Department for
Business, Energy
& Industrial Strategy

Low Voltage Network Capacity Study

Phase 2 Report—Quantitative Assessment of Phase 1 Shortlisted Options

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Executive Summary

This report forms part of the Low Voltage Network Capacity study, which aims to identify a range of possible solutions that can increase capacity on the GB low voltage network without the use of conventional methods of reinforcement. This report follows on from Phase 1 in which a shortlist of the most promising solutions was recommended for further analysis and modelling. In this second phase, the impacts of deploying the shortlisted options on the network were quantified using EA Technology's proprietary Transform Model® (hereafter referred to as "Transform") which runs a techno-economic analysis of the electricity network in Great Britain (GB).

Transform uses a single model of the GB electricity network at low voltage (LV), high voltage (HV), and extra high voltage (EHV)[1]. Various network archetypes are assumed at each voltage level, each with a typical make-up for that archetype, and national data is used to produce generic load profiles on each network. 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. Transform's merit order accounts for total expenditure (totex) required over the lifetime of the solution. A financial value is associated with the other aspects associated with the installation of a potential solution, such as: customer supply interruptions, digging up of roads to underground cable, and whether additional benefit can be realised through the redeployment of a solution.

The Transform model was updated to include the Shortlisted solutions utilising parameters identified in Phase 1 and from additional sources (detailed in Appendix 3):

Short-listed Solutions:

- **Active Transformer Cooling**
- **Behind-the-Meter Domestic Battery Storage for DSR**
- **Dynamic Voltage Management using OLTCs**
- **Dynamic Voltage Management using Power Electronics**
- **Manual Phase Balancing**
- **Network Data Monitoring**
- **Permanent Meshing**
- **Switched Capacitors**
- **Temporary Meshing**
- **Widening of the Design Voltage Tolerance**

The modelling has shown that the deployment of the Shortlisted solutions in combination with Conventional and Other Smart[2] solutions which are already captured in the model offers the

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[1] Extra High Voltage (EHV): 275kV-400kV. High Voltage (HV): 11kV-132kV. Low Voltage (LV): 230V-400V.

[2] 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

potential for a significant saving over the 2021 to 2050 period[3]. The following table shows the net present value (NPV) discounted totex expenditure comparison for each of the solution combinations:

Table 1: Comparison of total network reinforcement costs when different types of solutions are deployed.

Cumulative totex, NPV Discounted:	To 2050	To 2040	To 2030
Run 0 Conventional Only	£64.0bn	£39.7bn	£12.3bn
Run 1 Conventional + Shortlisted	£39.8bn	£26.8bn	£6.6bn
Run 2 Conventional + Shortlisted + Other Smart	£28.0bn	£18.5bn	£4.3bn
Conventional + Other Smart	£34.5bn	£25.6bn	£9.5bn

This shows that, between now and 2050, employing Shortlisted solutions as well as Conventional saves 38% of totex compared to using only the Conventional solutions. Furthermore, including ‘Other Smart’ solutions (which were already parameterised in Transform before this study) results in an even larger saving of 56% compared to using only the Conventional solutions. The combination of shortlisted and other solutions showed a greater benefit as some of the solutions supported each other in an increased release in LV network capacity. However, the following shortlisted solutions were not deployed during any of the study runs due to alternative smart solutions being more favourable:

- Dynamic Voltage Management using On-Load Tap Changers
- Dynamic Voltage Management using Power Electronics
- Temporary Meshing

The remaining shortlisted solutions were ranked based on their deployment in Run 2 (see Appendix 3: Transform Model Parameters for Shortlisted Solutions), as follows:

- **Behind-the-meter battery storage for DSR.**
- **Manual Phase Balancing.**

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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) chargepoints and electric heating, ventilation, and air conditioning (HVAC) systems.

[3] The demand scenario is based on CCC Balanced Net Zero pathway as detailed in the Phase 1 report. This includes increases in peak loading due to low carbon technologies as well as further pressures due to distributed generation.

- **Network Data Monitoring.**
- Permanent Meshing.
- Switched Capacitors.
- Widening of the Design Voltage Tolerance.
- Active Transformer Cooling.

The review of levels of deployment of the shortlisted solutions showed that the first three solutions in the ranked list are deployed in significantly the greatest numbers and therefore offer the most benefit from further consideration. Timescales of deployment was also examined which showed that the uptake of most shortlisted solutions occurred in the short-medium term, while Active Transformer Cooling, Switched Capacitors and Widening of the Design Voltage Tolerance were more likely to be deployed after 2040. It is important that the deployment and management of these solutions is accurately understood such that activities to accelerate their deployment, such as consumer engagement or development of alternative markets, can be identified, ensuring the potential benefits for LV network capacity management are realised.

Finally, we noted that cost reductions that result from deployment of non-conventional solutions are likely to impact on the cost of decarbonising heat through electrification. A reduced impact of reinforcement costs on electricity prices could mean that the consumer cost of operating heat pumps and electric heating technologies may be lower than has previously been forecast.

