Department for
Business, Energy
& Industrial Strategy

Low Voltage Network Capacity Study

Phase 2 Extension Report: Investigating Battery Storage Options

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Executive Summary

This report follows on directly from the Low Voltage Network Capacity Study Phase 2 Report, which investigated the impacts of deploying solutions to increase capacity on the low voltage (LV) network. This was carried out using EA Technology's proprietary Transform Model® (hereafter referred to as "Transform") which runs a techno-economic model of the electricity network in Great Britain (GB).

In this extension study, Transform was used to investigate the cost-effectiveness and uptake of different battery storage options, including Behind-the-meter, End-of-feeder, and Substation storage. Analysis carried out in Phase 2 found uptake of Behind-the-meter storage to be very high in comparison with other solutions, primarily as result of the assumption that the capital cost of the battery would be paid by the consumer, while the DNO would pay for the service provided by the battery as an annual opex. In this extension analysis we increased the opex of this implementation in discrete steps to test the elasticity of deployment of the solution with this opex. This showed that at 150% of the baseline cost, uptake fell to negligible levels[1]. This resulted in a totex increase of £1.9bn, 6.6% higher than the baseline of £28.0bn. Following this, the opex, which represents the compensation paid by DNOs to customers, was compared with typical capital and operating costs of domestic storage. This indicated that it is unlikely Behind-the-meter battery storage would offer savings relative to the counterfactual if DNOs were to pay all costs of the system.

V2G was not explicitly included in this analysis, however, it can be considered a subset of BtM battery storage, in which the battery costs are embedded in the cost of an electric vehicle purchase. As a result, the justification for investing extra capex not covered by DNO compensation is much stronger since customers will also benefit from use of an electric vehicle. In effect, this business case was considered in Phase 2, in which domestic battery storage was modelled without a capex cost and was found to be the solution most deployed by Transform for resolving constraints. In the case of V2G, the total storage per feeder would be expected to be distributed across a smaller quantity of larger batteries in vehicles, rather than a larger quantity of smaller batteries in homes.

Following analysis of Behind-the-meter storage, network-side solutions were examined through an investigation of both End-of-feeder and Substation storage. Running Transform with both solutions included showed that End-of-feeder storage was the most cost effective due to higher thermal and voltage headroom release on cables, higher levels of flexibility for redeployment, and shorter lead times. However, in reality, end-of-feeder storage may run into practical constraints regarding space for installation, particularly in more urban networks.

Removing End-of-feeder storage as an option in the model led to limited deployments of Substation storage, indicating that this is less cost-effective in comparison to other solutions at LV. This result also further supports the conclusion that Behind-the-meter storage is unlikely to be cost effective if fully paid for by the DNO (i.e. including capital costs as well as operational

[1] This refers to the baseline Opex in Phase 2 of this project, £1,920 per feeder.

costs) since Behind-the-meter storage is likely to have a higher cost for a given capacity release than substation storage. Therefore, it is probable that the business case for Behind-the-meter storage is only feasible when capital costs are borne by the consumer, as modelled in Phase 2 of this study.

Overall, the type of storage that should be selected for resolving network constraints at LV depends on the context of use. Behind-the-meter storage is most impactful in terms of managing electricity demands of individual heat pumps and also allows consumers to stack revenues using time-of-use tariffs, maximising use of own generation (e.g., roof-top PV), and potential payments for services provided to the DNO and other balancing services. However, from the perspective of the DNO it is likely to only be economic if consumers purchase their own battery storage systems. End-of-feeder storage is the cheapest option, but depending on the deployment location (i.e. rural or urban) the practicalities of installation may present challenges. Finally, at present, Substation storage is likely to see limited deployments relative to other available solutions, however, reductions in battery costs may result in this option offering greater savings in the future.

Finally, we note that cost reductions seen as a result of solutions deployed within this study are likely to impact on the cost of decarbonising heat through electrification. In addition to reducing electricity prices by deferring network reinforcement costs, battery storage can offer further savings through its capacity for peak shifting and revenue stacking alongside dynamic time-of use tariffs.

Acronyms

BEIS	Department for Business, Energy and Industrial Strategy
BtM	Behind-the-Meter
Capex	Capital expenditure
DNO	Distribution network operator
DSR	Demand-side response
EHV	Extra high voltage
GB	Great Britain
HV	High voltage
LV	Low voltage
NPV	Net present value
Ofgem	Office of Gas and Electricity Markets
Opex	Operational expenditure
Totex	Total expenditure
V2G	Vehicle-to-grid

Introduction

The Low Voltage Network Capacity Study seeks to research lower-cost, innovative options for increasing headroom on the low voltage (LV) distribution network. These innovative options are alternatives to the use of conventional network reinforcement for increasing capacity by the replacement of assets. Additional LV network capacity is desired so that forecast levels of demand and distributed generation can connect to the network over the coming decades, and network capacity does not constrain increased electrification of transport and heat. Furthermore, network reinforcement costs are passed on to electricity customers, so lower cost options for capacity increase would benefit customers financially, as well as possibly being less disruptive than asset replacement.

To explore potential innovative options for capacity increase (or demand reduction), the Phase 1 report[2] for this study undertook a literature review of innovative options for increasing capacity to produce a longlist of options, after which a methodology was devised to shortlist those options. Following this, each item in the shortlist was modelled using Transform. The methodology and results of this analysis are presented in the Phase 2 report[3].

This document follows on directly from the Low Voltage Network Capacity Study Phase 1 and Phase 2 reports and details an extension to the project focussed on electric battery storage. Behind-the-meter (BtM) Domestic Battery Storage for DSR (demand-side response) was found to be a particularly prominent solution in the Phase 2 modelling as a result of the assumption that the capital costs would fall on customers rather than the DNO. This report investigates the feasibility of this assumption, examining whether compensation paid by a DNO could be enough to allow customers to recover their expenditure on storage assets. This is then further compared with network-side storage, including a discussion of the practicalities of these options. Specifically, the further work included in this extension report includes:

- How deployment of the Behind-the-meter storage solution in the Transform model is affected by altering the operational expenditure (opex) associated with it, where this opex is assumed to be the cost to the DNO of deploying the solution (and is the cost used by Transform to compare Behind-the-meter storage to other potential solutions). The opex was to be increased in steps until the solution is chosen by the model only very rarely, to better quantify the upper bound cost below which this solution is viable.
- How network-side storage solutions at LV perform in Transform and which solution is preferable. These network-side solutions are storage at the high voltage (HV)/LV substation and storage at the end of the LV feeder.
- How behind-the-meter and network-side solutions compare.

[2] A. Speakman, O. Harris, C. Birkinshaw-Doyle, D. Mills, I. Walker, M. Sprawson, "Low Voltage Network Capacity Study – Phase 1 Report for The Department for Business, Energy and Industrial Strategy (BEIS)", *Element Energy and EA Technology*, 23rd July 2021

[3] O. Harris, D. Mills, A. Speakman, I. Walker, M. Sprawson, "Low Voltage Network Capacity Study – Phase 2 Report for The Department for Business, Energy and Industrial Strategy (BEIS)", *Element Energy and EA Technology*, 29th November 2021

The remainder of this extension report is structured as follows:

- *The Transform Model: An Overview* gives a brief explanation of the Transform model for context.
- *Parameterising the Storage Solutions* outlines the work undertaken for the storage solutions to be input into the model.
- The different runs of the model are subsequently described and their results analysed in *Modelling Behind-the-meter Storage with Varying Opex* and *Modelling Network-side Storage* for behind-the-meter storage and network-side storage, before their results are compared in *Comparison of Storage Solutions*.
- Finally, from these results, conclusions are drawn and presented in *Conclusions*.

