EnergyREV

Benefits of flexibility of Smart Local Energy Systems in supporting national decarbonisation

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The analysis presented in this Briefing Paper was undertaken in the EnergyREV project, specifically in Work Package 5.3. EnergyREV aims to drive forward research and innovation in SLES. Work Package 5.3, "Next Wave of Local Energy Systems in a Whole Systems Context", aims to understand how the development of SLES will relate to the national energy system as a whole and the extent to which the future investment in national electricity and gas grids may be altered by widespread deployment of SLES.

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Summary

This paper answers the question: what is the impact on costs to consumers and the electricity system as a whole of adopting Smart Local Energy Systems (SLES). The premise is that SLES, alongside their other features, help consumers to capture lower prices through demand-side response (DSR), use of local energy storage and self-consumption from rooftop solar PV. In doing so, altered electricity consumption patterns change the rest of the electricity system by lowering peak demand in local networks and being responsive to the availability of bulk renewables such as offshore wind. A whole-system, investment-optimising model has been used to examine the change in total cost of meeting electricity demand in a net-zero UK electricity system with and without SLES present.

We find that:

- Customers within SLES schemes are indeed likely to see a reduction in their electricity bills compared to non-SLES customers. Customers that provide DSR services could see their cost of electricity drop by about 7%-8%; those who have rooftop PV installed could see a further 30% reduction in bills, while implementing energy efficiency measures in heating would bring another 5%-7% in energy bill reductions.
- Deployment of SLES can deliver substantial savings in total system cost. In our Medium SLES deployment case, the cost savings from SLES were around £1.7bn/yr, or 4.2% of total annualised system cost. This results from substitution of grid-scale battery storage with SLES flexibility and avoidance of local network reinforcement through reduction of peak demand.
- System benefits of SLES will increase at higher deployment levels of SLES, but will also depend on the volume of flexibility present where there is no SLES. Savings for Low, Medium and High SLES uptake are estimated at £1.1bn, £1.7bn and £2.5bn per year, respectively.
- The mix of flexibility provision within SLES – the relative proportion of distributed battery storage and DSR – should adapt to scaling up of the uptake level of SLES. Distributed batteries tend to be less valuable at high SLES deployment levels due to the higher volume of DSR available because DSR is lower cost. It appears to be unattractive to include batteries within SLES beyond those present in the Low SLES deployment case.
- System benefits of SLES increase further if energy efficiency measures are included. Improved energy efficiency is estimated to bring additional system value of up to £0.5bn/yr, although this needs to be put into context of the investment needed for those efficiency improvements.
- Including rooftop PV in SLES has a mixed impact. It lowers bills for consumers within SLES. But it is not necessarily cost-efficient from a system perspective as this PV capacity displaces offshore wind capacity, which is cheaper in our cost assumptions. Removing rooftop PV from SLES therefore resulted in higher SLES benefits at system level through avoided generation investment cost.

Introduction

The UK's energy sector will need to undergo a radical transformation over the next few decades to deliver on the Government's target to reduce greenhouse gas emissions to net zero by 2050 (BEIS, 2021). In April 2021, the UK government announced a world-leading climate change target to reduce emissions by 78% by 2035 compared to 1990 levels, on a pathway to net zero emissions by 2050 (CCC, 2020).

Key pillars of decarbonising the energy system will include significant and continued investment in low-carbon energy sources such as renewables, nuclear and carbon capture and storage (CCS), and will most likely entail a significant degree of electrification of the heat and transport sectors. The electricity sector is projected to become net-zero carbon by 2035, 15 years ahead of the overall energy system, in order to enable wider decarbonisation. The Government's White Paper (BEIS, 2020) envisages expanding the offshore wind capacity to 40 GW by 2030, as well as expanding all other low-carbon generation options. It is notable that the analysis of the generation mix required for a net-zero system indicates that substantially higher wind capacities of around 100 GW are likely to be needed (CCC, 2020; Aunedi et al, 2021).

Although a large fraction of future electricity will be provided through investment in large-scale low-carbon technologies such as offshore wind and will therefore be provided to consumers via the transmission network, the provision of flexibility and resilience is expected to shift towards decentralised and distributed sources provided by consumers of end-use energy (Strbac et al, 2019). Recent analysis (Imperial College London, 2015) has demonstrated that cost savings in system operation and investment cost arising from the application of flexible technologies in the UK electricity system could reach £8bn/year in 2030. This arises because flexibility with respect to when energy is used enables energy needs to be satisfied with a smaller investment in network infrastructure and a smaller investment in generation capacity.

The UK Government's Smart Systems and Flexibility Plan (BEIS & Ofgem, 2021) set out a vision for delivering the smart and flexible electricity system that will be needed to underpin energy security and the transition to a net-zero carbon economy. Significant levels of flexibility will be needed in the electricity system to ensure it can rely entirely on low-carbon energy sources. Options for providing flexibility include DSR from end-consumers, energy storage and using interconnectors to export and import electricity to neighbouring countries. In its "Digitalising our energy system for net zero" strategy, the Government makes a further argument that a smart system transformation will only be possible if the capabilities of data and digitalisation are harnessed across the whole energy system to deliver the flexibility required for the net-zero transition (BEIS, Innovate UK & Ofgem, 2021).

There are, however, a number of barriers to using decentralised assets to provide flexibility under the current paradigm of centralised system design and operation. SLES are seen as a vehicle for unlocking the potential for decentralised flexibility, driven not only by an increased general recognition of the importance of flexibility but also by local stakeholders seeking to align the development of local energy systems with the objectives of the local community. There is a need to better understand and quantify the magnitude and nature of the contribution that SLES can make, not just towards local objectives but also to national objectives such as cost-efficient decarbonisation, and from this to quantify what economic costs and benefits arise.

SLES and their role in low-carbon energy transition

There is no single definition of SLES because there are various ways in which SLES could be implemented and configured, including variations in geographical boundaries, energy vectors included, types of assets (generation, storage, flexible demand) and the actors involved. A framework for understanding the process by which diverse SLES could potentially deliver both system and societal benefits has been established as part of the EnergyREV research programme (Ford et al, 2019) and the variety is further illustrated in the range of projects under Prospering from the Energy Revolution (PFER) (UKRI, 2022).

Previous EnergyREV work identified four common types of local energy system (LES) projects implemented in the UK over the past decade, characterised by geographic, scale, technological and institutional characteristics (Wilson et al, 2020). The energy policy implication of this variety is that there is no one-size-fits-all support mechanism that will work across all scheme types. On the other hand, the key message for energy system modelling looking at potential benefits of LES projects is that their variations can be captured efficiently using a small number of common types. Similar approaches have been proposed in the literature to reduce the complexity of evaluating LES on a system scale through specifying a manageable number of archetypal LES (Yazdanie et al, 2018).

EnergyREV (in Work Package 5.3) also looked at local conditions associated with LES projects by studying a dataset of 146 LES-type projects that began in the UK between 2010 and 2020 (Arvanitopoulos and Wilson, 2021). It found that LES projects are associated with local areas that have:

- More existing renewable power generation
- Fewer major power producers
- Less access to gas grid
- More electric vehicle (EV) charging infrastructure
- Higher likelihood of having energy and climate action plans
- More economic activity in information and communication technologies
- Less efficient building stock
- Less targeted investments in fuel poor households
- More home energy audits in owner-occupied households.

A recent estimate by WPI Economics (WPI Economics, 2020) stressed the need for end-use customers to become engaged at a local level with the transformation to a decarbonised and less-centralised energy system. It envisaged that with the right policy support the community energy sector in the UK could grow 12–20 times larger between 2020 and 2030 and could encompass up to 4,000 organisations.

How can SLES help to unlock local flexibility resources?

One of the key aspects of the value SLES bring to an electricity system as a whole is the benefits from providing local flexibility to the wider energy system, thus contributing to a more cost-effective integration of renewable energy sources (RES) (Thellufsen and Lund, 2016).

A key driver for the value of SLES is the argument that SLES would drive a higher uptake of local energy storage and encourage greater participation in DSR. A recent briefing paper by Imperial College's Energy Futures Lab (Carmichael et al, 2018) comprehensively assessed the evidence base on residential consumer engagement with DSR to identify barriers, drivers and opportunities for greater household consumer engagement. It found that DSR engagement tends to be stronger if consumers see a link to maximising the use of renewable energy and when there is a combination of supportive technologies such as EV, storage, smart appliances and smart heating controls. Therefore, if SLES combine these factors and achieve closer engagement with customers, such as promoting understanding of energy issues, encouraging the deployment of on-site renewables such as PV and storage and supporting the adoption of EVs and smart appliances and heating, it is plausible to assume that SLES will indeed increase participation in DSR.