Acronyms

BAU	Business-as-usual
BEIS	Department for Business, Energy and Industrial Strategy
BESS	Battery energy storage system
BtM	Behind-the-meter
Capex	Capital expenditure
DNO	Distribution network operator
DSM	Demand-side management
DSR	Demand-side response
DVM	Dynamic voltage management
EHV	Extra high voltage
ENA	Energy Networks Association
GB	Great Britain
HV	High voltage
LV	Low voltage
NPV	Net present value
Ofgem	Office of Gas and Electricity Markets
OLTC	On-load tap changer
Opex	Operational expenditure
Totex	Total expenditure
TRL	Technology readiness level

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 conventional network reinforcement which is used to increase capacity by the replacement of assets. Additional LV network capacity is desired so that forecast levels of new demand and generation can connect to the distribution 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 being potentially less disruptive than asset replacement.

To explore possible innovative options for capacity increase (or demand reduction), the Phase 1 report[4] for this study first presented scenarios projecting demand and generation profiles to 2050, before going on to discuss what methodologies are used by distribution network operators (DNOs) to estimate existing headroom (that is, capacity available before constraint) on their LV networks. The demand profiles were taken primarily from the CCC Balanced Net Zero pathway, which makes moderate assumptions regarding changes to consumer behaviour and examines a range of decarbonisation options that can be initiated in parallel to achieve net zero by 2050. This is one of the scenarios that Ofgem has asked DNOs to factor into their RIIO-ED2 business plans[5]. Data extracted for our analysis includes uptake rates of low carbon technologies, distributed generation and changes to consumer behaviour[6]. Following this, a literature review of innovative options for increasing capacity was undertaken to produce a longlist of options, after which a methodology was devised to shortlist those options. The options shortlisted, described in the Phase 1 report, were:

- **Active Transformer Cooling**
- **Behind-the-Meter Domestic Battery Storage for DSR**
- **Dynamic voltage management using OLTCs**
- **Dynamic voltage management using power electronics**
- **Manual Phase Balancing**
- **Network Data Monitoring**
- **Permanent Meshing**
- **Switched Capacitors**
- **Temporary Meshing**
- **Widening of the Design Voltage Tolerance**

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[4] 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

[5] Ofgem have asked the DNOs to develop scenarios based on the pathways outlined in the National Grid FES 2020 (Consumer Transformation, System Transformation and Leading the Way) along with the CCC 6th Carbon Budget (Balanced Pathway, Headwinds, Widespread Engagement, Widespread Innovation and Tailwinds).

[6] See Appendix 1 of the Phase 1 report for further details.

This document follows on directly from the Low Voltage Network Capacity Study Phase 1 Report and details the second phase of the project. In this phase, the impacts of deploying the shortlisted options on the network have been quantified using EA Technology's proprietary Transform tool which runs a techno-economic model of the electricity network in Great Britain (GB). This report gives a brief overview of Transform for context, then outlines the work undertaken which enabled the shortlisted solutions to be input into the model. The different runs of the model are subsequently described, and their results analysed. Finally, from these results we draw conclusions and present recommendations for the Department for Business, Energy and Industrial Strategy (BEIS).

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[7]. It has since been reviewed annually with DNO input, and version 5.4 was used for this study.

Transform uses a single model of the GB electricity network at LV, high voltage, and extra high voltage. Various network archetypes are assumed at each voltage level, each with a typical make-up for that archetype, and national data is used to produce generic load profiles on each network. 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', are characterised by 29 different parameters. These include the capital and operational 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. Solving constraints for a longer time window than this in the model would be more efficient and lead to lower costs over the long-term (but higher costs in the short-term), due to the model's fixed inputs. This may also overvalue non-conventional solutions which have a limited life, such as battery storage. If the time window were set to be longer, it is possible that long-term solutions (which might be conventional options) may rise in the merit order since, while they have a high unit cost, their longevity may make them the best option over several decades. However, it is arguable whether that would result in a more realistic model or not, due to:

- The real-life investment decisions that would be made over price controls.
- The diminishing accuracy of demand forecasts over many years ahead.
- The increased flexibility a network operator retains by solving a constraint for several years rather than decades (with a fixed asset that may become under-utilised for example).

Transform's merit order accounts for net present value (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,

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[7] 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]

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, manufacturing volumes, and changes to the prices of raw materials or components. However, there is not a similar capability in the model to change headroom released over time and therefore diminishing returns are not captured. For example, a solution such as LV Network Monitoring improves visibility of previously unknown headroom but has diminishing returns the more monitoring is deployed (as understanding of LV network headroom increases). As DNOs' understanding of LV headroom increases due to network monitoring data, this data will then be applied to business-as-usual processes such as network planning and these processes, being better informed, will become more efficient. The same starting headroom has been assumed for all runs but is different for each network archetype based on inputs updated as part of the annual DNO reviews.