The Transform Model: An Overview

The Transform Model® was originally developed in 2012 as part of the Department of Energy and Climate Change and the Office of Gas and Electricity Markets' (Ofgem's) Smart Grid Forum[4]. It has since been reviewed annually with input from the distribution network operators (DNOs), and version 5.4 was used for this study.

Transform uses a single model of the GB electricity network at LV, HV, and extra high voltage (EHV). The model uses various network archetypes at each voltage level, each with a typical make-up for that archetype, and uses national data to produce generic load profiles on each network. Then, once a network exceeds its assigned capacity for thermal transformer, thermal cable, voltage headroom, or voltage legroom constraints, Transform selects a solution or combination of solutions to deploy on that network. The solutions at Transform's disposal, both conventional reinforcement and 'smart'[5], are characterised by 29 different parameters. These include the capital expenditure (capex) and opex required, and what percentage of network headroom is released for each type of constraint.

The solution (or solutions) chosen depends on a number of factors. The model's choice is the most cost-effective means of resolving the given constraint over a pre-set time window from the given year, according to a dynamic merit order. For this study that time window was set to five years, consistent with the duration of the RIIO-2 price control periods and with previous work using Transform.

Transform's merit order accounts for net present value[6] (NPV) total expenditure (totex) required over the lifetime of the solution, discounted at 3.5%. The merit order is also influenced by many other parameters in the model, which are converted into costs that are added or subtracted from the totex. These parameters include the disruption caused by the deployment of a solution (due to customer supply interruptions, the digging up of roads to underground cable, and so on), a solution's flexibility once deployed (whether a solution could be redeployed elsewhere at little cost if no longer required or is a fixed asset), and the effect deploying a solution has on other voltage levels. While these alternative parameters are accounted for and lead to an adjusted totex, if the capex for a solution is large then this generally still dominates the adjusted totex and the solution is placed low in the merit order.

The discounted capex and opex values for solutions are set on one of five generic cost curves in Transform. These represent prices changing over time due to learning curves,

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[4] EA Technology, *Assessing the Impact of Low Carbon Technologies on Great Britain's Power Distribution Networks*. EA Technology: Capenhurst; 2012. Available at: https://www.ofgem.gov.uk/sites/default/files/docs/2012/08/ws3-ph2-report.pdf [Accessed 3rd November 2021]

[5] Smart functionality has been defined within this study in reference to standards and definitions used within BEIS. This includes the ability to send and receive information, respond to this information by increasing or decreasing the rate of electricity flowing through the assets, and change the time at which electricity flows through the assets. Smart solutions may be able to decrease the peak load on the electrical distribution networks to alleviate the need for network upgrades to handle new domestic appliance types, such as electric vehicle (EV) charge points and electric heating, ventilation, and air conditioning (HVAC) systems.

[6] This represents the value of the investment in today's money taking into consideration the growth that would have occurred through investment over time.

manufacturing volumes, and changes to the prices of raw materials or components. When a solution expires after its set lifetime, it is replaced if no new headroom is required, or if additional headroom is now required the model will return to its dynamic merit order and select a solution or combination of solutions in the same way as before.

Parameterising the Storage Solutions

Before modelling could be undertaken, parameters had to be chosen for the storage solutions. These parameters were drawn from sources examined in the Phase 1 literature review, additional sources[7,8], similar solutions already in Transform, and the engineering judgement of the teams at EA Technology and Element Energy. The parameters and the values chosen for them are tabulated in Appendix 1: Transform Model Parameters for Storage Solutions. The compatibility of these new solutions with the 105 solutions already in Transform, with each other, and with the 19 different LV network archetypes in Transform also had to be determined. Four LV feeders per distribution transformer and 40 consumers per feeder were assumed. Several assumptions were made in order to precisely define the solutions analysed later in this report.

- Behind-the-meter Domestic Battery Storage for DSR:
    - Parameterised as having zero capex but a given opex. This represents network operators compensating consumers for DSR such as flexibility services, but not paying the upfront cost of battery purchase and install; that capex is borne by consumers (or by alternative financial arrangements).
    - A total of 14kW, 72kWh storage is deployed per feeder which is equivalent to 1.2kW, 6kWh batteries in 30% of households.
- Substation Battery Storage:
    - Assumes the same capacity per feeder as for Behind-the-meter storage, with four feeders per substation leading to a total capacity of 56kW and 288kWh.
    - There will be limited benefit for capacity release down-stream of the substation and so thermal headroom release will only be on the transformer and not the cables. Voltage headroom / legroom release will still be applicable, but the amount will be reduced and has been assumed to be +/- 5%.
    - Assumes a solution lifetime of 20 years rather than 10 years assumed for behind-the-meter storage. Although the batteries may require replacement / refurbishment during this period this is covered by the assumed opex.
- End-of-feeder Battery Storage:
    - Assumes the same capacity release as Behind-the-meter storage and Substation storage. In reality the network-side storage will not offer the same benefit all the way along the feeder, but we assume that it would be located at the optimum location for headroom release.
    - Assumes a solution lifetime of 20 years rather than 10 years assumed for behind-the-meter storage. Although the batteries may require replacement / refurbishment during this period this is covered by the assumed opex.

[7] Northern Powergrid, "DS3-Distributed Storage and Solar Study, Final Report", February 2020
[8] Logan Goldie-Scot, "A Behind the Scenes Take on Lithium-ion Battery Prices", *BloombergNEF*, March 2019

Results of Previous Modelling

In Phase 2 of this study[3], a number of modelling runs were undertaken using Transform.

- In Run 0, the only solutions Transform could select from were 'Conventional' solutions.
- In Run 1, Transform could select from the solutions shortlisted in Phase 1, denoted as 'Shortlisted' solutions, as well as the Conventional solutions.
- In Run 2, in addition to the Shortlisted and Conventional solutions Transform could select from 'Other Smart' solutions. These are the solutions already contained in Transform and not covered by the previous categories, i.e. the remaining smart solutions for LV networks and all the smart solutions for HV and EHV networks.
- A number of sensitivity runs were also undertaken looking in more detail at different Shortlisted solutions.

For the modelling runs in this extension report, presented and discussed in later sections, Run 2 is used for comparison (referred to as the baseline). Run 2 is chosen because it is more realistic to model a greater range of solutions (all the solutions in Transform) rather than artificially restricting the selection to conventional solutions and those shortlisted in Phase 1. In Run 2 the cumulative discounted total expenditure (hereafter referred to as 'totex' unless otherwise stated) between 2021 and 2050 is modelled to be £28.0bn. For the LV network, the number of deployments for different solutions used to resolve constraints is shown in Figure 1.

Figure 1: Average number of LV interventions applied per year in Run 2, 2021-50.