ClientEarth's annual survey of UK attitudes towards climate change clearly identifies that the majority of consumers would like to install both solar panels and a home energy storage device for their homes, or switch to an electric or low-carbon vehicle, if greater assistance was available from the UK government or through community or commercial schemes (ClientEarth, 2019).

A recent study by Fell et al. on the effect of tariff design and marketing on willingness of consumers to adopt time-of-use and demand-side response tariffs (Fell et al, 2015) concluded that none of the variables such as age, gender, housing tenure, employment status, education, social grade, being on a pre-payment meter, or income were consistently associated with being more or less willing to switch tariffs. Instead, trust in suppliers was the most important predictor of using DSR tariffs and services, as people who trust their electricity supplier were more likely to say they would switch to a DSR tariff. This supports the assumption that a SLES with a close and trusted relationship with the customers would achieve enhanced DSR engagement.

Objective of briefing paper

The objective of this Briefing Paper is to quantify the benefits of SLES in a net-zero electricity system using an approach and assumptions that are updated and refined from those in our 2020 briefing paper "Early insights into system impacts of Smart Local Energy Systems" (Aunedi and Green, 2020). We aim to expand our understanding of key drivers behind the value proposition of SLES at the system level through several quantitative studies. Given the UK's strategic goal to rapidly decarbonise its energy sector, the focus of this study is on the role of SLES in a net-zero power system and therefore builds on our recent work on viable options for the net-zero UK electricity system (Aunedi et al, 2021).

More specifically, this briefing paper aims to:

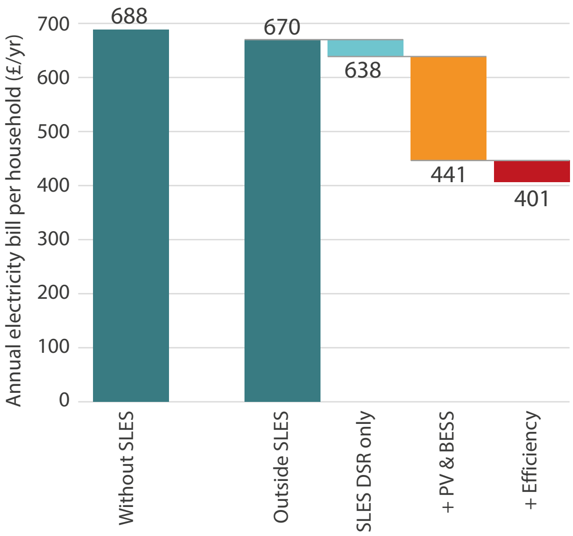
- Quantify the impact of SLES on customer bills
- Quantify the impact of SLES on the whole electricity system, including specific impacts on generation, networks and flexibility assets
- Understand how the system impact of SLES varies with its uptake level, non-SLES flexibility and the variations in the portfolio of distributed energy assets

How does SLES impact the system?

In this section we briefly illustrate and discuss at a high-level the nature of the impact SLES have on the whole-electricity system by presenting selected illustrative results. A more complete discussion of the results is provided later in the "Main findings" section.

Reduction in energy bills. The flexibility provided through the features of SLES reduces the overall cost of the electricity system, which also results in potentially lower electricity bills for all consumers but brings specific benefits to consumers within SLES. In Figure 1 we estimate the impact of SLES flexibility on customers' annual electricity bills by showing a typical household electricity cost with and without SLES present in the system. All customers see a slight reduction in cost because of reduced system cost, but customers within SLES who use their flexibility options can realise a substantial reduction in bills, especially if PV generation is installed and energy efficiency measures are implemented to reduce heating demand. Savings from these last two items need to be compared against the investment cost of these assets and solutions.

Figure 1: Waterfall chart for estimated customer electricity bills without SLES and with SLES including various technology options.



Impact on energy flows. In Figure 2 and Figure 3 we compare the energy flows in a net-zero UK power system before and after implementing SLES. The flexibility delivered by SLES, and in particular their DSR capability, displaces a significant proportion of energy throughput of other flexible options, such as grid-scale battery storage outside the smart local energy system and energy exchange through international interconnectors. There is also a slight reduction in overall system losses. On the generation side, the electricity from solar PV packaged into SLES displaces some of the energy produced using wind generation.

Figure 2: Energy flows in electricity system without SLES.

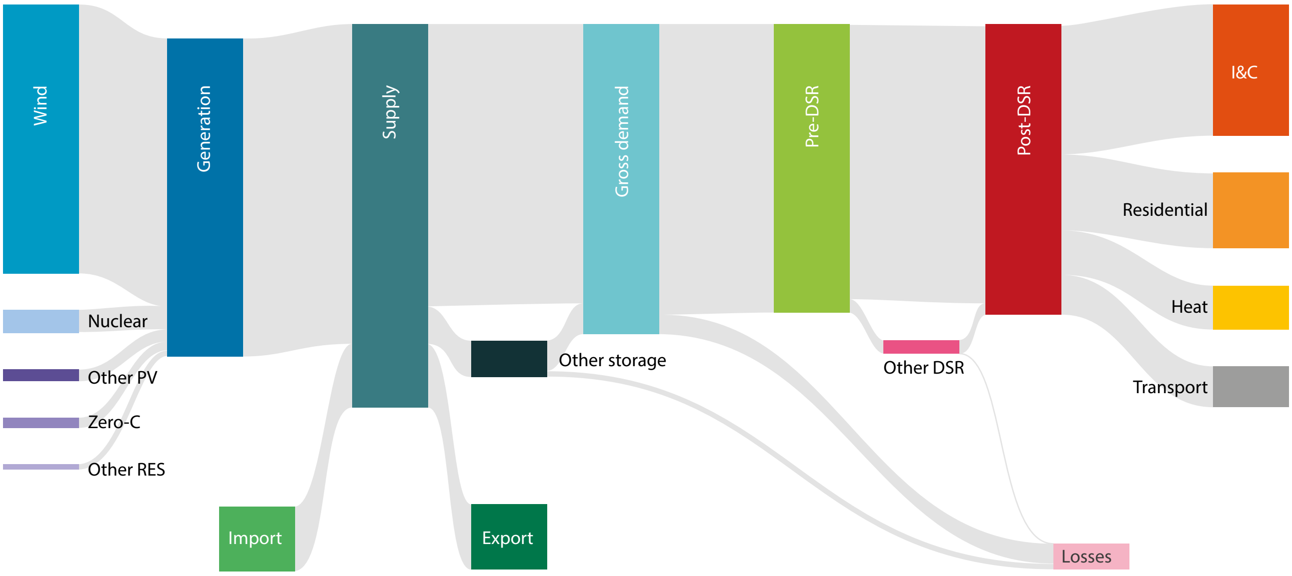
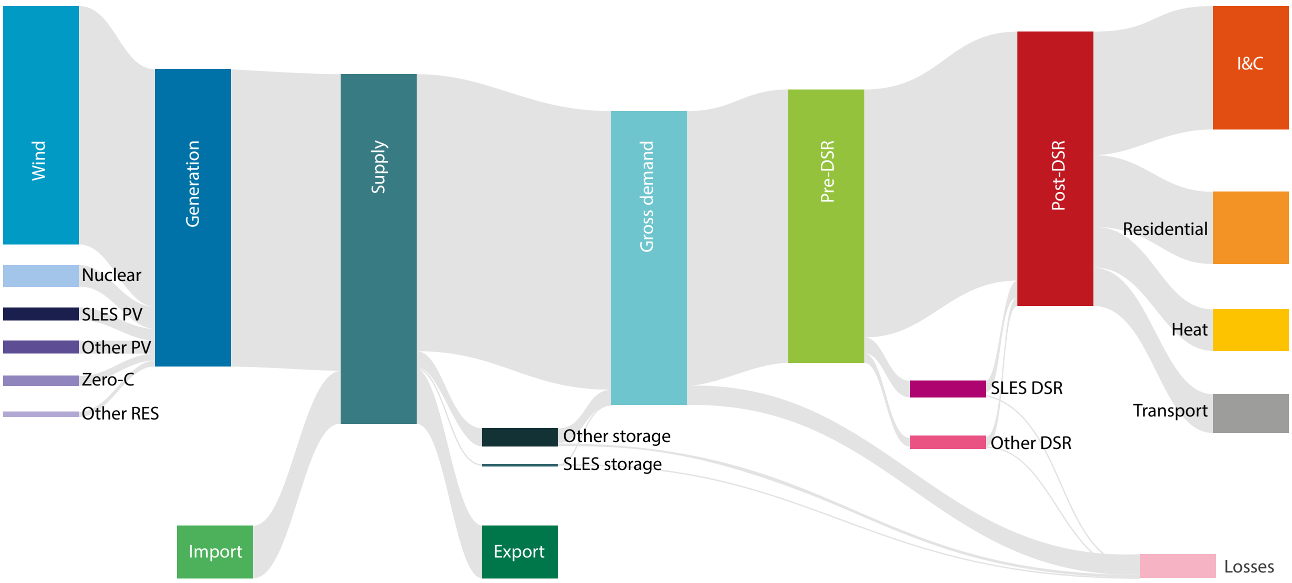


Figure 3: Energy flows in electricity system in Medium SLES case.