In Transform, the model can further edit its merit order, and other aspects of the model such as whether innovative 'smart' solutions are available or not, depending on the network investment strategy set. This network investment strategy can be set to 'BAU' (business-as-usual), 'Incremental', or 'Top-down':

- The BAU strategy makes solutions labelled as 'smart' unavailable, so only new circuits and transformers are available, and sees the model invest on a needs basis only.
- The Incremental strategy makes solutions labelled as 'smart' available and sees the model invest on a needs basis only.
- The Top-down strategy makes solutions labelled as 'smart' available and sees the model invest on a holistic basis, ahead of need.

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 Shortlisted Solutions

The smart solutions shortlisted in Phase 1 of the project are:

- **Active Transformer Cooling**
- **Behind-the-Meter Domestic Battery Storage for DSR**
- **Dynamic voltage management using OLTCs**
- **Dynamic voltage management using power electronics**
- **Manual Phase Balancing**
- **Network Data Monitoring**
- **Permanent Meshing**
- **Switched Capacitors**
- **Temporary Meshing**
- **Widening of the Design Voltage Tolerance**

Of these, Switched Capacitors and permanent and Temporary Meshing were already LV network solutions within the Transform tool[8]. Before modelling could be undertaken, parameters had to be decided on for the other seven solutions.

These parameters were drawn from sources examined in the Phase 1 literature review, additional sources, 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 3: Transform Model Parameters for Shortlisted Solutions. The compatibility of these new solutions with the 99 solutions already in Transform, with each other, and with the 19 different LV network archetypes in Transform also had to be determined, as well as which demand profiles could be shifted by solutions enabling demand-side response (DSR).

Inevitably, many assumptions were made during this decision-making process, and the addition of new solutions into the model has required the use of different sources to those on which the solutions inherent in the model were based. Although assumptions in the new solutions may not align directly with those previously used, assumptions are self-consistent, and every effort has been made to match the original model where possible. For example, in Transform, costs are given per feeder, so four LV feeders per distribution transformer and 40 customers per feeder were assumed. Also, values in the model (such as those for Switched Capacitors and meshing) are reviewed annually with DNO input so divergence from solutions' 2021 values should be minimal. Furthermore, the demand scenario used in this study is up to date because of the work undertaken on this aspect in Phase 1.

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[8] Permanent Meshing at LV is in Transform as two separate solutions, 'Permanent Meshing, urban' and 'Permanent Meshing, sub-urban'. These are applied to different network archetypes to enable the effects of meshing different network topologies to be studied. These two solutions were retained within the model, but in this report for clarity they have been counted as one solution and their outputs combined.

Several assumptions were made in order to define the short-listed solutions more precisely, *including a subset in italics which were later investigated as sensitivities – see Section: Modelling Sensitivities. These assumptions were as follows:*

- Active Transformer Cooling used a fan system.
- BtM Domestic Battery Storage for DSR is parameterised as having zero capex but a given opex. This represents network operators compensating customers for DSR such as flexibility services, but not paying the upfront cost of battery purchase and install; that capex is borne by customers. It is likely that this solution would not be cost-effective if all costs are paid by the DNO (i.e. including capital costs)—this is further investigated in the Phase 2 Extension Report.[9]
- BtM Domestic Battery Storage for DSR used a total of 14kW, 72kWh storage per feeder. This is equivalent to the total values presented in Northern Powergrid's Distributed Storage and Solar Study[10] which assumes 0.4kW, 2kWh hour batteries in 90% of households, however, we assume that a more realistic distribution would be 1.2kW, 6kWh batteries in 30% of households.
    - *Sensitivity around the installed levels of BtM Domestic Battery Storage was investigated by assuming 50% of this capacity*
- One dynamic voltage management solution used on-load tap changers (OLTCs).
    - *Another dynamic voltage management solution, added for a sensitivity, used hypothetical power electronic assisted OLTCs.*
- Manual Phase Balancing was used on overhead lines but not underground cables[11].
- Widening of the Design Voltage Tolerance used a new tolerance of ±10% rather than +10/-6%.

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[9] EV batteries were not included or modelled as part of this solution, however, it is acknowledged that these have the potential to form part of the solution in the future. This was noted in the *Distributed Storage and Solar* study: "The BESS can be fixed or on wheels and therefore in a world where the number of electric vehicles (EVs) increases and vehicle-to-grid (V2G) technology matures, they can help with the reduction of the evening peak demand."

[10] Northern Powergrid, *DS3 – Distributed Storage and Solar Study: Final Report*. Northern Powergrid: Newcastle upon Tyne; 2020. Available: https://www.northernpowergrid.com/asset/0/document/5396.pdf [Accessed 5th November 2021]. We've assumed similar total numbers to those found in DS3, which could be split as 1.2kW, 6kWh in 30% households and is a more reasonable assumption based on latest technology.

[11] Underground Manual Phase Balancing is unlikely to be any more cost effective than the counterfactual due to the disruption and cost of excavation. This cost is likely to significantly reduce if three phase supplies are available at the customer meter point (as has been proposed by several GB DNOs).