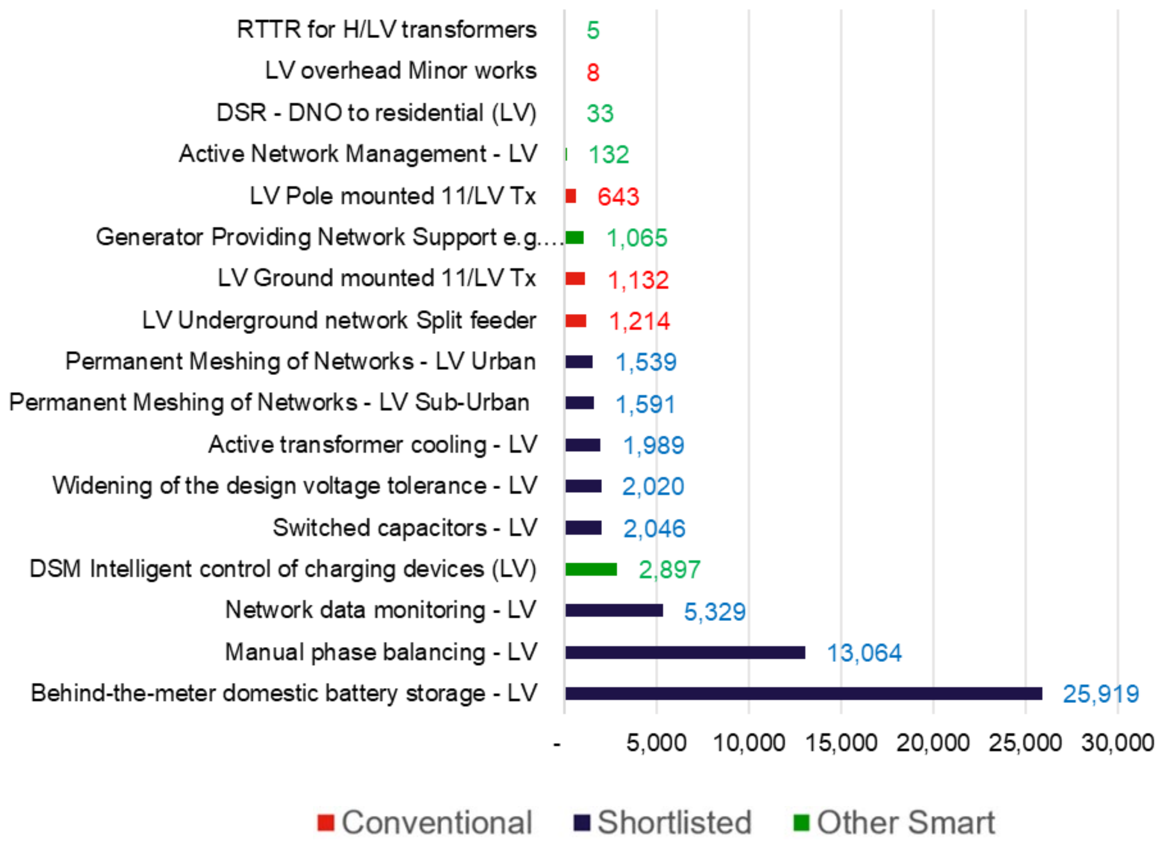


Figure 1 shows the 3 most-deployed solutions to be Behind-the-meter Domestic Battery Storage for DSR, Manual Phase Balancing, and Network Data Monitoring. A small number of solutions make up the vast majority of deployments, but in total 16 solutions are chosen: 4 Conventional, 7 Shortlisted, and 5 Other Smart. The high uptake of Behind-the-meter battery storage is not unexpected as it is the only solution which assumed a capital cost paid by the customer rather than the DNO. This study explores the feasibility of this assumption and compares it with other implementation options for battery storage.

Modelling Behind-the-meter Storage with Varying Opex

Methodology

To investigate how deployment of the Behind-the-meter Domestic Battery Storage for DSR solution in the Transform model is affected by altering the opex, the opex used in Run 2 was increased in four steps, expressed as a percentage of the Run 2 opex (baseline). These four runs are listed in Table 1. The upper bound to the opex increase was set to be the point at which Behind-the-meter storage was selected in negligible quantities.

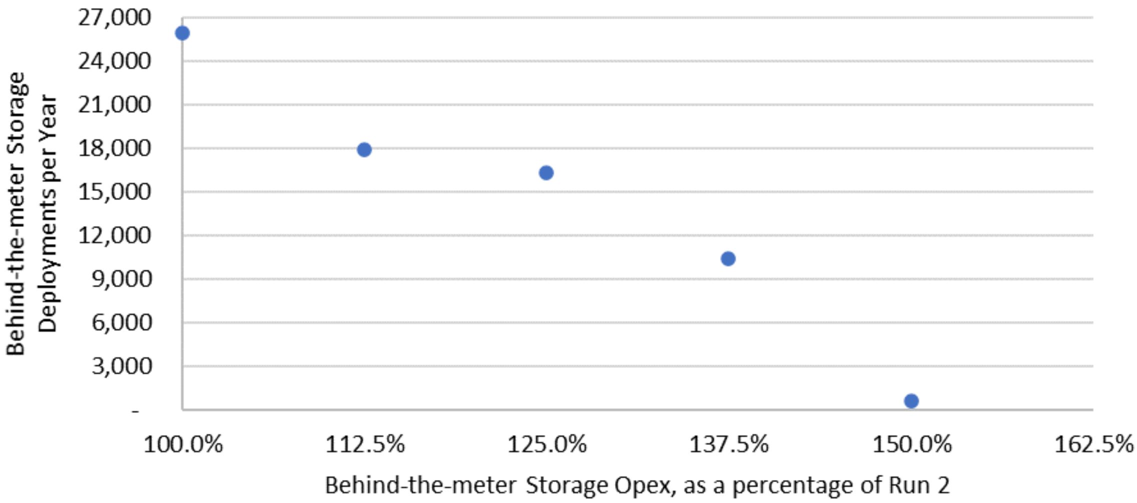
Table 1: Runs of the Transform model used in the investigation into behind-the-meter storage, summarised by which solutions were included.

Run #	Solutions Included
2	Conventional, Shortlisted, Other Smart
E1	As Run 2, with opex of behind-the-meter domestic battery storage solution set to 112.5% of in Run 2
E2	As Run 2, with opex of behind-the-meter domestic battery storage solution set to 125% of in Run 2
E3	As Run 2, with opex of behind-the-meter domestic battery storage solution set to 137.5% of in Run 2
E4	As Run 2, with opex of behind-the-meter domestic battery storage solution set to 150% of in Run 2

Results

In Run 2, the opex per year for Behind-the-meter Domestic Battery Storage for DSR was input as £1,920 per feeder. The reduction in deployments of this solution caused by increasing the opex to 112.5%, 125.0%, 137.5%, and 150.0% of this Run 2 value is presented in Figure 2.

Figure 2: Average number of deployments per year of the Behind-the-meter Domestic Battery Storage for DSR solution, 2021-50, as a function of the solution's opex.



After undertaking the four modelling runs listed in Table 1, an opex of 150% of that value (£2,880) was found to reduce the number of deployments by 97.7% (an average of 25,919 per year to 598 per year). This means that, for the parameters selected such as storage size and headroom release, an opex of approximately £2,880 per feeder per year is sufficiently large for Behind-the-meter Domestic Battery Storage for DSR to be judged less cost-effective than other solutions.