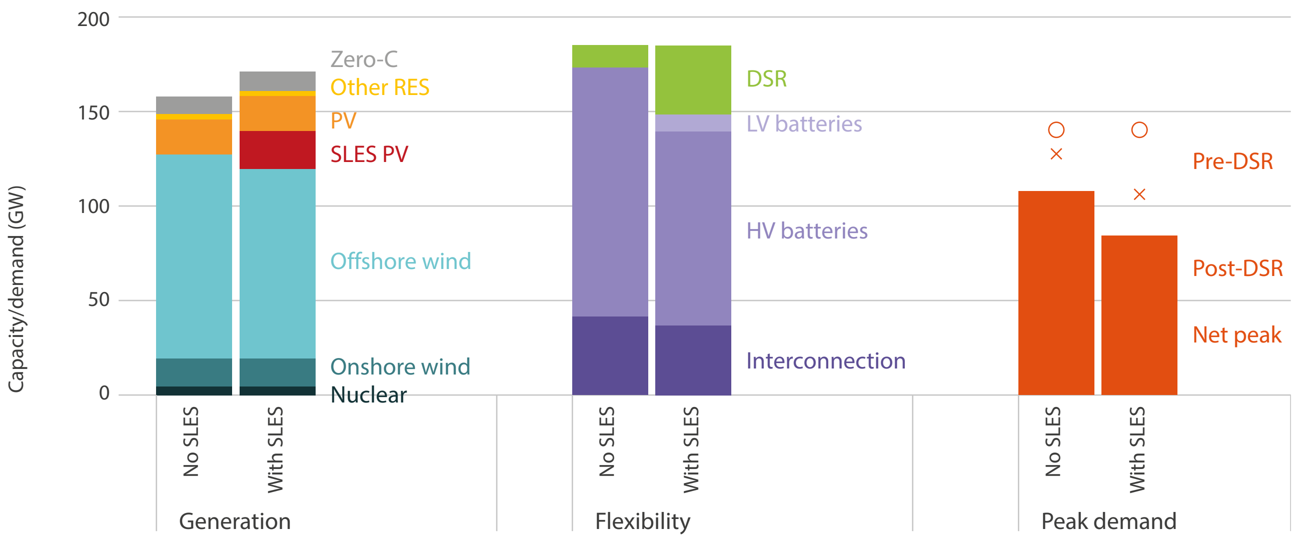


Impact on generation capacity. As illustrated in the left-hand side of Figure 4, the addition of rooftop PV as part of SLES displaces wind generation capacity. In this example, 20 GW of SLES PV generation displaces about 8 GW of offshore wind. Given that the annual utilisation (or load factor) of PV in the UK is about 4 times lower than for offshore wind, the 20 GW of added PV capacity would only displace about 5 GW of offshore wind on a MWh-for-MWh basis. The remaining 3 GW reduction in offshore wind capacity comes from the reduced need for total generation capacity required to meet the demand when the flexibility of DSR and storage in SLES is exploited.

Displacement of large-scale flexibility. Under the assumption that SLES unlock extra distributed flexibility resources in the form of DSR and low-voltage (LV) batteries, a significant amount of large-scale flexibility such as grid-scale batteries (here described as high-voltage (HV) batteries) or, to a lower extent, international interconnector capacity is displaced. This effect is illustrated in Figure 4 (centre), which further suggests that flexibility is substituted proportionately, so that the total volume of flexibility in GW remains broadly constant after adding SLES.

Reduction of net peak demand and network loading. Given that SLES unlock localised sources of flexibility, their effect on the loading of the local network will be substantial, as shown in Figure 4 (right). In the no-SLES scenario, DSR and batteries help to reduce the net peak loading of the grid from about 140 GW to 108 GW, whereas in the presence of SLES the net peak further reduces to 84 GW. Reduced peak loading means fewer or lower-capacity network assets are needed and so investment costs in distribution networks are reduced and the total system cost reduced.

Figure 4: Installed capacity of generation and flexibility assets and peak demand with and without SLES.



Approach to quantifying system impact of SLES

In order to assess the benefits of SLES in a net-zero UK electricity system, we have incorporated the flexibility provided through SLES into our whole-system modelling framework, allowing us to directly quantify cost savings arising from the deployment of SLES. Only the high-level features of our whole-system modelling approach are described here; more detail can be found in (Aunedi et al, 2021) and (Pudjianto et al, 2014).

Capturing the interactions across various time-scales and different types of assets at sufficient temporal and spatial granularity is essential for the analysis of low-carbon electricity systems with high shares of variable renewables. This approach is needed to adequately account for the operation of flexible technologies such as energy storage and DSR. The Whole-electricity System Investment Model (WeSIM) was developed at Imperial College London to meet this need and capture the effects and trade-offs between different flexible technologies (Pudjianto et al, 2014).

WeSIM is a comprehensive system analysis model that is able to simultaneously optimise decisions on long-term investment in generation, network and storage assets, as well as short-term operation decisions in order to satisfy electricity demand at least cost. The model also ensures an adequate level of security of supply and sufficient volume of ancillary services, while meeting a specified system-wide carbon emission target.

In addition, WeSIM can quantify trade-offs between using various sources of flexibility for real-time balancing and for management of transmission and distribution network constraints.

In this way it captures the synergies and conflicts between local/district-level and national-level infrastructure requirements, which are particularly relevant when studying SLES. Another prominent feature of WeSIM is the ability to quantify the necessary investments in distribution networks to accommodate future demand growth, based on the concept of statistically representative distribution networks.

Representing SLES in whole-system modelling

As identified in Wilson et al. (2020), SLES could materialise in a variety of configurations and therefore it is not straightforward to develop a generalised representation of SLES in an energy system model such as WeSIM. For the purpose of the analysis presented in this briefing paper, it is assumed that SLES can unlock flexible resources at, or close to, end-use customers, as explained earlier in the paper. More specifically, SLES are assumed to facilitate uptake of building- or household-scale DSR and highly distributed battery storage (at kilowatt scale) much more so than with current market signals alone. These small-scale DSR and battery assets would be connected at the low-voltage level of the local distribution grids, thus creating opportunities to deliver both highly localised benefits and grid services to the national transmission system. It was assumed that the flexible loads able to provide DSR services enabled by SLES will include: EVs, electric heat pumps, smart domestic appliances and small-scale commercial DSR. By stating a certain penetration of SLES there is an assumed enablement of a proportional share of highly distributed DSR and battery storage.

In this analysis we assume that SLES enable the installation of the following assets:

- DSR assets in EV, heating, appliances and small commercial segments
- Distributed (LV) batteries
- Rooftop PV generation

The cost of LV batteries and rooftop PV was explicitly accounted for, as elaborated later in this section, while for reasons of uncertainty the cost of DSR was not considered.

We also assume that other, non-distributed, sources of flexibility exist in the system outside of SLES in the no-SLES case, which serves as our counterfactual. These include controllable generation, grid-scale (HV) storage, international interconnectors and large-scale industrial and commercial (I&C) DSR.

Electricity system scenarios

Our net-zero system scenarios build on the findings of the recent white paper on cost-effective options for net-zero generation and storage portfolios in the UK (Aunedi et al, 2021). Our analysis is notionally focused on the year 2035, although it is not firmly rooted in a particular year and instead defined by having net-zero carbon emissions for the selected demand scenario that includes EV charging and heat pump use consistent with the 6th Carbon Budget from the Climate Change Committee (CCC, 2020). In all model runs we imposed an explicit net-zero carbon emission constraint, and allowed the model to cost-optimise the portfolio of low-carbon generation and energy storage to meet demand.

