is made up-front and could be used to finance the implementation of ES.

To enable the analysis, we extend our previous modelling framework in [6] so that the capacity of ES could be optimally allocated among energy arbitrage, balancing service, wind support, network support, FR provision and capacity market. The extended stochastic storage scheduling model is presented in Appendix A.

2.2 Case studies

A set of studies are carried out to investigate the application of ES for multiple commercial activities. As shown in Table 1, the value of ES is quantified and compared under different operation strategies. There are in total six services that are considered and the cases are presented in a stacked service nature whereby the benefits of adding extra services are illustrated step-by-step.

Table 1 Service provision in each case study

	Case1	Case2	Case3	Case4	Case5	Case6
Energy arbitrage	✔	✔	✔	✔	✔	✔
Balancing		✔	✔	✔	✔	✔
Wind support			✔	✔	✔	✔
Network support				✔	✔	✔
FR provision					✔	✔
Capacity market						✔

Instead of using historic data, this paper analyses the value of ES under 2030 UK Gone Green system scenario [17]. The generation mix is shown in Fig. 3, while the technical, economic and emission characteristics of generation technologies as well as fuel and carbon prices are adopted from [7]. The energy prices, imbalance prices and FR prices are calculated based on the above assumption by using the advanced stochastic unit commitment model, while the payment from capacity market is assumed to be 80 £/kW per year. This section investigates the ES equipped with 4h energy capacity and 75% round-trip efficiency.

Fig. 4 shows the value of ES in energy and balancing market. The value of ES is about 42 £/kW per year if only performing arbitrage, while the value increases to 180 £/kW per year if providing both arbitrage and balancing service. This is due to the increased balancing challenges in future UK system with high penetration of renewable energy. In particular, frequent activation of OCGT with high marginal cost to manage unexpected sudden wind drops lead to extreme high imbalance prices. Therefore, providing balancing service enhance the value of ES.

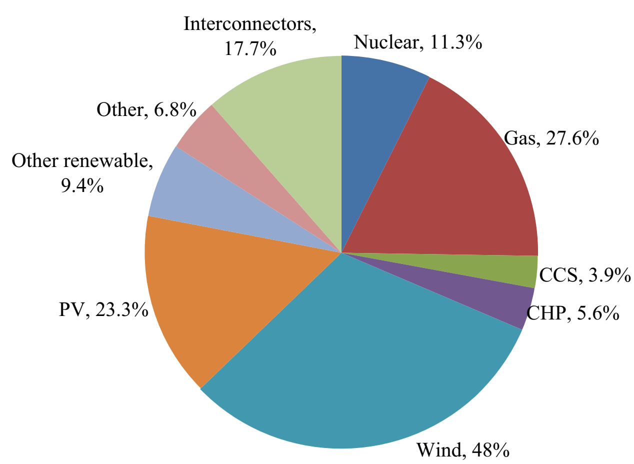

Fig. 3 Generation system mix

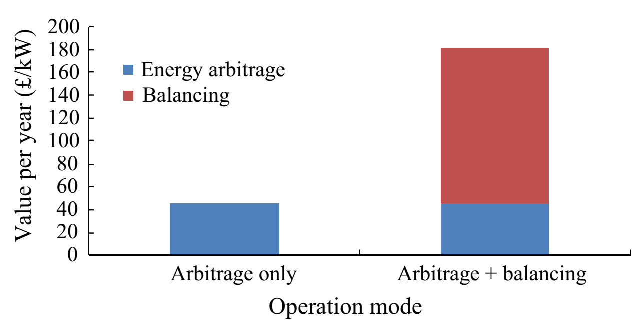

Fig. 4 Value of ES in energy & balancing market

Another potential application of ES is to be jointly operated with a WF by mitigating imbalance charges driven by the forecasting error and wind curtailment driven by the network limit. We investigate the value of a 5/25 MW ES when co-operated with a 100 MW WF in a network with 50/100 MW limit. The results in Fig. 5 suggest that joint operation strategy may increase the value of ES by up to 100 £/kW per year through reducing the imbalance charge on WF, although the added value decrease with increased capacity of ES combined with this WF. This implies an optimal sizing problem for ES to be co-operated with a WF. Furthermore, limited connection capacity between WF and grid may lead to wind curtailment during high wind conditions. ES could be used to manage network constraints by storing these excess wind generation, which may in turn enhance the business case of combined operation of ES and WF. We therefore analysed the value of a 25 MW ES under combined operation strategy in the presence of local network limits. The results in Fig. 5 show that by supporting network management, the value of ES could be further increased by 80 £/kW per year in the case of 50 MW local network limit.