This opex, which represents the compensation that a DNO would pay to customers for the use of their storage does not cover the purchasing costs of the domestic energy storage system. Typical capex for a domestic battery installation may be assumed to be £700/kWh[9] which based on a 14kW/72kWh system equates to £50,400. Taking the upper bound (150%) of the DNO payment at £2,880/feeder/year, customers on a single feeder could expect to receive £28,800[10] over the 10-year lifetime of their battery system, leaving a -£21,600 shortfall. At a more likely level of DNO payment, e.g. £1,920/feeder/year, the shortfall would be even greater. Therefore, customers would not fully recoup the cost of their installation from DNO payments alone, but would be expected to derive further benefit (savings or revenue) from the flexibility offered by domestic batteries, for example by taking advantage of time of use tariffs along with rooftop PV (as noted in the Phase 1 study). The business case would only be expected to improve as battery costs reduce further[11].

V2G was not explicitly included in this analysis, however, it can be considered a subset of BtM battery storage, in which the battery costs are embedded in the cost of an electric vehicle purchase. As a result, the justification for investing extra capex not covered by DNO compensation is much stronger since customers will also benefit from use of an electric

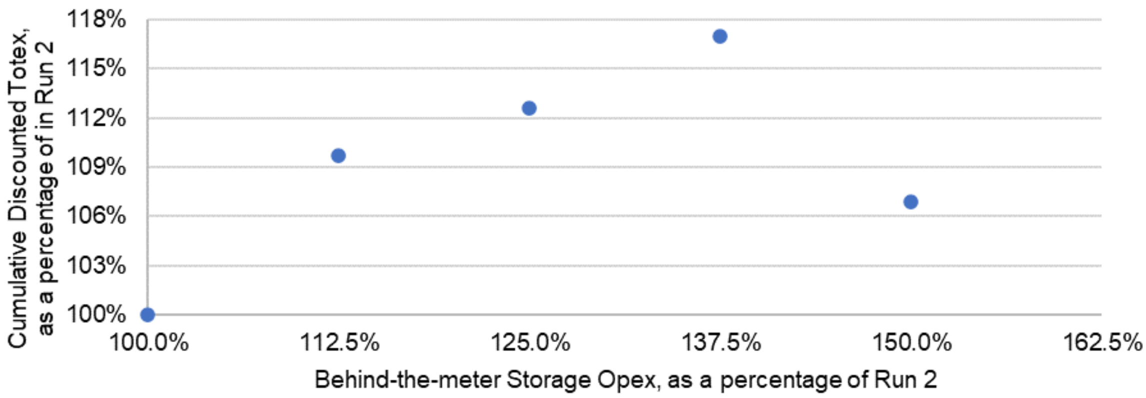
[9] See Phase 1 report.
[10] Cost to customer per feeder = capex/kWh = 72kWh x £700/kWh = £50,400. Compensation paid by DNO per feeder = £2,880 x 10 years = £28,800.
[11] Bloomberg, *A Behind the Scenes Take on Lithium-ion Battery Prices (2019), Why an Electric Car Battery Is So Expensive, For Now, (2021)*. Bloomberg NEF finds that battery back prices have come down by 89% since 2010, from $1191/kWh to $137/kWh and it is expected that costs will continue to fall to an average of $58/kWh by 2030.

vehicle. In effect, this business case was considered in Phase 2, in which domestic battery storage was modelled without a capex cost and was found to be the solution most deployed by Transform for resolving constraints. In the case of V2G, the total storage per feeder would be expected to be distributed across a smaller quantity of larger batteries in vehicles, rather than a larger quantity of smaller batteries in homes.

Also, it is notable in Figure 2 that there is a 31.0% decrease in deployments for the first opex increase of 12.5%. This shows how sensitive Transform is to cost increases, in that for a relatively small cost increase a previously favourable solution becomes significantly less attractive. Furthermore, deployments do not decrease smoothly with increases in opex. For an opex increase of 37.5%, three times the first 12.5% increase, deployments drop by 59.7% which is less than double the drop in deployments of the first step (31.0%). However, the deployments decrease markedly again by 97.7% (compared to the original 100% opex deployment level) as opex is increased from 137.5% to 150% opex. This illustrates how step changes of different sizes occur when different solutions overtake Behind-the-meter Domestic Battery Storage for DSR in Transform's dynamic merit order.

The impact of the cost increases of Behind-the-meter storage (and other solutions being deployed instead) on the totex is shown in Figure 3.

Figure 3: Cumulative discounted totex of whole network model, 2021-50, as a function of the Behind-the-meter Domestic Battery Storage for DSR solution's opex.

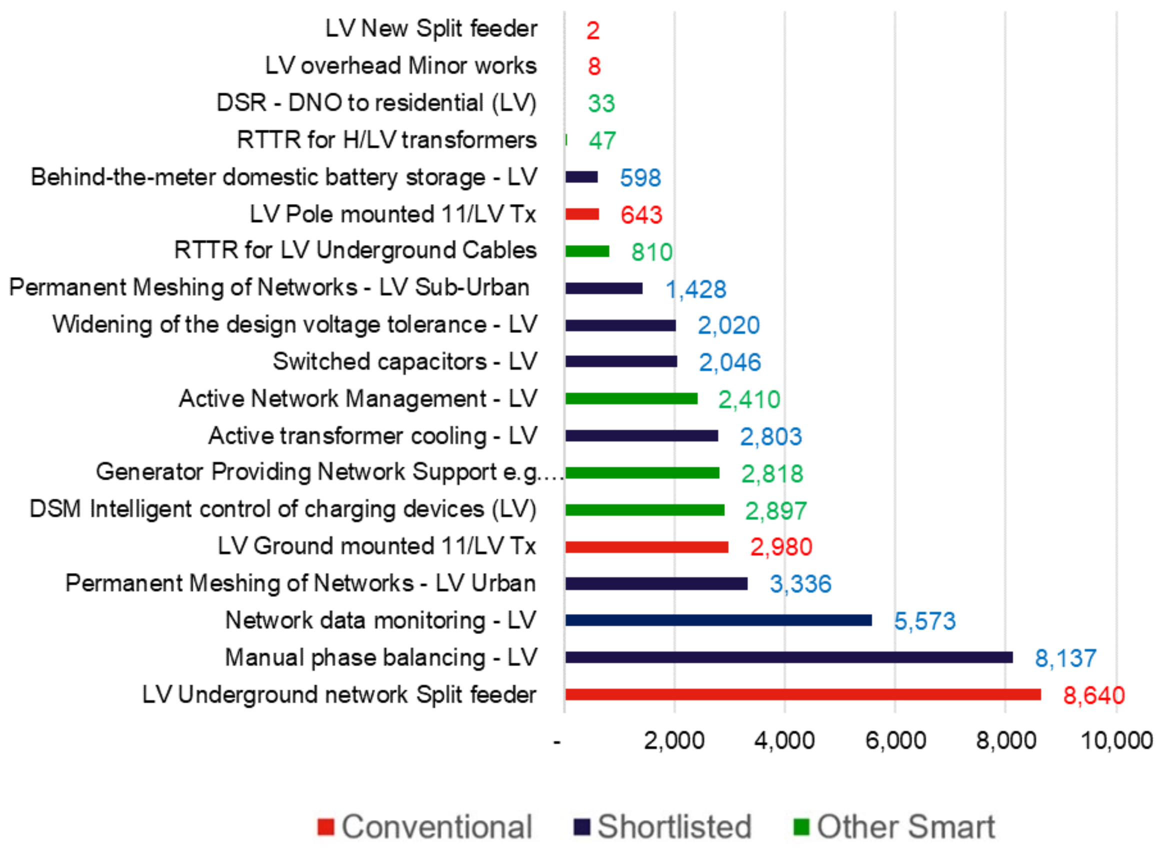


As Behind-the-meter storage costs are incremented, totex for the period between 2021 and 2050 peaks at £32.6bn, an increase of £4.6bn (+16.3%) on the baseline. It is worth noting that between an opex increase of 37.5% and 50.0%, the trend reverses, and an opex increase of 50% sees a totex increase of £1.9bn (+6.6% from the baseline). This change in the trend is as a result of a sharp decrease in deployments of the BtM storage solution, which is comparatively very expensive, and an increase in deployments of other solutions which are relatively cheaper. Behind-the-meter storage was still the second-most deployed solution in the 137.5% opex run. For the most part it is Conventional solutions, particularly LV Underground Network Split Feeder, that take the place of Behind-the-meter storage. LV Underground Network Split Feeder becomes the solution deployed most often in the 150% opex run. Such solutions resolve constraints for a longer time period than the 10-year lifespan of Behind-the-meter storage, and any replacement of these higher capex Conventional solutions beyond