Most of the system-level assumptions on demand, generation and flexibility options were aligned with (Aunedi et al, 2021). Key assumptions used in this paper are summarised in Table 1.

Table 1: Assumptions for electricity system scenarios

Annual demand (TWh)	
Industrial & Commercial	204.8
Residential	118.8
Transport	64.1
Heat	67.8
Levelised cost of generation (£/MWh)	
Offshore wind	35
Onshore wind	50
Solar PV	50
Nuclear	93
Battery storage investment cost (£/kWh)	
HV batteries	180
LV batteries	270

As demonstrated in our previous briefing paper (Aunedi and Green, 2020), the benefits of SLES will depend on how flexible the system is before the uptake of SLES starts to ramp from zero. We therefore look at three different versions of the counterfactual with different degrees of flexibility: Pessimistic, Central and Optimistic. These three counterfactuals differ in the assumed volume of DSR and distributed energy assets, as specified in Table 2. In each of the three counterfactual scenarios, the grid-scale flexibility assets of HV batteries, generation and interconnection were subject to cost-optimisation.

Table 2: Assumptions on DSR uptake, battery storage and PV uptake for three counterfactual scenarios

	Pessimistic	Central	Optimistic
I&C DSR	15%	25%	35%
Smart EV	15%	25%	35%
Smart heat	-	10%	20%
LV storage	None	None	None
SLES rooftop PV	None	None	None

Note that the assumption on the DSR uptake in the context of WeSIM refers to the volume of DSR relative to its maximum theoretical potential, which is quantified separately for each demand category based on our previous bottom-up modelling of demand flexibility. For instance, for a full DSR penetration (i.e., 100% uptake) it is assumed that up to 10% of I&C demand can be shifted away from peak hours to other hours in the same day. For a lower DSR uptake level, e.g. 25%, this assumption is scaled down proportionally, so that 25% uptake allows up to 2.5% of the baseline demand to be shifted in each 24-hour period.

Due to high uncertainty in the investment cost necessary to deliver DSR schemes, its deployment was not cost-optimised but only varied through uptake assumptions, and its cost has not been included in the results.

SLES uptake cases

For each counterfactual scenario we looked at three different uptake levels for SLES: Low, Medium and High, which were associated with increasing volumes of distributed energy assets enabled by SLES, including DSR, distributed battery storage and small-scale solar PV.

Table 3 summarises the assumptions on incremental uptake of various DSR types as well as LV batteries and rooftop PV for each of the three uptake levels for SLES. Note that for rooftop PV the assumptions in Table 3 are equivalent to around 2 kW per household (with the number of households within SLES growing as the uptake of SLES increases).

Table 3: Incremental uptake levels for DSR, battery storage and PV above counterfactual, for various SLES penetration levels

	Low	Medium	High
I&C DSR	+5%	+10%	+15%
Smart EV	+15%	+30%	+60%
Smart heat	+15%	+30%	+60%
LV storage	Optimised	Optimised*	Optimised*
SLES rooftop PV	10 GW	20 GW	40 GW

Note: Optimised* – volume of LV storage is found by optimising above the cost-optimal volume for the Low SLES uptake case.

Note that the DSR uptake levels in Table 3 represent increments above the assumed uptake in the relevant counterfactual case (Table 2). As an illustration, the penetration of smart EVs in the Medium SLES uptake scenario with Central counterfactual is found as 25% + 30% = 55%. A detailed table with technology penetration levels across all combinations of counterfactuals and uptake levels of SLES is provided in the Appendix.

Scaling of LV battery storage between Low, Medium and High cases is done differently to DSR and rooftop PV. We use a "myopic" approach, where for each counterfactual we cost-optimise the LV storage deployment for the Low SLES uptake case. This LV storage volume is used as a minimum starting point for Medium and High SLES uptake cases, where the model was allowed to add more LV batteries if cost-efficient.

We chose this approach to avoid flooding the system with flexibility by scaling both DSR and storage assets proportionately, although we examine this topic further as part of the sensitivity analysis.

Finally, we assumed that the uptake of SLES occurs uniformly across the UK without any relative regional differences in uptake levels of SLES.

Sensitivity studies

In addition to variations in the flexibility of the counterfactual system and variations in SLES uptake, we also examined the sensitivity of our findings to the following variables:

- **Improvements in energy efficiency**. There is an expectation that in addition to energy assets, SLES could also act as a facilitator for implementing energy efficiency measures such as improving building thermal insulation levels. We simulate this effect by assuming that SLES deliver a 20% reduction in demand for space heating for participating households due to improved energy efficiency.
- **Alternative approaches to scaling up LV storage**. Our main scenarios assume the so-called "myopic" scaling up of LV batteries with increasing uptake of SLES in which the volume of LV batteries in Medium and High SLES cases is cost-optimised but subject to a minimum value set by the Low SLES case. We consider two alternative scale-up approaches and quantify their impact on the system value of SLES:
    * Optimised, where LV battery volume is fully optimised in all SLES uptake cases with no minimum volume; and
    * Proportional, where LV battery storage scales up from the Low SLES case proportionately to other SLES energy assets such as rooftop PV (i.e. by a factor of 2 in the Medium SLES case and 4 in the High SLES case). In other words, all SLES, at whatever stage of uptake, have the same features.
- **Variations in cost uplift of LV storage**. Our default assumption for the cost of local (LV) battery storage is 50% higher than for grid-scale (HV) batteries because of the diseconomies of small-scale deployment. Alternative cost uplifts of 25% and 75% were used to investigate the impact of this assumption.
- **No rooftop PV included in SLES**. In this sensitivity investigation we vary our default assumption that SLES include rooftop PV of approximately 2 kW per household and run system studies where SLES do not include additional PV.

Estimating household electricity bills for SLES and non-SLES customers

We estimate annual household electricity bills based on the assumption of a perfectly efficient and cost-reflective electricity market, where wholesale prices are found as the long-run locational marginal prices (LMPs) obtained as shadow prices from the WeSIM model. We then convert those wholesale price estimates to household retail prices. Given that the reinforcement cost of distribution and transmission networks captured by the model is small compared with the sunk cost of the existing networks, we adopt a simple approach of multiplying wholesale prices with a fixed factor of 2.2 to account for other components of retail electricity prices (e.g., supply margins or transmission and distribution use of system charges) that also need to be recovered.[1] A more detailed analysis of network cost and customer bills could be performed but is beyond the scope of this analysis.

Note that these results only have illustrative value, because: a) they do not account for the way actual retail markets operate today; and b) they only consider the cost of energy (i.e. the effect of demand shifting) without looking at potential revenues from system services that flexible SLES customers could provide. The bill reduction may therefore be underestimating the total benefits to SLES customers, as it does not include potential revenues from providing flexibility services such as frequency response that can be delivered by certain types of flexible loads, such as refrigeration or EVs, or battery storage.

1 Factor of 2.2 between retail and wholesale price has been chosen based on Octopus Agile tariff.

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Main findings

In this section, we present the numerical outputs of our modelling, focusing on the benefits of SLES in a net-zero carbon power system, including:

- Lower electricity bills for end customers,
- Reduced total system cost through the following two factors:
    * Avoidance of reinforcement of local distribution networks through reduced peak demand,
    * Reduced cost of investing in low-carbon generation to meet the net-zero carbon target through better generation utilisation.

We quantify the value of SLES for delivering the above benefits across the range of scenarios and sensitivity studies described earlier.

Benefits of SLES for customer energy bills

In the first step, we use our modelling results to estimate the annual electricity bills for customers included in SLES schemes and contrast this to those that are not. As discussed earlier, the estimated bill reduction is likely to be conservative. Also, note that no investment cost has been included in bill estimates for PV, DSR, batteries or energy efficiency, so any savings reported here should be compared against the cost of implementing these options.

We present the summary of variations in estimated annual electricity bills per household in Table 4, which includes all three counterfactual scenarios (Pessimistic, Central and Optimistic) and all uptake levels of SLES including the case without SLES. For each of the three SLES uptakes (Low, Medium and High) we distinguish between the following types of customers:

1. 'Inflexible' customers outside SLES, who do not partake in any DSR or other flexibility schemes
2. SLES customers that only provide DSR services through demand shifting (labelled '+ DSR');
3. SLES customers that in addition to DSR also have rooftop PV and distributed batteries installed (labelled '+ PV & BESS');
4. SLES customers that have implemented DSR, rooftop PV, battery storage and energy efficiency measures (labelled '+ Efficiency').