Furthermore, the valued of ES with FR provision under different market arrangements are summarized in Fig. 6. Under the present market arrangement, 25%, 50% or 75% of the ES's capacity is dedicated to FR services either during all day or only during peak hours. In general, the results suggest that participating in FR market would increase the overall profit of ES, although the profits from other streams decline. The arrangement of FR market also shows dramatic impact on this added value. Under all-day provision assumption, the value obtained by ES increases along with increased provision of FR by up to 90 £/ kW-year. However, if ES provides FR at only peak hours of the day, the profit from FR market is largely offset by the reduced profit from other markets. It is due to the fact that other services (e.g. balancing) are in general more valuable during peak hours and providing FR would prevent ES from obtaining revenues from these markets. The added value with optimal FR provision is much higher than that with present market arrangement. This high value is driven by the flexibility to provide optimal amount of FR under different system conditions. On one hand, if the prices from other markets are higher, ES could be used to provide other services instead of FR. On the other hand, during hours with high FR price, ES could choose to charge at the maximum rate and offer up to twice of its power capacity in the FR market. Under optimal FR provision, ES could obtain large amount of profit from FR market with only limited compromise on the profits from other markets. In summary, FR provision from ES could significantly increase its value, but this highly depends on the arrangements of FR market.

Fig. 7 shows the additional value of ES when participating in the capacity market. Two cases are considered in order to provide robust estimation: 1) Zero Output: ES is assumed to stay idle during the contracted hours; 2) Full Output: ES is assumed to be called and produce at the contracted amount during the contracted hours. The 'true' value will lie somewhere between the two cases. The results suggest that there is only slightly reduction of the profit from other markets when ES participating in the capacity market. This is due to the fact that capacity market participation only affects the operation of ES over 40 hours of the year and more importantly these 40 hours are chosen

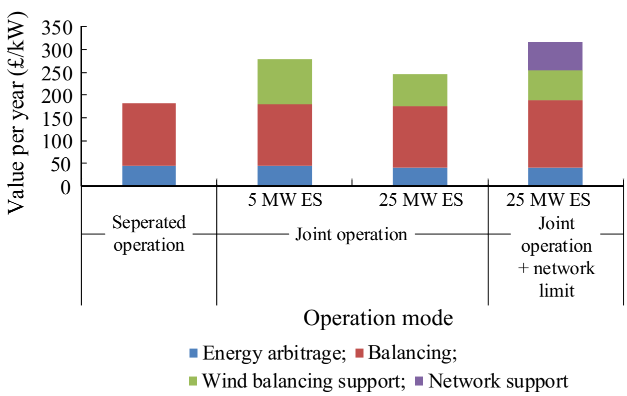

Fig. 5 Value of ES under joint operation with WF

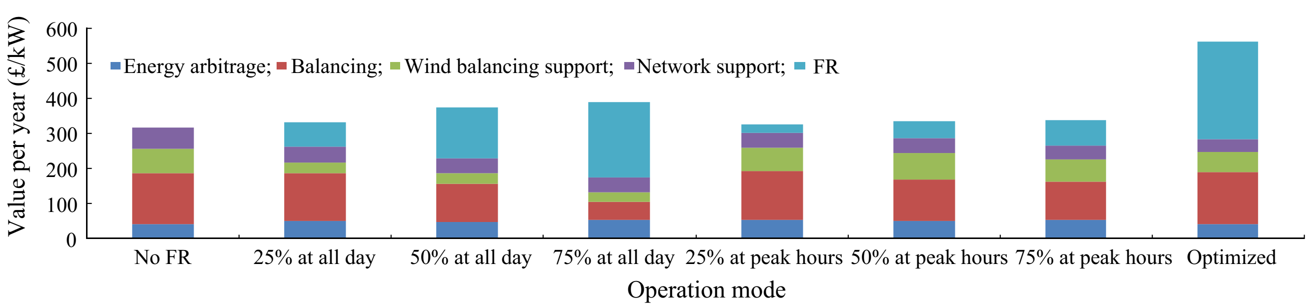

Fig. 6 Value of ES with primary frequency response provision

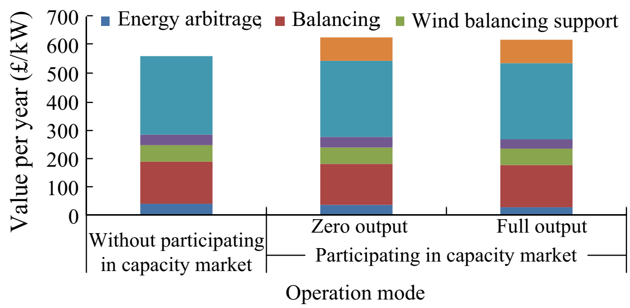

Fig. 7 Value of ES with Capacity Market

from the peak demand periods when FR price tends to be low.