Modelling Methodology

Solution Categories

The solutions were categorised into three types[12]:

- **Conventional** – solutions already in the Transform model not categorised as “smart”.
- **Shortlisted** – solutions shortlisted in Phase 1, whether already in Transform (in the cases of meshing and Switched Capacitors) or added into the model after defining their parameters.
- **Other Smart** – solutions already in Transform that are categorised as “smart” but were not shortlisted.

For LV networks, there were 10 Conventional solutions, 9 Shortlisted[13], and 20 Other Smart[14]. These, and the HV and EHV solutions in the Conventional and Other Smart categories, are listed in Appendix 1: Solutions in the Transform Model.

Transform has been run with three combinations of the above:

- Only the Conventional solutions. This is to provide a counterfactual case.
- Both the Conventional and Shortlisted solutions.
- All the Conventional, Shortlisted, and Other Smart solutions.

Modelling Sensitivities

Transform has also been run to test three sensitivities. These are what happens if:

- The Widening of the Design Voltage Tolerance solution is removed from the model.
- BtM battery storage for demand-side response is only available at 50% capacity to that assumed before. Therefore, in this sensitivity the battery storage solution releases half as much of each type of capacity but costs half as much.
- A new solution, dynamic voltage management which uses power electronics assisted OLTCs, becomes available in 2035. This new solution costs 50% as much in 2035 as Dynamic Voltage Management using OLTCs does in the model in 2020 but releases the same capacity.

The widening the voltage tolerance sensitivity is instructive because it is a policy-based solution. This contrasts with the other Shortlisted solutions which are either network-side solutions applying technologies to increase headroom or customer-side solutions which

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[12] A table of what is considered for Conventional, Shortlisted and Other solutions is set out in Appendix 1.
[13] One additional solution, Dynamic Voltage Management using Power Electronics, was later added for one of the sensitivities, bringing the total to 10.
[14] These are largely solutions that were considered in Phase 1 but not shortlisted.

change how customers use electricity. As a result, it is informative to examine the impact of this solution so that decisions around it can be made on a stronger evidence base, especially since it has not been explored as widely in trials as many other solutions reviewed in Phase 1.

The battery storage sensitivity was performed because it tests the impact of the installed capacity chosen for BtM Domestic Battery Storage for DSR. Specifically, this enables exploration of how the viability of domestic DSR is affected according to Transform if storage capacity is significantly reduced.

The dynamic voltage management sensitivity was performed because there are low technology readiness level power electronic components which may in the future be able to assist OLTCs, resulting in lower cost dynamic voltage management. In the absence of clear parameters for any future high TRL dynamic voltage tolerance solution using power electronics, this sensitivity was designed to test whether a lower cost dynamic voltage tolerance solution would be chosen by the model. If so, this solution could be a candidate solution for the long term.

Modelling Runs

Each of these sensitivities has been run using both Run 1 and Run 2 as baselines, so there are two different model runs for each sensitivity. This results in nine runs in total, listed in Table 2.

Table 2: Runs of the Transform model used in this study, summarised by which solutions were included.

Run #	Solutions Included
0	Conventional
1	Conventional, Shortlisted
2	Conventional, Shortlisted, Other Smart
3	As Run 1, with Widening of the Design Voltage Tolerance solution removed
4	As Run 2, with Widening of the Design Voltage Tolerance solution removed
5	As Run 1, with storage capacity of BtM domestic battery storage solution halved
6	As Run 2, with storage capacity of BtM domestic battery storage solution halved

7	As Run 1, with Dynamic Voltage Management using Power Electronics solution added
8	As Run 2, with Dynamic Voltage Management using Power Electronics solution added

The counterfactual run was undertaken using Transform's BAU network investment scenario, because this run was intended to represent such a business-as-usual case. The Incremental strategy was chosen for all other runs, because at present DNOs' make investment decisions in a manner that's closer to a needs basis than the holistic basis, which the Top-down scenario models[15].

Modelling Results

The results of the Transform modelling undertaken are presented in this Section:

- *Section: Counterfactual: Modelling Conventional Solutions Only* presents the results of the counterfactual, Run 0.
- *Section: Overall Trends* introduces overall trends in the results from modelling runs 1 to 8: which Shortlisted solutions are deployed the most in every run and which are never selected.
- *Section: Modelling Conventional and Shortlisted Solutions (Run 1)* presents Run 1 and compares the results with the counterfactual.
- *Section: Modelling Conventional, Shortlisted, and Other Smart Solutions (Run 2)* presents Run 2 and compares it with the counterfactual in the same way, before going on to contrast Runs 1 and 2 with each other.
- The *Sensitivities* sections go on to explore the three sensitivities, on Widening the Design Voltage Tolerance, BtM Domestic Battery Storage for DSR and dynamic voltage management respectively. These cover Runs 3 to 8.
- *Section: Deployments Over Time for Shortlisted Solutions* presents Shortlisted solutions' deployments over time to show which solutions are expected to be of relevance over the short- medium- and long-term.
- *Section: Overall Evaluation of Solutions* discusses the relative importance of the Shortlisted solutions according to the modelling results presented in the above subsections.