2050 is not captured in the 2020-50 period. As a result, the apparent reduction in overall totex is a result of the timespan being considered and a significantly different result could be expected should a solution window past 2050 be considered.

The average number of deployments of LV solutions per year is shown in Figure 4 for the run with Behind-the-meter Domestic Battery Storage for DSR's opex at 150% of in Run 2. Despite various changes, Manual Phase Balancing and Network Data Monitoring remain second- and third-most deployed solutions respectively. As noted in Phase 2 of this study, where battery storage is removed as an option or, in this case, is too expensive, splitting the feeder remains a favourable option for resolving network constraints. As a result, this counterfactual option is selected most often in Transform when battery storage costs are too high.

Figure 4: Average number of LV interventions applied per year in Run E4 (behind-the-meter storage opex at 150% of in Run 2), 2021-50.



Modelling Network-side Storage

Methodology

To investigate how LV network-side storage solutions perform in Transform, the Substation Storage and End-of-feeder Storage solutions were parameterised and then modelled. One run was undertaken including both types of network-side storage but excluding the behind-the-meter storage. Since this yielded deployment of End-of-feeder storage only, a further run was undertaken which excluded End-of-feeder storage. Both runs are outlined in Table 2.

Table 2: Runs of the Transform model used in the investigation into network-side storage, summarised by which solutions were included.

Run #	Solutions Included
2	Conventional, Shortlisted, Other Smart
E5	As Run 2, with Behind-the-meter Domestic Battery Storage for DSR solution removed and Substation Battery Storage and End-of-feeder Battery Storage solutions added
E6	As Run 2, with Behind-the-meter Domestic Battery Storage for DSR solution removed and Substation Battery Storage solution added

Results

Substation and End-of-feeder Battery Storage

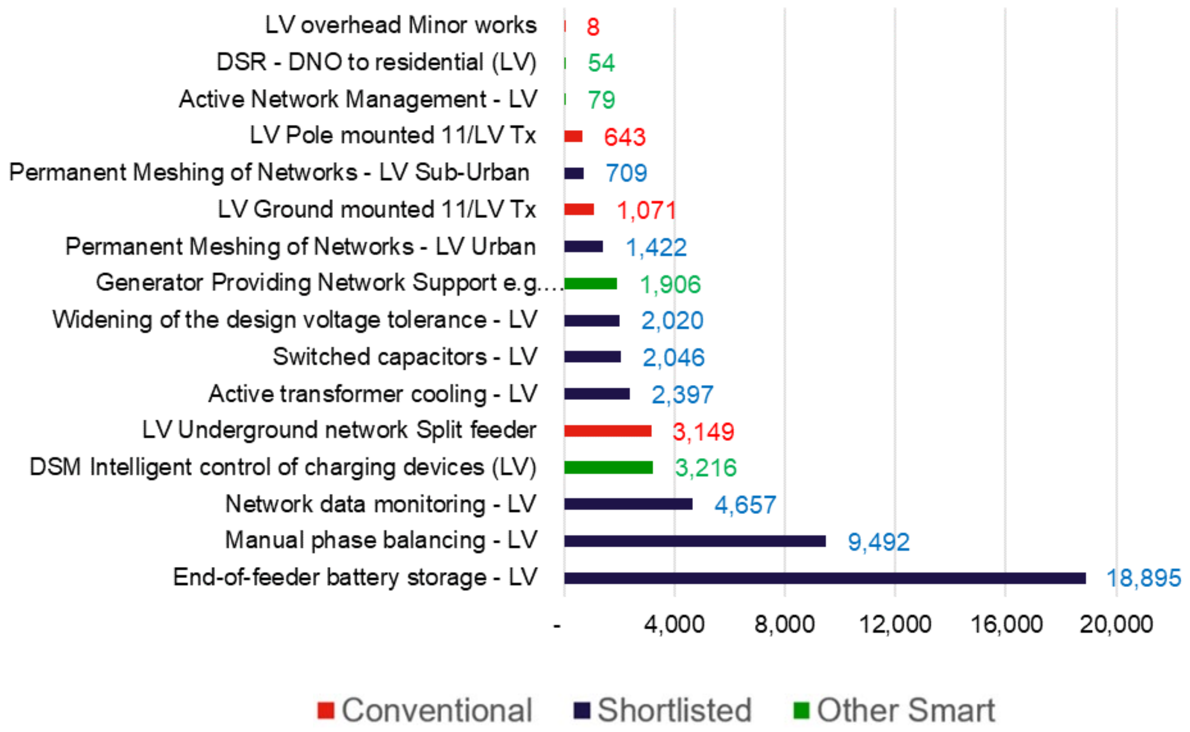
In the Transform run including both the Substation Battery Storage and End-of-feeder Battery Storage solutions (E5), of the two new storage solutions only the End-of-feeder Battery Storage is selected for deployment by the model. This is a result of the parameters input for each solution (given in Appendix 1: Transform Model Parameters for Storage Solutions). Substation Battery Storage is lower down Transform’s dynamic merit order than End-of-feeder Storage in every case, because:

- Both are available on the same network archetypes.
- End-of-feeder Battery Storage releases the same percentage of thermal transformer headroom, but greater percentages of thermal cable headroom, voltage headroom, and voltage legroom.
- End-of-feeder Battery Storage has a more favourable ‘flexibility rating’, that is, it can be moved and redeployed if no longer needed where initially sited with less effort.

- End-of-feeder Battery Storage has a shorter lead time since it is assumed a standardised designs will be utilised and generally there may be increased levels of land availability.
- Substation storage and end-of-feeder storage cannot be deployed together.