In addition to the annual profit from electricity markets, the life time of ES is another key barrier in the deployment of ES. Some studies have shown significant impact of battery life degradation on the lift-time value of ES [18]. In fact, our analysis demonstrates that allowing ES to provide multiple services in an optimised way not only increases the annual profit of ES but also may reduce the lift-time degradation. Fig. 8 shows the state of charge of ES when providing energy arbitrage only or both energy arbitrage and balancing service over a month. It is clear that when ES performs arbitrage only, it charges and discharges both more frequently and deeper in order to maximise the revenue through capturing the market price differences across time. While when providing both arbitrage and balancing service, ES tends to keep state of charge above certain level to be ready to capture the rare but extreme high imbalance prices.

3 Domestic energy storage in retail market

The previous study discusses the potential value of large scale ES with optimized multiple service provision in the wholesale electricity market. This case, on the other hand, will examine the application of kW-scale domestic ES systems in the retail market.

Since the introduction of FiT, the installed capacity of distributed PV systems has increased significantly in UK. The FiT rewards not only the energy produced by PV but also the ability to self-consume the output. Due to the significant difference between the retail price and the export tariff (4.85 p/kWh), it may be attractive to apply ES to maximise the FiT revenue of domestic PV system. Moreover, with the fast roll-out of smart meter, ToU tariff (as shown in Fig. 9) has been proposed to stimulate the electricity consumption during off-peak periods, which creates opportunities for ES to reduce the household bills by shifting the electricity consumption away from peak periods. In addition to reducing electricity charges, ES is capable to support distribution network management through minimizing the dynamic DUoS charge. Finally, aggregated domestic ES in the community level could also provide grid services to enhance its value proposition.

In this context, a year-round ES optimisation is performed to maximise the profit of ES by minimizing the household or the community electricity bills and providing grid services. The mathematical model behind this study is presented in Appendix B. This section firstly looks at the effects on an individual household level, and how ES can be used to reduce the household's bills. This is referred as the individual domestic ES scenario. Secondly, we proceed to view the effects from a community level. This is referred as the aggregated ES scenario. Under this scenario, the case is presented in a stacked service manner whereby the benefits of adding services are illustrated.

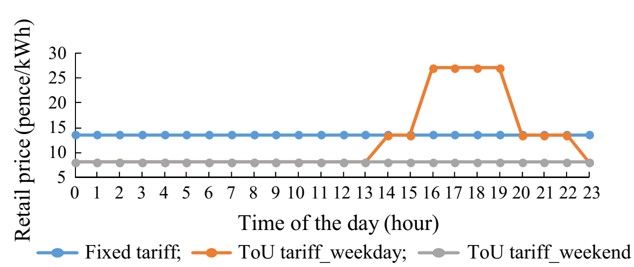

Fig. 9 Fixed tariff and ToU tariff

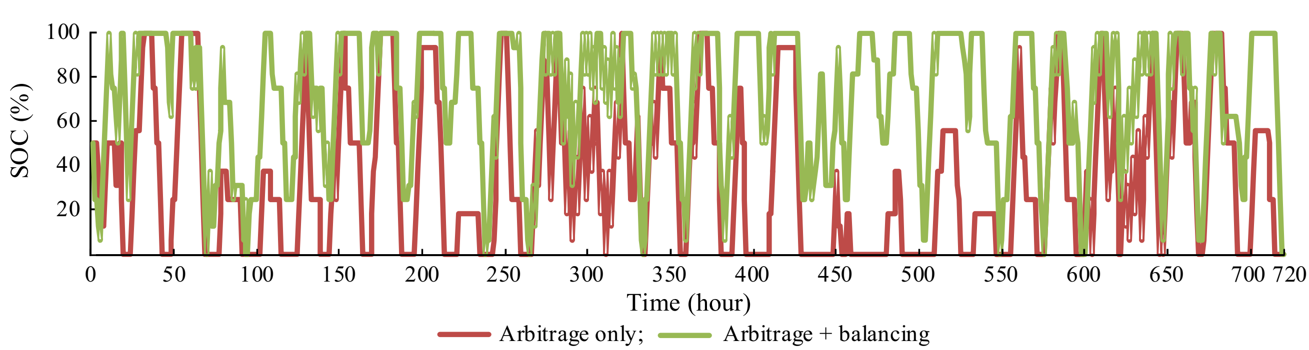

Fig. 8 State of charge of ES providing arbitrage only or arbitrage and wind management