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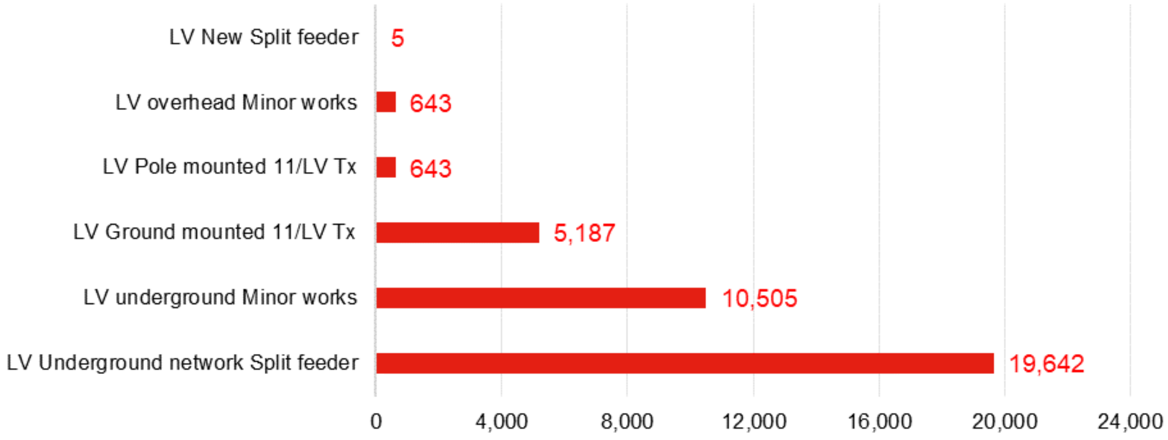
[15] The original Transform analysis compared incremental to top-down methodologies and showed that top-down is marginally cheaper than an incremental approach. The top-down scenario means least-regrets enablers can be deployed ahead of need, so the shape of the totex over time curve may shift slightly, but the interventions themselves would not occur earlier.

Counterfactual: Modelling Conventional Solutions Only

Run 0 modelled Conventional solutions to provide a counterfactual to compare other runs against. From Run 0, the totex between 2021 and 2050 is modelled to be £64.0bn. 19% of this would be spent up to and including 2030, and 62% up to and including 2040. For the LV network, the number of deployments for different Conventional solutions used to resolve constraints (incurring this cost) is shown in Figure 1.

Figure 1: Average number of LV interventions applied per year in Run 0, 2021-50.



Although 6 conventional solutions are used in Run 0, between them the 3 deployed most often, LV underground network split feeder, LV underground minor works, and LV ground mounted 11kV/LV transformer, make up 96% of all deployments:

- LV Underground Minor Works – This is the construction of one new substation electrically adjacent to an area experiencing headroom constraints. In the case of an LV underground network this is a second distribution transformer near to the location of the original transformer. Some HV cabling is allowed for, along with several new LV circuits. This deviates from “Major Works” which would be the construction of several new substations in an area and the associated new HV and LV circuits.
- LV Ground Mounted 11/LV Tx – This is the replacement of an existing distribution transformer with a larger unit.
- U/G Split Feeder – This requires the laying of a new LV feeder from a distribution substation, part way along the already split LV feeder. Some cross jointing between the old and new feeder assumes approximately one third of load is transferred to the new split feeder.

It is these 3 solutions that any smart solution will have to be more cost-effective than, if it is to deliver appreciable increases in network headroom in more than a niche number of cases[16]. Of the three solutions, LV underground minor works is significantly more expensive that the other

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[16] The Transform tool was used by DNOs ahead of RIIO-ED1 and the DNOs have an opportunity annually to update the model’s inputs, so the tool should be aligned well with their assumptions. However, the DNOs have not been consulted on the inputs and outputs of the modelling work and so this does not necessarily represent their plans.

two options with a new LV ground mounted transformer being the cheapest per installation. Based on those deployment numbers the ratio of expense is approximately 63% LV Underground minor works, 35% LV Underground Network Split Feeder, 2% LV Ground Mounted 11/LV Tx.

Overall Trends

Across all the modelling runs other than the counterfactual, the top three solutions in terms of the number of deployments remained the same. These are all Shortlisted solutions:

- BtM Domestic Battery Storage for DSR.
- Manual Phase Balancing.
- Network Data Monitoring.

Notably, two of these three – BtM Domestic Battery Storage for DSR and Network Data Monitoring – are low capex solutions, demonstrating the influence of capex on Transform's merit order, as described in *The Transform Model: An Overview*[17].