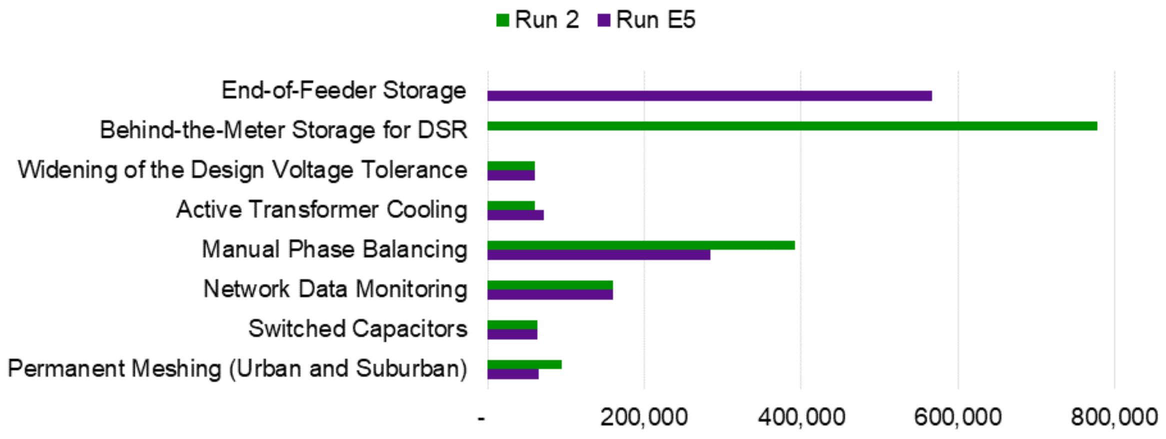
The average number of deployments of LV solutions per year is shown in Figure 5. The deployment results shown in Figure 5 are broadly similar to the baseline model run (Figure 1), albeit with End-of-feeder Battery Storage deployed in the absence of Behind-the-meter Domestic Battery Storage for DSR. Manual Phase Balancing and Network Data Monitoring remain second- and third-most deployed solutions respectively.

Figure 5: Average number of LV interventions applied per year in Run E5 (network-side storage), 2021-50.



However, a more detailed comparison of this run with Run 2 reveals that the use of end-of-feeder rather than behind-the-meter storage does affect some solutions in significant numbers. This is shown in Figure 6.

Figure 6: Average number of Shortlisted LV interventions applied per year in Runs 2 and E5 (network-side storage), 2021-50.

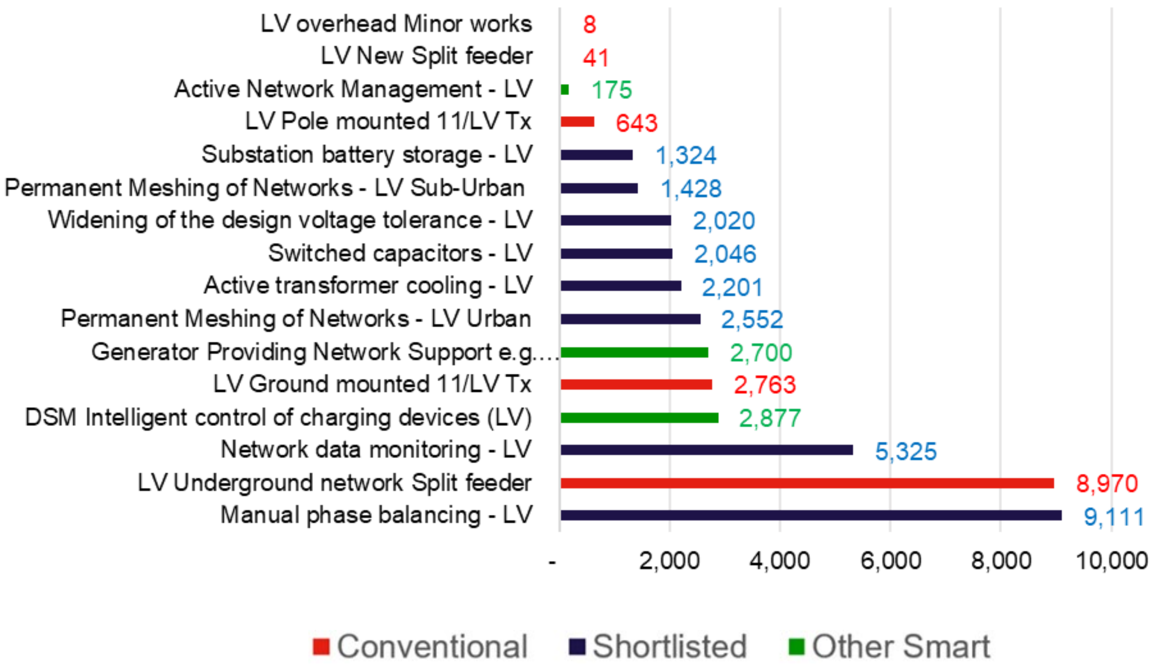


Overall, the use of end-of-feeder storage reduces the total number of interventions that are necessary, this is due to the 20-year lifetime assumed for the end-of-feeder storage which avoids the need for some feeders to be revisited during later years of the analysis. Specifically, the deployment of Permanent Meshing is reduced by 31% compared to Run 2. This reduction disproportionately affects sub-urban networks, with deployment of meshing of urban networks decreasing by 7% and decreasing on sub-urban networks by 55%. Similarly, Manual Phase Balancing is deployed 27% less. Of all the Shortlisted solutions Transform deployed in Run 2, Permanent Meshing and Manual Phase Balancing are the ones with the highest capex, so these solutions are being displaced. Conversely, Active Transformer Cooling sees a 21% increase in deployments compared to Run 2. Furthermore, this run where the End-of-feeder Storage is the most deployed solution has a totex of £23.8bn (2021-50), which is a saving of £3.2bn (11.7%) on Run 2's £27.0bn. Further discussion around this is presented in *Comparison of Storage Solutions*.

Substation Battery Storage Only

As noted in *Substation and End-of-feeder Battery Storage*, the Substation Battery Storage solution was not chosen by Transform because End-of-feeder Battery Storage ranks higher in Transform's merit order. In order to test the effects of Substation Battery Storage, another model run (E6) was undertaken, which excluded End-of-feeder Battery Storage as well as behind-the-meter storage. The average number of deployments of LV solutions per year for this run is shown in Figure 7.

Figure 7: Average number of LV interventions applied per year in Run E6 (substation storage only), 2021-50.



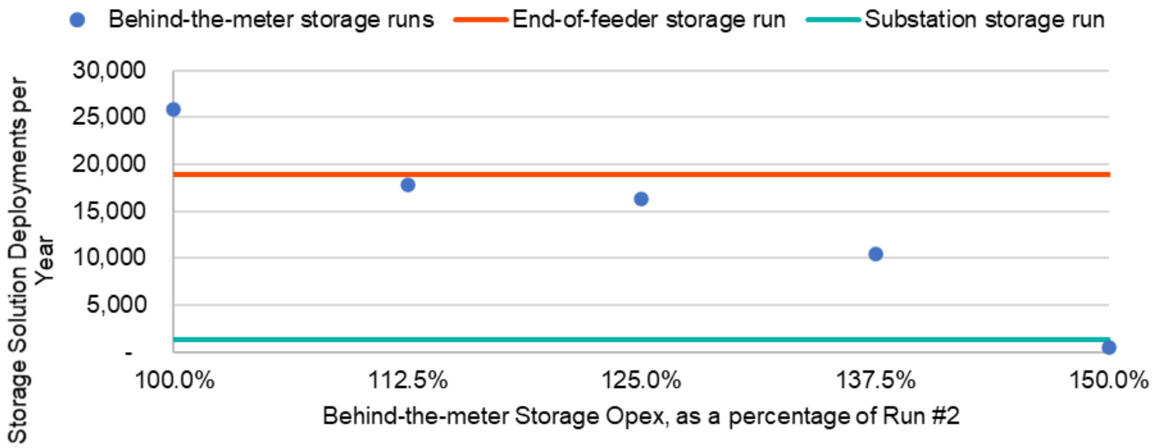
The deployment results shown in Figure 7 are somewhat similar to the Run E4 (Figure 4), where BtM storage opex was increased by 50%. Substation Battery Storage deployed in relatively small numbers in a similar way to Behind-the-meter Domestic Battery Storage for DSR when it was at 150% of its baseline opex, and Manual Phase Balancing and LV Underground Network Split Feeder are deployed the most and in similar numbers. This shows the difference in parameters between Substation Battery Storage and End-of-feeder Battery Storage discussed in *Substation and End-of-feeder Battery Storage* to have had a substantial impact on deployment of both solutions, with substation storage being deployed less as a result of the model selecting different solutions instead. Furthermore, this result supports the conclusion that BtM storage is unlikely to offer savings relative to the counterfactual in the case that the full cost is paid by the DNO, since costs for this implementation are higher still than substation storage. Therefore, it is unlikely that the LV network would see high deployment of BtM storage unless capital costs are paid by the customer, as modelled in Phase 2.