As the variation of demand profiles, the value of ES could vary dramatically from household to household. It is hence important to cover a wide range of households in order to obtain a robust estimation of its value. In this section, we use the measured demand profiles from Low Carbon London trails in UK. As shown in Table 2, these demand profiles are categorized into nine groups based on the income of occupants and household size. 10 profiles are randomly chosen from each group and hence in total 90 demand profiles are analysed. The case studies assume that a 2 kW roof PV system is installed in each household and the value of a Tesla Powerwall-type Li-ion battery (2 kW/7 kWh/92.5% efficiency) is assessed.

Fig. 10 shows the distribution of the values of ES across all 90 households under investigation. The value of ES varies significantly, depending on the demand profiles as well as the electricity tariffs. Under fixed electricity tariff, the values lay in a relative narrow range, mostly between 30 £/kW per year and 40 £/kW per year. While under ToU tariff, the value increases to between 40 £/kW per year and 80 £/kW per year for most of the households.

Furthermore, the average value of ES in each demand category is summarised in Fig. 11. Under the fixed tariff, the values of ES are similar for all demand categories, while under ToU tariff, there is a clear trend that the higher annual electricity consumption, the higher value for ES. Moreover, for demand category 1, 2, 4 and 7, the introduction of ToU tariff shows limited impact on the value of ES. This is due to the fact that relatively low consumptions during peak hours in these categories could already been supplied by PV generation and therefore there is no opportunity for ES to shift demand away from peak hours. For these users, the value of ES is mainly from increasing the self-consumption of PV. While for category 3, 5, 6, 8 and 9, which consume relatively high electricity during peak hours, the value of ES is dramatically increased under ToU tariff.

Table 2 Properties of demand profiles

Data subset	Income	Number of people	Annual consumption (kWh)
C1	Adversity	1	2012
C2	Adversity	2	3188
C3	Adversity	3+	4150
C4	Comfortable	1	2176
C5	Comfortable	2	3557
C6	Comfortable	3+	4663
C7	Affluent	1	2772
C8	Affluent	2	3964
C9	Affluent	3+	5761

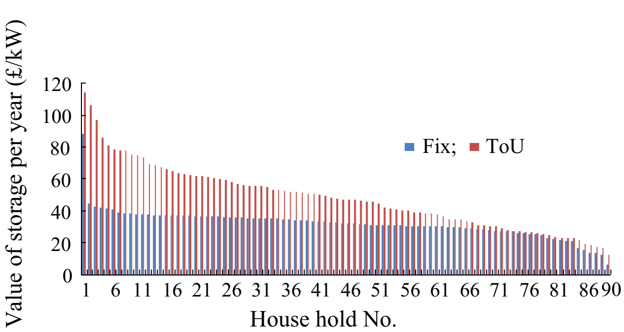

Fig. 10 Value of ES across all the demand profiles

Furthermore, ES is capable to support distribution network management through reducing the peak consumption. However, under most of the present tariff design, DUoS charge is calculated proportional to the annual electricity consumption and hence provides no incentives for ES to support the distribution network. A large portion of DNOs' cost is driven by the level of peak demand. Therefore, to properly reflect the driver of the cost and potentially reduce the network investment by incentivising peak load reduction, dynamic DUoS has been proposed by some DNOs in UK to charge the customers only during peak hours.

To analyse the impact on the value of domestic ES, case studies are carried out with the assumption that 23 p/kWh is charged from 5 pm to 8 pm during weekdays between November and March. Therefore, ES could reduce DUoS by shifting consumption away from these hours. The results in Fig. 11 clearly demonstrate that dynamic DUoS could further justify the implementation of domestic ES, particularly for the household with high annual energy consumption (e.g. category 3, 5, 6, 8 and 9).

The value of ES is then assessed under aggregated scenario by assuming the presence of a third party that can deploy a software system to coordinate and optimise across a series of kW-scale storage assets in the community. As a comparison with individual scenario, we consider a community with the same 90 households as used in the individual scenario. As shown in Fig. 12, the optimized operation of aggregated ES allows the ES unit to leverage other demand profiles; thus ES delivers greater value than the individual domestic ES scenario.