Like the above three solutions, Permanent Meshing, Switched Capacitors and Active Transformer Cooling are also chosen on each available run, albeit in smaller numbers. Widening of the Design Voltage Tolerance is another very low capex solution, but one that only releases a small amount of voltage legroom so is applicable to relatively few constraints. Raising the upper limit was not tested here since peak winter capacity is constrained primarily by voltage legroom. Voltage headroom can potentially be increased but would only release capacity during low demand, high generation scenarios.

There are three Shortlisted solutions that are never chosen:

- Dynamic Voltage Management using OLTCs.
- Dynamic Voltage Management using Power Electronics (included in Runs 7 and 8 only).
- Temporary Meshing.

Dynamic Voltage Management using OLTCs is a solution with a high capex, so is not favoured by the model, for reasons described in *The Transform Model: An Overview*. Dynamic Voltage Management using Power Electronics is discussed further in *Sensitivity: Dynamic Voltage Management Cost (Runs 7 and 8)*. Temporary Meshing is not chosen because one of the Permanent Meshing solutions is always higher up the tool's dynamic merit order[18]. This has

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[17] Behind-the-meter storage is low capex because this cost is assumed to fall on the consumer rather than the DNO, who offer compensation to consumers for the use of their storage assets. Were capital costs to be paid by the DNO this solution would be categorized as a high capex solution as it was in Phase 1. This point is further investigated in the Phase 2 Extension Report.

[18] Permanent Meshing is the permanent connection between two sections of LV network. Temporary Meshing is the use of smart technologies to enable meshing to be switched based on local network requirements (i.e. close mesh during high demand, open mesh during high fault level). The cost of implementation is higher and based on the headroom values assumed provides less benefit.

been discussed further in previous work using Transform; Permanent Meshing was also selected repeatedly by the model during modelling for Smart Grid Forum's Workstream 3.[7],[8]

Of the 19 LV network archetypes included in Transform, the archetype with the most totex accumulated over the entire modelling period was the same in all runs: The terraced street archetype. This archetype also had more totex spent on it than any HV or EHV archetype. The archetype, suburban street (3- to 4-bedroom semi-detached houses) had the second highest totex spent on it of all the LV network archetypes in all runs, and new build housing estate had the third highest of the LV archetypes[19].

Modelling Conventional and Shortlisted Solutions (Run 1)

Run 1 modelled the Conventional solutions as in the counterfactual, with the addition of the Shortlisted solutions. This addition had a profound effect on this run's results. The totex between 2021 and 2050 is modelled to be £38.8bn, a saving of over one-third (£24.2bn) on the counterfactual cost. Although the discounted totex to 2050 is modelled to be lower in Run 1 than Run 0, a greater proportion would have to be spent earlier. Of the total cost, 17% would be spent up to and including 2030 compared to 19% in the counterfactual, and 67% up to and including 2040 compared to 62%.

For the LV network, the number of deployments for different Shortlisted and Conventional solutions used to resolve constraints is shown in Figure 2. Figure 2 shows the 6 solutions deployed most often are all categorised as Shortlisted. They are:

- **Behind-the-Meter Domestic Battery Storage for DSR**
- **Manual Phase Balancing**
- **Network Data Monitoring**
- Permanent Meshing
- Switched Capacitors
- Active Transformer Cooling

The 3 most-deployed solutions amount to 81% of all total deployments, compared to 96% for the 3 most-deployed Conventional solutions in Run 0. Although a small number of solutions still make up the vast majority of deployments, there is nonetheless a greater diversity than in the counterfactual. In total, 10 solutions are chosen rather than Run 0's 6.