Note that the effects of DSR, PV, batteries and energy efficiency are averaged across all SLES households. The impact on bills of an individual household could be greater or smaller if their use of flexibility assets are higher or lower than average.

Table 4: Estimated customer electricity bill per household (in GBP per year) across various counterfactual scenarios, SLES uptake cases and technology options[2]

		Pessimistic	Central	Optimistic
No SLES		685	688	675
Low SLES (7.1 million)	Inflexible	674	674	677
	+ DSR	637	634	635
	+ PV & BESS	445	445	444
	+ Efficiency	397	397	394
Medium SLES (11.3 million)	Inflexible	667	670	673
	+ DSR	637	638	642
	+ PV & BESS	440	441	443
	+ Efficiency	400	401	403
High SLES (19.8 million)	Inflexible	676	677	680
	+ DSR	656	657	660
	+ PV & BESS	453	452	454
	+ Efficiency	418	418	419

Note: BESS = Battery Energy Storage Systems. Numbers for each SLES uptake indicate the number of SLES customers. Numbers in brackets represent the assumed number of SLES customers.

The results in Table 4 show the following:

- We estimate that in the net-zero UK power system without SLES the customers would pay £675-£688 annually for their household electricity, where a higher level of counterfactual flexibility (i.e. higher level of non-SLES DSR) results in lower overall electricity bills. These costs are based on the assumed costs of generation and network technologies outlined earlier in the paper.
- If SLES materialise, they would generally bring benefits not only for SLES customers, but also for those outside SLES, as a more flexible and cost-efficient system would also result in lower electricity bills for inflexible customers.
- Customers who are part of SLES and provide DSR are likely to see a reduction in their electricity bills compared to non-SLES customers. For SLES customers that take advantage of shifting their demand to periods with lower prices, the annual cost of typical electricity consumption drop by £40-£54 (Low SLES), £33-£50 (Medium SLES) and £15-£31 (High SLES) compared to a no SLES case. Note that any annual saving in bills would need to be set against the cost of facilitating DSR through smart appliances etc.
- SLES customers with rooftop PV and small-scale battery storage would see further energy bill reductions. With the assumed average deployment of about 2 kW of PV and 0.3 kW of battery capacity per SLES customer, the cost of bought-in electricity would reduce by about £200 per year, which represents an annual saving of about 30%. Again, this saving should be compared against the investment cost of PV and batteries.
- Where the creation of the SLES includes support for improvements to the thermal energy efficiency of customers' homes, which here was taken to achieve a reduction of 20% in heating demand, this would further reduce the energy bill by £34-£50 per year (5%-7% reduction).
- There is little variation in customer savings between the three counterfactual scenarios. Savings diminish slightly as the uptake of SLES ramps up from Low to High, which can be explained by the flexibility resources flattening price variations and therefore reducing cost-saving opportunities. Nevertheless, the number of customers enjoying these benefits increases several times between Low and High SLES uptakes, as indicated in Table 4.

It appears that from the customer perspective there is no substantial difference in savings between early and late adopters of the SLES concept. The results are also fairly robust to variations in counterfactual flexibility.

2 Note that due to limited numerical accuracy of our optimisation model the bill estimates may vary from the "true" value by several pounds.

System benefits of SLES in a net-zero power system

The monetary benefit of SLES presented here is quantified as the difference in total system cost, as found by the model, between a given SLES uptake case and the appropriate counterfactual scenario. Cost-benefits of SLES are disaggregated into (i) investment cost (CAPEX) for generation, network and storage assets, and (ii) operating cost (OPEX) of electricity generation. Note that the benefits of SLES are a net system value in the limited sense that they include the investment cost of LV battery storage as a negative component of the benefit but, as noted before, the cost of implementing DSR schemes is not included in the results.

In Figure 5 we quantify the system cost savings driven by SLES across the whole range of counterfactual flexibility scenarios and SLES uptake levels. The results suggest that the deployment of SLES can deliver substantial savings in total system cost. For instance, in the Medium SLES case and Central counterfactual we find that the total system cost savings from SLES are around £1.7bn/yr, or 4.2% of the total annualised system cost. The main mechanism for SLES delivering system cost savings is through displacing grid-scale battery storage.

The main two sources of cost savings are in low-cost DSR facilitated by SLES displacing grid-scale battery storage and reducing network reinforcement cost. Another key source of cost saving arises from SLES' flexibility helping to displace some interconnection capacity. The cost of LV battery storage represents a net cost increase; therefore, it is shown as a negative component of total savings in Figure 5.

In most of the SLES uptake cases there is an increase in the generation cost component of the system. Figure 6 illustrates the changes in generation and storage capacity resulting from various SLES uptake levels, relative to the three counterfactual scenarios. Because our central assumption is that SLES also deliver rooftop PV generation as part of its energy asset portfolio, it displaces some of the wind generation capacity from the counterfactual. As shown in Table 1, the levelised cost of offshore wind assumed in this study is lower than that of PV (in each case specific to the UK context) and therefore substituting offshore wind with rooftop PV slightly increases total system cost.

Figure 5: Cost savings from SLES across various uptake levels and counterfactual scenarios.

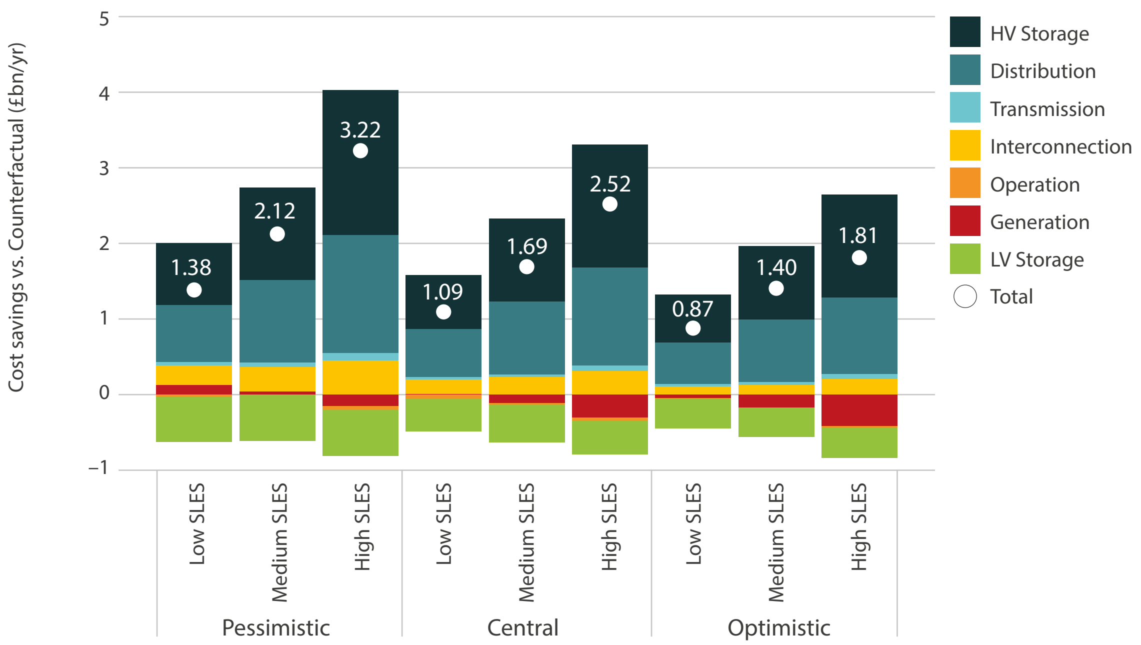
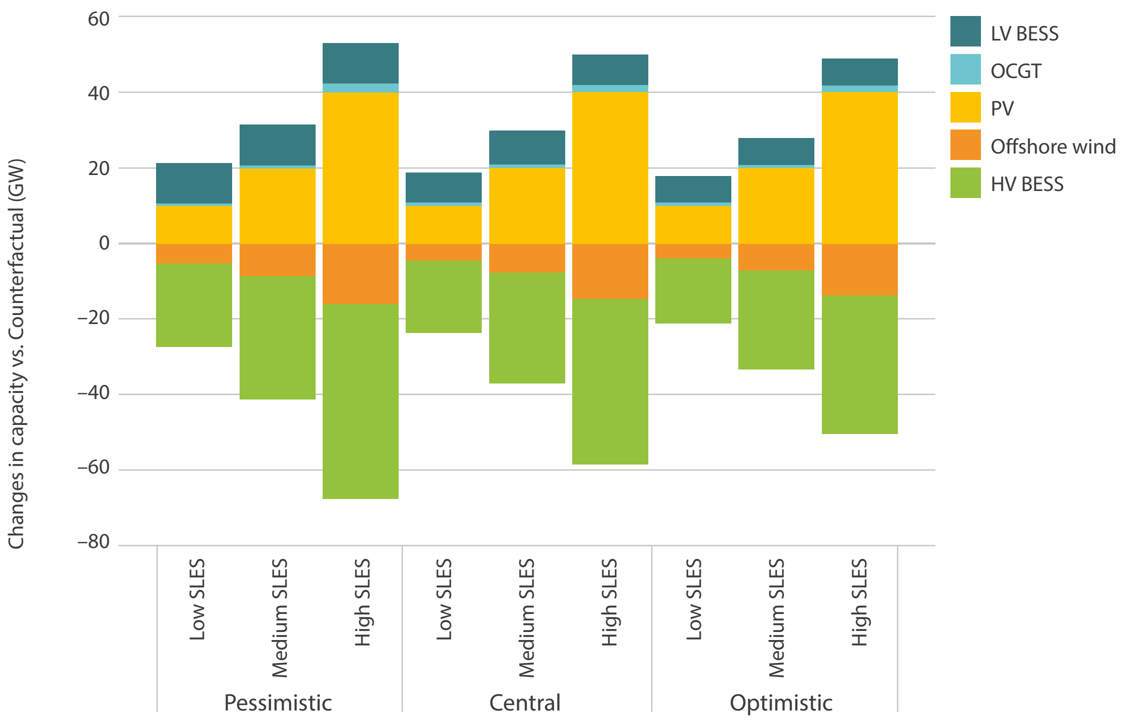