Further analysis is carried out to investigate the impact of installed capacity and FR provision on the value of ES. As shown in Fig. 13, the value of ES increases from 70 £/kW per year to 240 £/kW per year, when the installed capacity in this community decreases from 180 to 50 kW. The coordinated operation of aggregated ES would increase the utilisation of assets and hence reduce the required overall capacity of ES for the community. Moreover, the aggregated ES may also enable the potential sources of revenue beyond the household through engaging

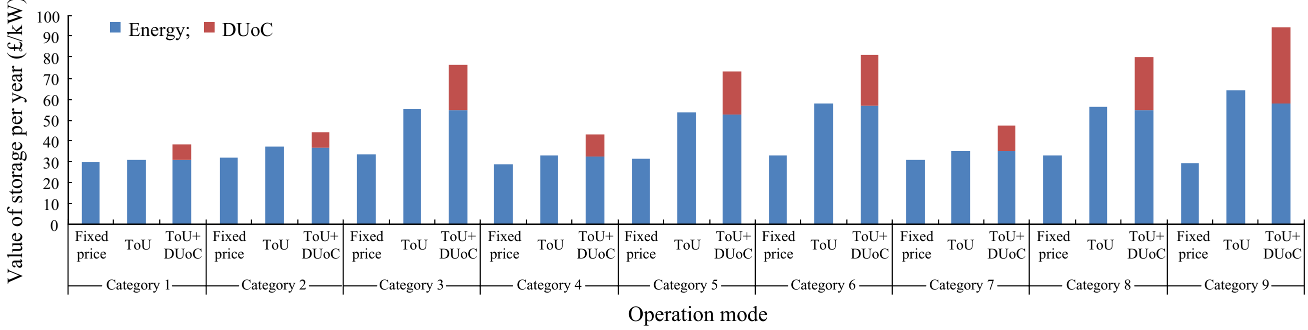

Fig. 11 Average values of ES in each demand category under different tariffs

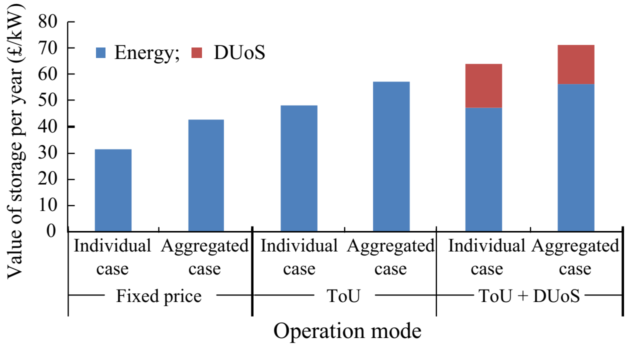

Fig. 12 Value of domestic ES: household level vs community level

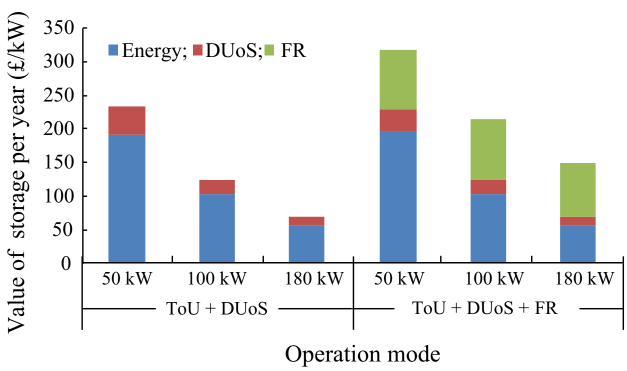

Fig. 13 Value of domestic ES with different installed capacity in the community

with other markets. In this study, it is assumed that the aggregator's ICT system has the ability to optimise the ES unit to provide FR when required. The price for FR is assumed to be 21.75 £/MW/h. Providing additional FR services using the ES asset increase the value of storage by more than 60 £/kW per year and hence further improves the economics of this business case, particularly when there is large amount of ES available in the community. It is also worth noting that provision of FR to gain the additional revenue does not compromise the cost savings from PV/demand shifting.

4 Conclusion

This paper quantifies the value that ES may deliver to its owner and informs the business case for its multiple functions. In particular, we analysed the value of large-scale ES in the wholesale electricity market and kW-scale ES in the retail market.

For large-scale ES, the value of ES with stacked service provision is summarized in Fig. 14. The value of ES varies from 42 £/kW per year to 620 £/kW per year, depending how many services ES simultaneously provides. It is clear that the value of ES under any single service provision hardly justify its high investment cost. The optimized multiple service provision is the key for ES to make a profitable business case. The results suggest a considerably added value for ES to be co-located and operated together with WF, particularly when there is an active network constraint. Fast response characteristic of ES allows it to provide FR, which may significantly enhance the value proposition. Participation in capacity market could secure substantial upfront payment for ES while only slightly reduces the profit from other markets. Furthermore, our analysis demonstrates that allowing ES to provide multiple services in an optimised way not only increase the annual profit but may also reduce the lift-time degradation.