However, one point to note is that Substation Battery Storage has been assumed to have the same storage capacity per feeder, but when deployed in the substation to serve 4 feeders. So even though Substation Battery Storage is deployed 1,324 times per year, that is the same storage capacity as deploying the End-of-feeder Battery Storage or Behind-the-meter Domestic Battery Storage for DSR solutions 5,296 times. Nevertheless, this Substation Storage run has a totex of £30.1bn (2021-50). This is an increase of £2.1bn (7.4%) on the baseline (Run 2) cost of £28.0bn, and an increase of £5.2bn (21.9%) on Run E5 where End-of-feeder Battery Storage was selected.

Comparison of Storage Solutions

The previous sections have examined behind-the-meter and network-side storage. In this section we compare these results quantitatively, followed by a discussion around practical considerations. The level of deployment for each storage solution in this study is summarised in Figure 8 showing that BtM opex could be 12.5% or 50% higher and achieve the same deployment rates as End-of-feeder and Substation Battery Storage levels respectively.

Figure 8: Average number of deployments per year of storage solutions for all runs, 2021-50.



The solutions have also been shown to have different effects on the other solutions deployed in the model, discussed in the preceding sections. Cumulative discounted totex for the whole network model from 2021 to 2050 is graphed in Figure 9 for the model runs discussed in this extension report.

Figure 9: Cumulative discounted totex for all runs, 2021-50.

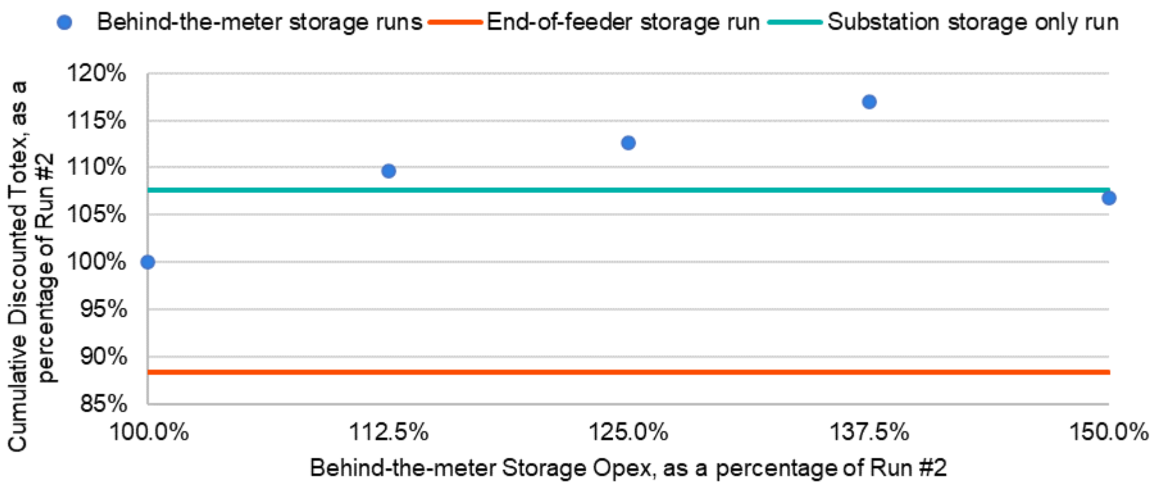


Figure 9 shows that deploying storage at the end-of-feeder but not behind-the-meter or at substations yields a significantly lower totex. Deploying storage BtM yields a lower totex than deployment of storage at the substation. The run where End-of-feeder Battery Storage is selected (E5) is the run which results in the lowest totex. The biggest driver for this reduction in totex is because of the assumed longer lifetime for the solution and therefore resulting lower deployment numbers, however, there are several assumptions and practical considerations around this solution which need to be considered and are discussed further in in the following section.

Practical Implementation of End-of-feeder Storage

Battery Energy Storage Systems (BESS) can have varying effects on the LV network depending on their placement. In this report we have examined the shortlisted solution of behind-the-meter storage as well as grid-scale systems at substations or at the end of LV feeders. Grid-scale storage at the substation was considered in Phase 1 of this project, however, while it can be less expensive[12] than behind-the-meter storage, it was ultimately not taken forward due to its limited functionality in managing feeder level constraints such as those resulting from heat pump demand at individual residences[13]. Conversely, behind-the-meter storage offers a more localised approach which can be used to manage the demands of individual residential and commercial premises. Behind-the-meter storage can be charged outside of peak times and drawn upon when required to power electric heating or other appliances. Moreover, this approach may be combined with dynamic time-of-use tariffs to incentivise charging and discharging during certain hours, thereby flattening demand profiles and alleviating network loading.

The evidence presented in this report has shown the value of placing storage at the end of a feeder, and it is therefore pertinent to discuss some of the practical considerations surrounding this implementation. Storage brings maximum benefit when it is installed at the point of load, which statistically lies in the middle third of the feeder. This means if the optimal location for storage is past halfway, then it may be preferable to locate storage at the end of the feeder rather than the substation. In rural networks where feeders can be very long, this may help to address issues with voltage management, as well as resolving thermal constraints. Voltage support may be offered by using reactive power capabilities to optimise power factor and reduce losses. Smart management of this type of storage through controlled timing and phase selection can optimise the technology to balance peaks and troughs[14].

However, it has been noted in energy storage trials that space constraints can be a significant issue for this type of implementation[15] as a result of the number of additional systems required,

[12] This refers to absolute cost of grid-scale vs behind-the-meter storage, rather than that seen by the DNO or the customer. In Phase 2 of this study, the DNO does not pay the capex of behind-the-meter storage so would see this as a cheaper solution, however, this cost must still be paid by the customer and is likely to be more expensive per unit of energy stored than a grid-scale solution.
[13] Where batteries are connected behind the meter, they may be able to better address local power and voltage variations caused by heat pumps and domestic generation. Therefore, for the specific case of shifting heat pump demand, domestic storage is expected to present the most promising option. Conversely, grid-scale storage is less able to address such issues since the solution is more centralised (i.e. located at the substation).
[14] SSEN, *New Thames Valley Vision Learning Outcome Report, LV Network Storage – ESMU Trials*, (2017)
[15] Northern Powergrid, *Customer Led Network Revolution Lessons Learned Report: Electrical Energy Storage*, (2014)

including “resilient communications, router, firewall and alarm control systems, all with appropriate power supplies”. Moreover, space issues are most significant in dense urban networks which are the most likely to be thermally constrained. This has been demonstrated by modelling in this study, which highlighted the terraced street LV network archetype as the archetype requiring the greatest expenditure to 2050. In behind-the-meter systems, space constraints are less prevalent since storage is distributed across a number of smaller locations (in consumers’ premises). Therefore, while the total required area may be the same or greater for a behind-the-meter system of the same capacity, it is generally less disruptive and easier to install than grid-scale storage.