Figure 6: Changes in installed capacity driven by SLES across various uptake levels and counterfactual scenarios.

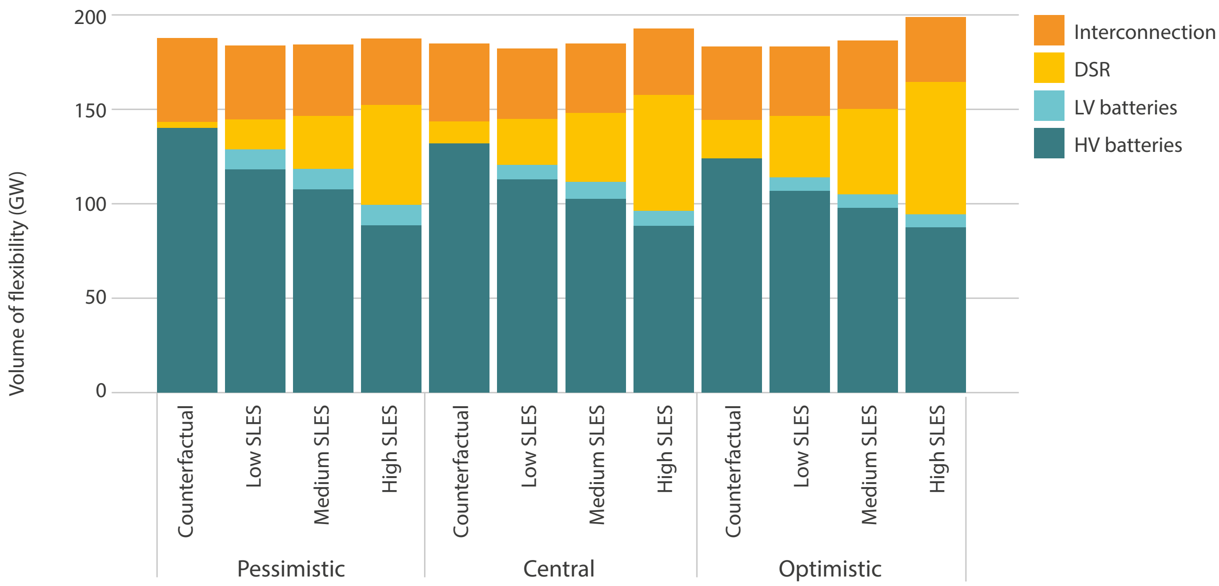


Impact of SLES uptake and non-SLES (counterfactual) flexibility

We observe from Figure 5 that system cost savings of SLES increase at higher levels of SLES deployment although there are diminishing returns from increasing the SLES uptake. The savings for Low, Medium and High SLES against the Central counterfactual are estimated at £1.1bn, £1.7bn and £2.5bn per year, respectively. We also find that SLES benefits are sensitive to counterfactual system flexibility. For instance, system benefits for Medium SLES uptake could increase from £1.7bn to £2.1bn per year in case of a Pessimistic counterfactual, but could drop to £1.4bn/year with an Optimistic counterfactual.

One of the key mechanisms for SLES delivering value in a net-zero system is that SLES-enabled DSR can substitute some of the grid-scale energy storage capacity. We find that the volume of flexibility needed to run a zero-carbon system is approximately constant in terms of capacity, while its split between DSR and battery storage can vary. This substitution effect is illustrated in Figure 7. It shows the capacities in GW of the main flexibility resources - grid-scale HV batteries, SLES LV batteries, DSR and interconnection – across all combinations of counterfactual scenarios and SLES uptake levels. The results suggest that an increase in DSR capacity delivered by SLES displaces large-scale flexible resources, primarily HV batteries but also interconnectors to a smaller extent. A similar but smaller effect is seen for an increase in LV battery storage.

Figure 7: Volume of flexibility options across various SLES uptake levels and counterfactual scenarios.



Impact of distributed battery storage

As discussed earlier, our main scenarios assume "myopic" scaling up of LV batteries with increasing uptake of SLES, where LV battery volume in Medium and High SLES uptake cases is cost-optimised but subject to a lower limit of the cost-optimal volume found in the Low SLES case. We also consider two alternative scale-up approaches:

- Optimised, where LV battery volume is fully optimised from zero in all SLES uptake cases;
- Proportional, where LV battery storage scales up from the Low SLES case proportionately to other SLES energy assets.

The resulting volumes of DSR and HV and LV battery storage across various scaling approaches and SLES uptake cases are shown in Figure 8. All cases are based on the Central counterfactual scenario.

By design, all three scale-up approaches have the same volume of LV battery storage in the Low SLES case. In the proportional scaling studies the LV battery volume increases by fixed factors of two and four in Medium and High SLES cases, respectively, and as a result displaces a considerable volume of HV batteries. At the other end of the spectrum, where LV battery volume is cost-optimised from zero in each SLES uptake case, we observe the cost-optimal volume of LV batteries shrinks to virtually zero in the High SLES case. This is the result of the fact that at High SLES uptake there is more than enough flexibility provided by DSR to obviate the need for LV batteries.

A logical consequence of this finding is that a cost-efficient portfolio of flexible assets in SLES should not simply scale up at higher penetrations of SLES but should rather adapt to SLES uptake level. It may be beneficial to include LV batteries to some extent in nearly all SLES, but as the SLES uptake increases, the need for LV batteries diminishes because the need for flexibility is met by the abundant DSR resource available.

Figure 8: Volume of batteries and DSR for various LV BESS scaling approaches and SLES uptake levels (for Central Counterfactual).