For the application of domestic ES in the household level, the value varies significantly, depending on the demand profiles and electricity tariffs. Fig. 15 summaries the key results in both household and community level. In general, the value of ES tends to be higher in the household

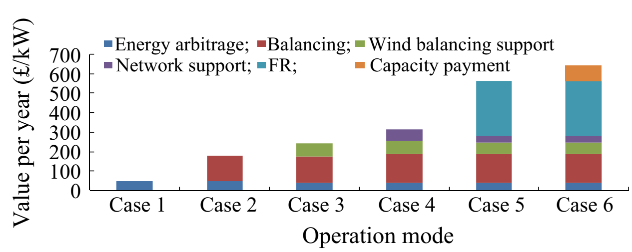

Fig. 14 Value of large scale ES

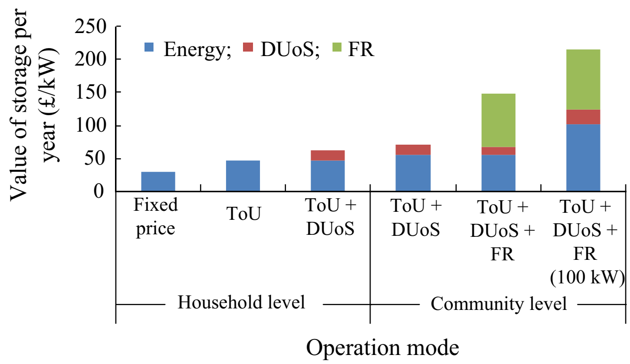

Fig. 15 Value of domestic ES

with higher annual electricity consumption. The implementation of ToU tariff and dynamic DUoS charge could enhance the value proposition of domestic ES. The optimized operation of aggregated ES in the community level allows ES to leverage other demand profiles and thus delivers greater value than the individual scenario. Moreover, the aggregated ES could provide grid service to increase the value and optimal sizing of ES in the community level may further justify the application of domestic ES.

This paper uses 2030 UK Gone Green system scenario as an example to demonstrate the impact of multiple service provision on the value of ES. However, to actually estimate the value of ES in 2030 UK system, sensitivity studies with different system scenarios need to be carried out in the future. Furthermore, as discussed in [19], the present market and regulatory barriers may prevent the realization of the quantified profits which are sourced from multiple energy sectors. It is therefore important for the policy makers to act in order to align the commercial incentives in investing ES with the societal benefits covering multiple sectors [12] that ES may deliver.

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Appendix A

This section presents the mathematical model used to optimize the operation of ES in wholesale market. The notations in the model are shown in the below:

$N_S(n)$	Charge/discharge state of ES at node n
$E_S(n)$	Stored energy of ES at node n
$P_s^c/P_s^c(n)$	Charge/discharge rate of ES at node n
$P_d^E/P_c^E(n)$	Charge/discharge rate of ES in energy market at node n
$P_d^{Imb}/P_c^{Imb}(n)$	Charge/discharge rate of ES in balancing market at node n
$P_d^W/P_c^W(n)$	Charge/discharge rate of ES in supporting wind balancing at node n
$P_c^N(n)$	Charge rate of ES in supporting network at node n
$P_s^{FR}(n)$	Scheduled FR of ES at node n
$P_s^{Cap}(n)$	Capacity of ES to deliver at node n
E_s^{min}/E_s^{max}	Min/max stored energy of ES
$\underline{P}_s^c/\overline{P}_s^c$	Min/max charge power rate of ES
$\underline{P}_s^d/\overline{P}_s^d$	Min/max discharge power rate of ES
$\overline{P}_s^{FR}$	Max FR capability of ES
P_{NET}^{Max}	Max network transfer capacity
η_s^c/η_s^d	Charge/discharge efficiency of ES
ρ_S	Loss rate of ES
$P_W^{Imb0}(n)$	WF imbalance at node n
$P_W^{c0}(n)$	Wind curtailment without ES at node n
$P_W^c(n)$	Wind curtailment with ES at node n
$Pr_E(n)$	Energy price at node n
$Pr_I(n)$	Imbalance price at node n
$Pr_{FR}(n)$	FR price at node n
Pr_{Wind}	Wind curtailment price
$\pi(n)$	Probability at node n
$a(n)$	Parent node of n