The Transform Model input parameters considered in this study allow for some consideration with regards to land availability and space constraints. However, these are generalised input parameters whereas the actual constraints and disruption to supplies during the installation of end-of-feeder energy storage solutions will be significantly more localised. Due to the increased complexity and disruption of installing grid scale storage it has been assumed to have a useful lifetime of 20 years rather than the 10 years assumed for behind-the-meter. This increased lifetime reduces the overall number of solutions that are deployed and therefore over the window considered in this study results in a reduction in overall totex. However, this is on the assumption that sufficient land can be obtained in the most appropriate location for end-of-feeder storage.

In cases where there is adequate space for placement of storage on the feeder, it may still not be the best option for extending network capacity. This is because with that space it may be possible to build a new substation instead, which compared to storage will introduce more headroom and have a longer lifespan. Substations are also a more reliable means of increasing headroom, owing to the additional systems required for storage, as noted above, that increase solution complexity, and because battery solutions need to spend some of the time charging so are not always available for network support.

Conclusions

This report has investigated three different implementations of battery storage on the LV network comparing each option in terms of its cost-effectiveness and its resulting uptake between now and 2050. Behind-the-meter, End-of-feeder, and Substation storage were analysed by leveraging EA Technology’s proprietary Transform ModelTM to assess levels of deployment of each solution alternative, given the parameters and properties ascribed to each one.

First, domestic storage was analysed by increasing the baseline opex in steps of 12.5%, up to a maximum of 150%. At 150% of the baseline opex, it was found that domestic behind-the-meter storage was only deployed in negligible quantities, indicating that this is approximately the level at which the implementation is no longer cost-effective at LV. The resulting increase in totex between 2021 and 2050 for this analysis was £1.9bn (+6.6%), bringing the cost to £29.9bn from £28.0bn. Such increases in opex may be used to give an estimation of the cost at which storage is no longer cost effective—this was compared with existing battery storage costs which indicated that compensation to customers from a DNO, even at 150% of the baseline, is unlikely to pay for all costs associated with a Behind-the-meter system.

Network-side storage was subsequently investigated by examining both substation storage and end-of-feeder storage. Capacity and costs were parameterised and input into Transform for both implementation alternatives, which resulted in a high uptake of End-of-feeder storage and no uptake of substation storage. The reason for this is that while both are available on the same network archetypes, End-of-feeder storage is higher in the dynamic merit order in all cases. This is a result of it bringing greater thermal and voltage headroom to LV feeders, a higher level of flexibility, and shorter lead times in the case of End-of-feeder storage. Deployment of End-of-feeder storage leads to lower totex costs over the 2021-2050 period, with an overall saving of approximately £3.2bn (11.3%) compared with the baseline.

Substation storage was further investigated by removing End-of-feeder storage as an option in Transform, such that the only storage solution was Substation storage. When this model is run, totex increases by approximately £2.1bn relative to the baseline and Substation storage is not deployed in large numbers compared with Behind-the-meter or End-of feeder storage. This analysis provides further evidence to indicate that feeder level storage is the most effective and that Behind-the-meter storage is only cost-effective when capital costs are paid for by customers. The full capex costs of Behind-the-meter storage are expected to be even higher than those of substation storage, which would result in an even lower/negligible uptake on the LV network. Of the three implementation alternatives, End-of-feeder storage is likely to be lowest in cost, but there are practical issues surrounding its implementation, primarily relating to space constraints.

Overall, choice of storage depends on the intention of its use. For alleviating demand from heat pumps BtM is preferable, but this is likely to be cost-effective only if paid for by consumers. End-of-feeder storage offers the cheapest alternative but may run into practical constraints that are not captured by the Transform model, specifically regarding finding the required space for installations and installation costs associated with customer disruption. Substation storage is not taken up in large numbers by the model, so is not estimated to be very cost effective at present but may offer the best compromise in terms of practicalities of installation, and alleviating network constraints at low cost.

Cost reductions seen as a result of battery storage, as well as other solutions examined in this study are likely to have impacts on the advantages of decarbonisation of heat by electrification. Lower reinforcement costs would be expected to lead to lower electricity prices, meaning that the consumer cost of operating heat pumps and electric heating technologies may be lower than has previously been forecast. Furthermore, the specific implementation of battery storage and the ability to use this for peak shifting and revenue stacking in the context of dynamic time-of-use tariffs may lead to further cost reductions for electric heating, therefore strengthening the case for decarbonisation through this approach.

Appendix 1: Transform Model Parameters for Storage Solutions

Table 3: Transform model parameters for storage solutions, input into the 'Solution Costs' tab.

Solution	Capex (£)	Opex (£/yr)	Duration (yr)	Capex Optimism Bias	Opex Optimism Bias	Disruption Rating	Cross Network Benefits Rating	Flexibility Rating	Lead Time (months)	First Curve
Behind-the-Meter Domestic Battery Storage [Run 2]	-	1,920	10	1.3	1.3	2	1	3	6	5
Behind-the-Meter Domestic Battery Storage [Run E1]	-	2,160	10	1.3	1.3	2	1	3	6	5
Behind-the-Meter Domestic Battery Storage [Run E2]	-	2,400	10	1.3	1.3	2	1	3	6	5
Behind-the-Meter Domestic Battery Storage [Run E3]	-	2,640	10	1.3	1.3	2	1	3	6	5
Behind-the-Meter Domestic Battery Storage [Run E4]	-	2,880	10	1.3	1.3	2	1	3	6	5

End-of-feeder Battery Storage	9,327	597	20	1.3	1.3	3	1	3	6	4
Substation Battery Storage	9,327	597	20	1.3	1.3	3	1	2	18	4

Table 4: Transform model parameters for storage solutions, input into the 'Solution Headrooms' tab.

Solution	Thermal Transformer	Thermal Cable	Voltage Headroom	Voltage Legroom	Power Quality	Fault Level
Behind-the-Meter Domestic Battery Storage	50	50	20	20	10	-5
End-of-feeder Battery Storage	50	50	20	20	10	-5
Substation Battery Storage	50	0	5	5	10	-5

Table 5: Transform model parameters for storage solutions, input into the 'Solution Misc. Settings' tab.

Solution	Effect On Copper Losses (%)	Effect on Iron Losses (%)	Effect On Interruptions (%)	Year Available (yr)	Year Unavailable (yr)
Behind-the-Meter Domestic Battery Storage	-5	0	0	2020	2080
End-of-feeder Battery Storage	-5	15	0	2020	2080
Substation Battery Storage	-5	15	0	2020	2080

Table 6: Transform model parameters for storage solutions, input into the 'Solution Misc. Settings' tab (continued).

Solution	Storage (kW)	Storage (kWh)	Enable DSM? (T/F)	Feederised Solution (Substation Deployment) [T/F]	Underground Solution? (T/F)	Overhead Solution? (T/F)
Behind-the-Meter Domestic Battery Storage	14.4	72	TRUE	FALSE	FALSE	FALSE
End-of-feeder Battery Storage	14.4	72	FALSE	FALSE	FALSE	FALSE
Substation Battery Storage	14.4	72	FALSE	TRUE	FALSE	FALSE

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