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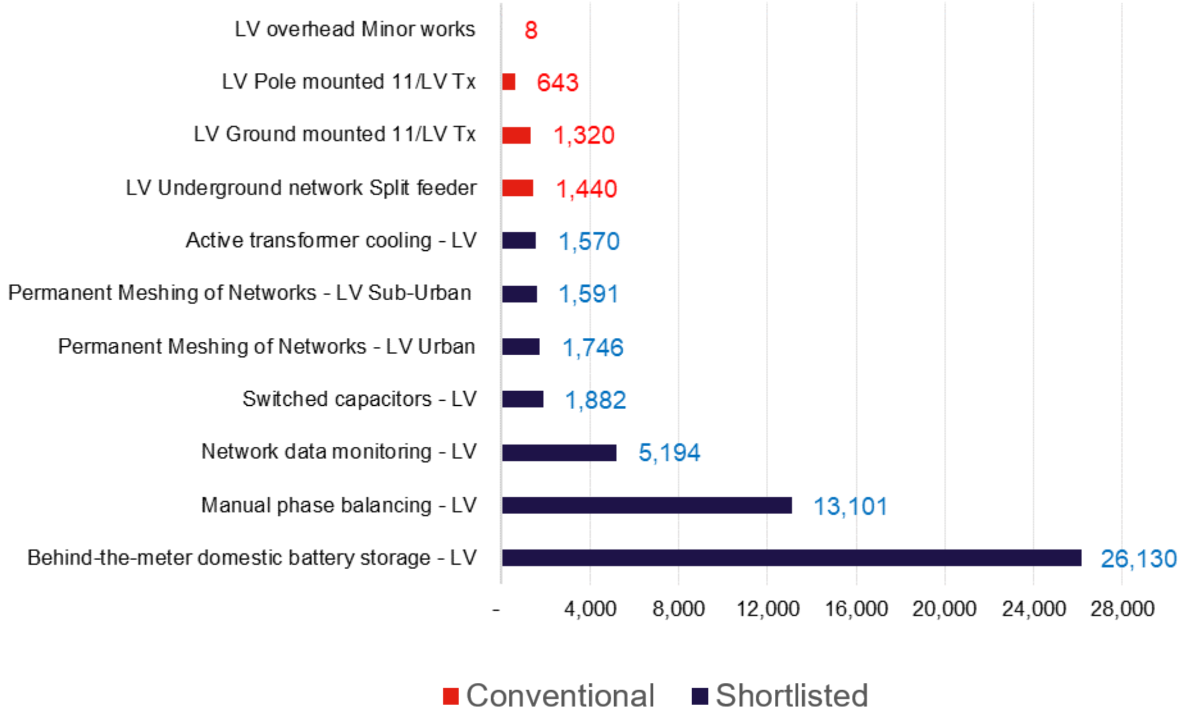
[19] Transform is based on a parametric model and therefore does not place customer or networks geospatially. Therefore it is not possible to calculate the totex / customer for each archetype but it is recognised that a terraced street has a higher customer density than a rural feeder and as such the totex / customer may well be lower in an urban environment.

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



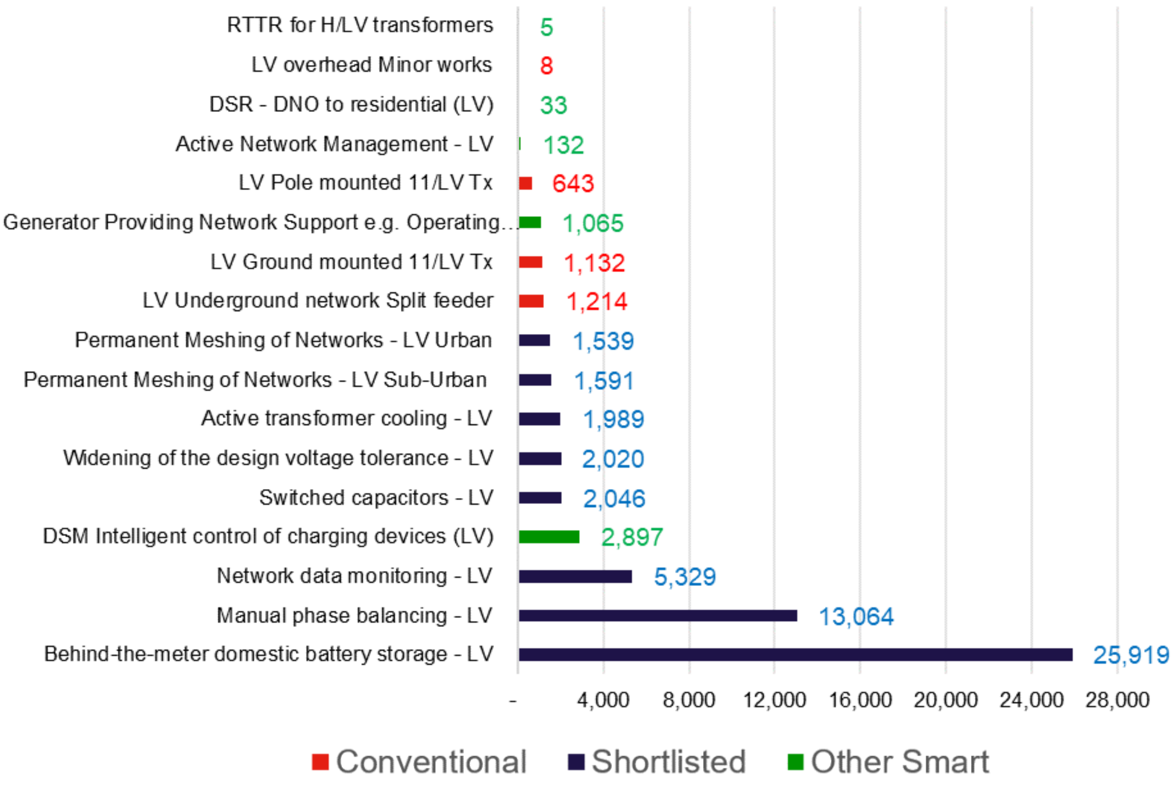
Four conventional solutions are used in Run 1, two less than in the counterfactual, with LV underground minor works and LV new split feeder being superseded by the Shortlisted solutions and no longer being selected by the model. 6 Shortlisted solutions are deployed of the 9 available. The reasons behind Dynamic Voltage Management and Temporary Meshing not being chosen were discussed in *Overall Trends*. The Widening of the Design Voltage Tolerance solution is also not selected in this case and is discussed further in *Modelling Conventional, Shortlisted, and Other Smart Solutions (Run 2)*.