The objective is to maximize the expected profit from multiple sources[1], including energy market (A2), balancing market (A3), wind balancing support (A4) and (A5), network support (A6) and FR provision (A7):

$$\sum_{n\in N}\pi(n)\left(P_E(n)+P_B(n)+P_B^W(n)+P_N(n)+P_{FR}(n)\right) \tag{A1}$$

$$P_E(n)=Pr_E(n)\left(P_d^E(n)-P_C^E(n)\right) \tag{A2}$$

$$P_B(n)=Pr_I(n)\left(P_d^{Imb}(n)-P_C^{Imb}(n)\right) \tag{A3}$$

if the direction of WF imbalance is the same as the overall system imbalance:

$$P_B^W(n)=Pr_I(n)\left(P_d^W(n)-P_C^W(n)\right) \tag{A4}$$

[1] Please note that capacity market is contracted on the annual basis and therefore not optimized in the daily operation.

otherwise:

$$P_{\mathrm{B}}^{\mathrm{W}}(n) = Pr_{\mathrm{E}}(n)\left(P_{\mathrm{d}}^{\mathrm{W}}(n) - P_{\mathrm{C}}^{\mathrm{W}}(n)\right) \tag{A5}$$

$$P_{\mathrm{N}}(n) = Pr_{\mathrm{Wind}} P_{\mathrm{c}}^{\mathrm{N}}(n) \tag{A6}$$

$$P_{\mathrm{FR}}(n) = Pr_{\mathrm{FR}}(n) P_{\mathrm{s}}^{\mathrm{FR}}(n) \tag{A7}$$

Physical constraints of ES are applied including: ① charge rate limits (A10) and charge rate limits (A11); ② stored energy balance constraints (A12); ③ constraints associated with the amount of energy that can be stored (A13):

$$P_{\mathrm{s}}^{\mathrm{c}}(n) = P_{\mathrm{c}}^{\mathrm{E}}(n) + P_{\mathrm{c}}^{\mathrm{Imb}}(n) + P_{\mathrm{c}}^{\mathrm{W}}(n) + P_{\mathrm{c}}^{\mathrm{N}}(n) \tag{A8}$$

$$P_{\mathrm{s}}^{\mathrm{d}}(n) = P_{\mathrm{d}}^{\mathrm{E}}(n) + P_{\mathrm{d}}^{\mathrm{Imb}}(n) + P_{\mathrm{d}}^{\mathrm{W}}(n) \tag{A9}$$

$$\left(1 - N_{\mathrm{s}}(n)\right)\underline{P}_{\mathrm{s}}^{\mathrm{d}} \le P_{\mathrm{s}}^{\mathrm{d}}(n) \le \left(1 - N_{\mathrm{s}}(n)\right)\overline{P}_{\mathrm{s}}^{\mathrm{d}} \tag{A10}$$

$$N_{\mathrm{s}}(n)\underline{P}_{\mathrm{s}}^{\mathrm{c}} \le P_{\mathrm{s}}^{\mathrm{c}}(n) \le N_{\mathrm{s}}(n)\overline{P}_{\mathrm{s}}^{\mathrm{c}} \tag{A11}$$

$$E_{\mathrm{s}}(n) = \rho_{\mathrm{s}} E_{\mathrm{s}}(a(n)) + \left(\eta_{\mathrm{s}}^{\mathrm{c}} P_{\mathrm{s}}^{\mathrm{c}}(n) - \frac{P_{\mathrm{s}}^{\mathrm{d}}(n)}{\eta_{\mathrm{s}}^{\mathrm{d}}}\right) \tag{A12}$$

$$E_{\mathrm{s}}^{\min} \le E_{\mathrm{s}}(n) \le E_{\mathrm{s}}^{\max} \tag{A13}$$

The maximum amount of balancing support from ES is limited by the amount if WF imbalance as in (A14–A15):

$$(N_{\mathrm{w}}(n) - 1)M \le P_{\mathrm{W}}^{\mathrm{Imb0}}(n) \le N_{\mathrm{w}}(n)M \tag{A14}$$

$$\begin{aligned} -N_{\mathrm{w}}(n)P_{\mathrm{W}}^{\mathrm{Imb0}}(n) &\le P_{\mathrm{d}}^{\mathrm{w}}(n) - P_{\mathrm{c}}^{\mathrm{w}}(n) \\ &\le (N_{\mathrm{w}}(n) - 1)P_{\mathrm{W}}^{\mathrm{Imb0}}(n) \end{aligned} \tag{A15}$$