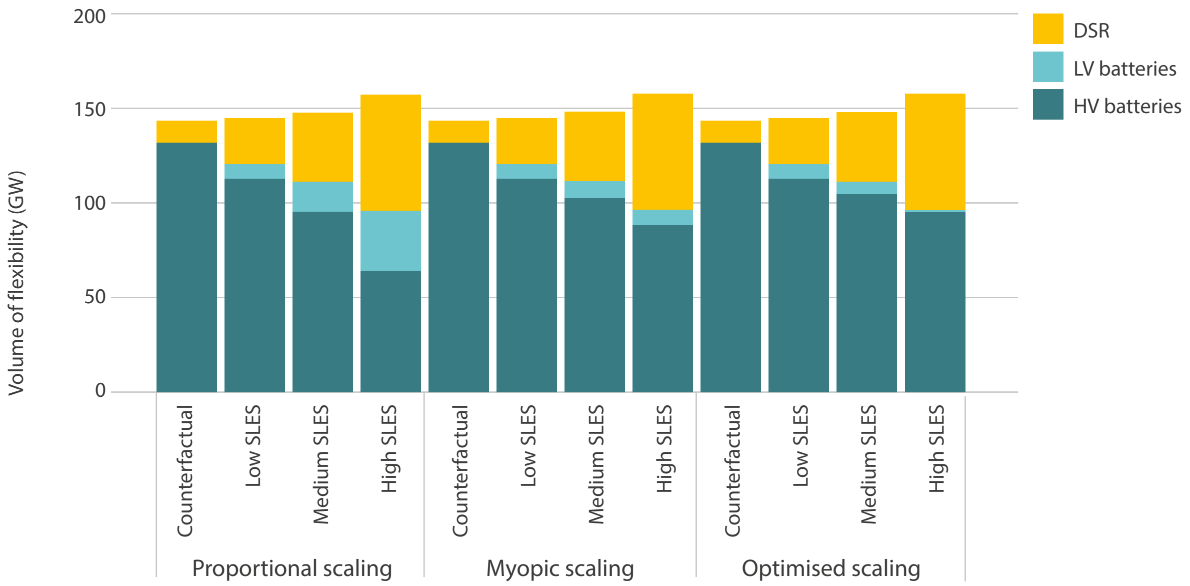
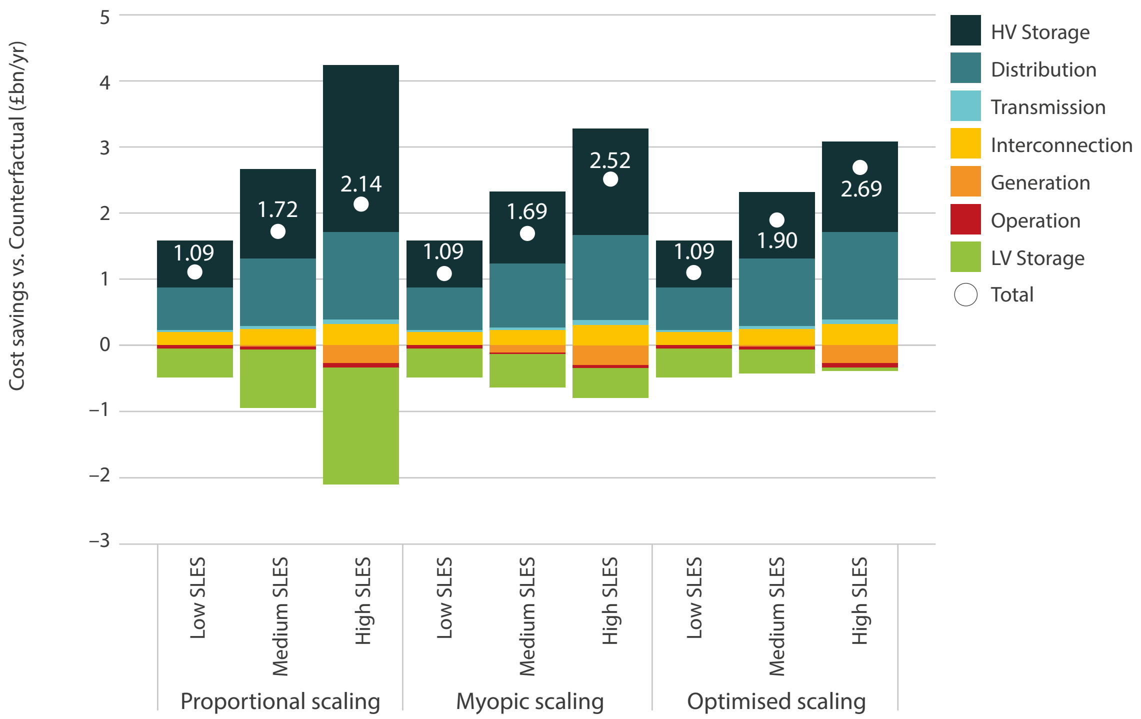


Figure 9: System benefits of SLES for various LV battery storage scaling approaches and various uptake levels (for Central Counterfactual).



It is also interesting to study how system benefits of SLES vary with alternative LV battery scaling approaches. This is illustrated in Figure 9, where cost savings across the three SLES uptake levels are presented for all three scaling approaches. The results show that LV batteries tend to be less valuable at high deployment levels of SLES as the DSR and battery storage components compete against each other, and DSR is assumed to be available at a very low cost. Proportional upscaling fails to consider the competition between LV storage and DSR and therefore results in a lower value in the High SLES case than with our default ("myopic") scaling approach. As expected, optimised scaling performs slightly better than our default approach; however, it would not be realistic that LV batteries installed in the Low SLES case are decommissioned as the uptake of SLES increases.

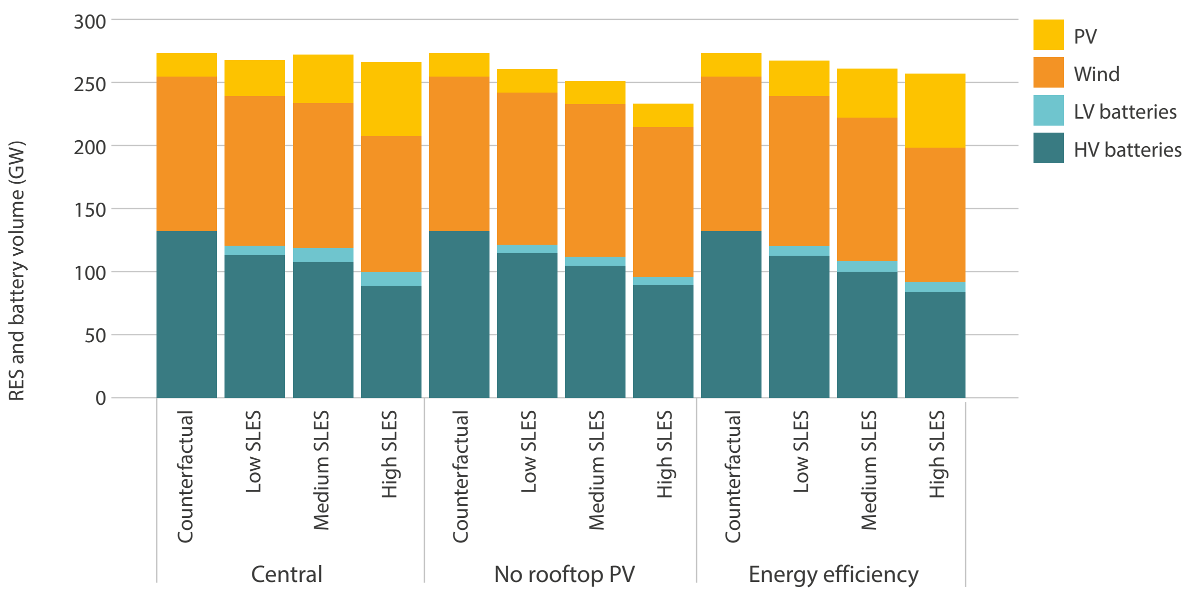
We also conducted sensitivity studies with variations in cost uplift for LV battery storage (relative to HV batteries), varying our default assumption of 50% between 25% and 75%. The impact of these cost variations on the results was very small. This is not surprising in light of previously presented results, which suggested that very little LV battery storage is added beyond the Low SLES uptake case as it faces increased competition from DSR resources. Given its limited volume, the resulting impact of cost variations on system benefits is also very small.

Impact of solar PV and energy efficiency

In the final sensitivity study, we show that system benefits of SLES could increase further if they do not include rooftop PV and if they include energy efficiency measures.

As shown in Figure 10, adding rooftop PV to the system as part of SLES displaces wind generation capacity in the net-zero UK power system. According to our assumptions for the future UK system, the levelised cost of electricity of offshore wind is expected to be lower than for rooftop PV. Therefore, removing rooftop PV from SLES resulted in higher benefits from SLES at the system level through avoided generation investment cost.

Figure 10: Volume of wind, PV and batteries without rooftop PV and with energy efficiency compared to Central Counterfactual across various SLES uptake levels.



The impact of the two variations in default assumptions on system benefits of SLES is shown in Figure 11. Not including rooftop PV as part of SLES results in additional annual system benefits of £0.13bn in Low SLES case, £0.24bn in Medium SLES case and £0.55bn in High SLES case. The increase in cost savings arises due to avoided generation investment cost, as the less cost-effective rooftop PV is no longer displacing more cost-effective offshore wind.