Network constraint (A16) is imposed in the case that ES is co-located with WF in the network with limited transfer capability. Provision of network support from ES is compensated through payment on the reduced wind curtailment (A17):

$$P_{\mathrm{W}}^{\mathrm{R}}(n) - P_{\mathrm{W}}^{\mathrm{c}}(n) + P_{\mathrm{s}}^{\mathrm{d}}(n) - P_{\mathrm{s}}^{\mathrm{c}}(n) \le P_{\mathrm{NET}}^{\mathrm{Max}} \tag{A16}$$

$$0 \le P_{\mathrm{c}}^{\mathrm{N}}(n) \le P_{\mathrm{W}}^{\mathrm{c0}}(n) - P_{\mathrm{W}}^{\mathrm{c}}(n) \tag{A17}$$

FR provision constraints are proposed including: ① maximum FR capability (A18); ② storage headroom constraints associated with FR provision (A19); ③ stored energy constraints associated with response provision (A20). In the case of present FR market, constraints (A21) is imposed to maintain FR available follow the pre-contacted amount:

$$0 \le P_{\mathrm{s}}^{\mathrm{FR}}(n) \le \overline{P}_{\mathrm{s}}^{\mathrm{FR}} \tag{A18}$$

$$P_{\mathrm{s}}^{\mathrm{FR}}(n) \le \overline{P}_{\mathrm{s}}^{\mathrm{d}} - P_{\mathrm{s}}^{\mathrm{d}}(n) + P_{\mathrm{s}}^{\mathrm{c}}(n) \tag{A19}$$

$$0.5P_{\mathrm{s}}^{\mathrm{FR}}(n) \le E_{\mathrm{s}}(n) - E_{\mathrm{s}}^{\min} \tag{A20}$$

$$P_{\mathrm{s}}^{\mathrm{FR_{Fixed}}}(t(n)) \le P_{\mathrm{s}}^{\mathrm{FR}}(n) \tag{A21}$$

To access the payment from capacity market, ES need to be available to produce at the contacted rate for 4 hours during pre-selected hours (A22)–(A23). Different assumptions on the delivery of contacted capacity is realized through (A24);

$$4P_{\mathrm{s}}^{\mathrm{Cap}}(n) \le E_{\mathrm{s}}(n) - E_{\mathrm{s}}^{\min} \tag{A22}$$

$$P_{\mathrm{s}}^{\mathrm{Cap}}(n) \le \overline{P}_{\mathrm{s}}^{\mathrm{d}} - P_{\mathrm{s}}^{\mathrm{FR}}(n) \tag{A23}$$

$$\underline{P}_{\mathrm{s}}^{\mathrm{Cap_{Fixed}}}(n) \le P_{\mathrm{s}}^{\mathrm{d}}(n) - P_{\mathrm{s}}^{\mathrm{c}}(n) \le \overline{P}_{\mathrm{s}}^{\mathrm{Cap_{Fixed}}}(n) \tag{A24}$$

Appendix B

This section presents the mathematical model used to optimize the operation of ES in retail market. The notations in the model are shown in the below:

$D(t)$	Local demand level at hour t
$Pr_{\mathrm{G}}/.Pr_{\mathrm{E}}$	Generation/exporting tariff
$Pr_{\mathrm{R}}/Pr_{\mathrm{D}}(t)$	Retail/ DUoS tariff
$R(t)$	Electricity from retailer at hour t
$P_{\mathrm{PV}}^{\mathrm{G}}/P_{\mathrm{PV}}^{\mathrm{E}}(t)$	PV generation/exporting at hour t
$P_{\mathrm{s}}^{\mathrm{c}}/P_{\mathrm{s}}^{\mathrm{d}}(t)$	Charge/discharge rate of ES at hour t

The objective is to minimize the total payment:

$$\begin{aligned} \sum_{n \in T} \big(&Pr_{\mathrm{R}}(t)P_{\mathrm{R}}(t) + Pr_{\mathrm{D}}(t)P_{\mathrm{R}}(t) - Pr_{\mathrm{G}}P_{\mathrm{PV}}^{\mathrm{G}}(t) - \\ &Pr_{\mathrm{E}}P_{\mathrm{PV}}^{\mathrm{E}}(t) - Pr_{\mathrm{FR}}P_{\mathrm{s}}^{\mathrm{FR}}(t)\big) \end{aligned} \tag{B1}$$

subject to load balance constraint (B2) and other physical constraints (A10–A13) as well as FR constraints (A18–A20):

$$D(t) = P_{\mathrm{R}}(t) + P_{\mathrm{PV}}^{\mathrm{G}}(t) + P_{\mathrm{PV}}^{\mathrm{E}}(t) - P_{\mathrm{s}}^{\mathrm{c}}(t) + P_{\mathrm{s}}^{\mathrm{d}}(t) \tag{B2}$$

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