With the assumption that implementing SLES also brings an additional 20% reduction in demand for space heating due to improved energy efficiency, the system value of SLES further increases by £0.06bn/yr, £0.38bn/yr and £0.52bn/yr in Low, Medium and High SLES case, respectively. However, these benefits need to be set against the investment needed to implement the efficiency improvements.

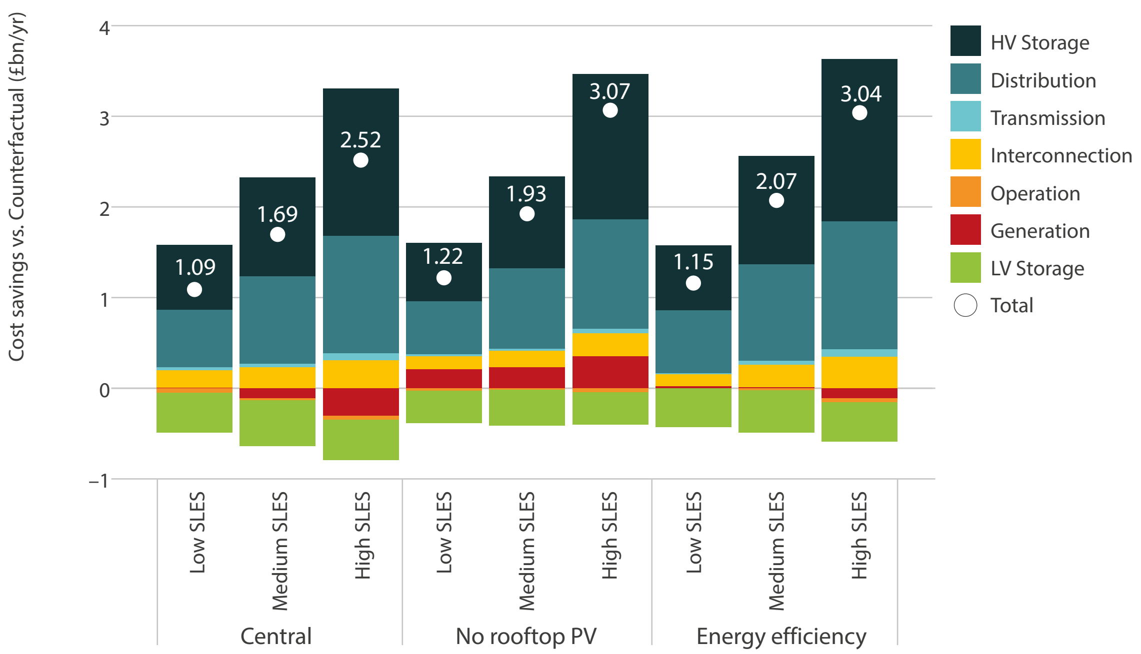
Comparison with the "early insights" briefing paper

Due to significant differences in input assumptions, the net benefits of SLES presented in this paper for the net-zero UK system are considerably lower than in our 2020 "early insights" paper (Aunedi and Green, 2020). The early insights paper had two principal differences that affected the system benefits of SLES.

First, the carbon emissions target was low but was not zero. A consequence of that was that the cost-optimal system featured Carbon Capture and Storage (CCS) plant. The bulk of value of introducing SLES came from replacing CCS generation with cheaper offshore wind, as its integration became more cost-effective with additional flexibility provided by SLES. For this paper, with its net-zero constraint, CCS does not appear in the counterfactual because it has residual emissions. Thus, introducing SLES to a zero-carbon counterfactual makes modest reductions in offshore wind and large-scale battery capacity, which has a smaller impact on system cost.

Second, the flexibility in the counterfactual for the early insights paper was very limited and much lower than optimal for a low-carbon system with a very high capacity of variable renewable generation. As a consequence, the additional flexibility of SLES was able to realise a high value and displace a large volume of CCS in favour of the lower-cost offshore wind.

Figure 11: System benefits of SLES without rooftop PV and with energy efficiency compared to Central Counterfactual across various uptake levels



Conclusions

In this briefing paper, we assessed the expected benefits that SLES could deliver for the whole electricity system in the context of transition to net-zero carbon electricity. From a wide range of scenarios and sensitivity studies, we draw the following conclusions:

1. Customers within SLES schemes are likely to see a reduction in their electricity bills compared to non-SLES customers.

For SLES customers that provide DSR services by shifting their demand to periods with lower prices, the cost of electricity would drop by about 7%-8%. SLES customers who implement rooftop PV could see a further 30% reduction in bills, while implementing energy efficiency measures would bring another 5%-7% in energy bill reductions. The annual savings are gross, i.e., they need to be considered against the cost of implementing DSR, rooftop PV, batteries and energy efficiency measures. We also find that energy bill reductions for SLES customers are reasonably robust across different penetration levels of SLES and counterfactual scenarios.

2. Deployment of SLES can deliver substantial savings in total system cost.

For Medium SLES deployment and the Central Counterfactual we found that the total system cost savings from SLES were around £1.7bn/yr, or 4.2% of the total annualised system cost. The main mechanism for SLES delivering system cost savings is through substituting grid-scale battery storage with low-cost DSR facilitated by SLES. A second major source of cost savings arises from the flexibility of SLES reducing peak demand and thereby avoiding local network reinforcement.

3. System benefits of SLES will depend on their deployment level but also on the volume of flexibility present in the counterfactual.

We observe that system cost savings of SLES increase at higher levels of deployment of SLES although there are diminishing returns from increasing the SLES uptake. Under the Central counterfactual, the savings for Low, Medium and High SLES uptake are estimated at £1.1bn, £1.7bn and £2.5bn per year, respectively. We also find that the benefits of SLES will be sensitive to how flexible the counterfactual is; system benefits for Medium SLES uptake could increase from £1.7bn to £2.1bn per year in case of a Pessimistic counterfactual, but could reduce to £1.4bn/year with an Optimistic counterfactual.

4. Cost-optimal flexibility mix in SLES should adapt to the upscaling of SLES.

Our results suggest that distributed batteries deployed as part of SLES tend to be less valuable at high levels of SLES deployment because the DSR and battery storage components compete against each other and DSR is assumed to be available at a very low cost. Therefore, proportional scaling of LV battery capacity from Low to Medium and High SLES uptake levels produces less efficient system outcomes than the approach where LV battery volume is optimised in recognition of the volume of DSR available in the system.

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5. System benefits of SLES could increase further if they include energy efficiency measures or exclude rooftop PV.

For SLES that facilitate household energy efficiency measures, it was assumed that a 20% reduction in demand for space heating would be achieved. This was found to reduce system costs by £0.5bn/yr. However, this benefit needs to be set against the investment needed for those efficiency improvements. Our default assumption was that SLES also entails rooftop PV installations, and therefore scaling up SLES resulted in this PV capacity displacing offshore wind capacity, which was assumed to be cheaper. Removing rooftop PV from SLES resulted in higher benefits of SLES at the system level through avoided generation investment cost.

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Appendix

The table below provides detailed assumptions on the uptake of DSR, battery storage and PV for various SLES uptake levels and no-SLES counterfactuals.

	Pessimistic				Central				Optimistic			
	C/F	Low	Med	High	C/F	Low	Med	High	C/F	Low	Med	High
I&C DSR	15%	20%	25%	30%	25%	30%	35%	40%	35%	40%	45%	50%
Smart EV	15%	30%	45%	75%	25%	40%	55%	85%	35%	50%	65%	95%
Smart heat	-	15%	30%	60%	10%	25%	40%	70%	20%	35%	50%	80%
LV storage	None	Opt.	Opt.*	Opt.*	None	Opt.	Opt.*	Opt.*	None	Opt.	Opt.*	Opt.*
SLES PV	None	10 GW	20 GW	40 GW	None	10 GW	20 GW	40 GW	None	10 GW	20 GW	40 GW

Notes: C/F = Counterfactual, Opt. = Optimised, Opt.* = Optimised above the cost-optimal volume for Low SLES uptake.

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About EnergyREV

EnergyREV was established in 2018 (December) under the UK's Industrial Strategy Challenge Fund Prospering from the Energy Revolution programme. It brings together a team of over 50 people across 22 UK universities to help drive forward research and innovation in Smart Local Energy Systems.

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