Modelling Conventional, Shortlisted, and Other Smart Solutions (Run 2)

Run 2 modelled the Conventional and Shortlisted solutions as in Run 1, with the addition of the Other Smart solutions already within the Transform tool. The addition of these further reduced the totex between 2021 and 2050 to £28.0bn. This is a saving of a further £11.8bn compared to Run 1, bringing the saving on the counterfactual cost to £36.0bn, over half the Run 0 cost. Here, 15% of the total cost would be spent up to and including 2030 compared to 19% in the counterfactual and 17% in Run 1. Up to and including 2040, 66% of the 2050 cost would have to be spent compared to 62% in the counterfactual and 67% in Run 1. For the LV network, the number of deployments for different solutions used to resolve constraints is shown in Figure 3.

Figure 3 shows the same 3 solutions deployed most often and in the same order as Figure 2, despite the addition of the Other Smart solutions to Run 2. In this run, the 3 most-deployed solutions amount to 73% of all total deployments, down on 81% for the 3 most-deployed solutions in Run 1. Again, a small number of solutions still make up the vast majority of deployments but with a greater diversity than in the counterfactual. In total, 16 solutions are chosen rather than Run 1’s 10. These are made up of 4 Conventional solutions (the same as in Run 1), 7 Shortlisted solutions (6 as in Run 1 with the addition of Widening of the Design Voltage Tolerance), and 5 Other Smart solutions not available in Run 1.

Figure 3: Average number of LV interventions applied per year in Run 2, 2021-50.



Five of the 20 LV Other Smart solutions were selected by the model, but DSM (Demand-side management) intelligent control of charging devices[20] is the only Other Smart solution to outperform any Shortlisted solutions, other than the 2 not picked (Dynamic Voltage Management using OLTCs and Temporary Meshing). The only additional Other Smart option to have more than a 1% share of total deployments was the Generator Providing Network Support. This implies that the shortlisting undertaken in Phase 1 of this study was robust and generally extracted the most promising smart solutions, because seven out of the top eight innovative solutions are Shortlisted ones. Moreover, DSM intelligent control of charging devices (equivalent to the smart EV charging option in Phase 1), which is an ‘Other Smart solution’, was also a technology that performed well in the shortlisting process. However, a decision was made in Phase 1 not to shortlist this option due to the large amount of research and policy focus placed on it to date compared to most other shortlisted solutions.

Comparing the deployments of Shortlisted solutions in Run 2 to Run 1, Active Transformer Cooling is selected more in Run 2 (with 127% of Run 1 deployments) and Switched Capacitors and Network Data Monitoring slightly more than in Run 1 (8% and 3%). Meanwhile Manual Phase Balancing, BtM Battery Storage for DSR, and Permanent Meshing are all deployed

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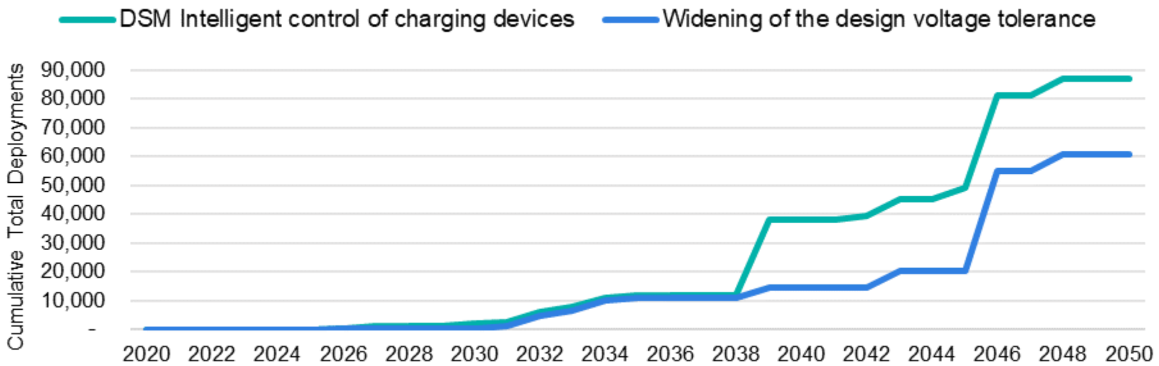
[20] ‘DSM intelligent control of smart devices’ is the name used in the Transform model to represent 'Smart EV charging’, as it was called in Phase 1. DSM and DSR have the same meaning. The original Transform work used DSM (demand side management) but over time this has been refined to DSR (demand side response).

slightly less than in Run 1 (99.7%, 99.2%, and 93.9% of the run 1 levels). These decrease in number of deployments due to some ‘Other Smart solutions’ being taken-up preferentially. Meanwhile the increase of other Shortlisted solutions is because in some cases, such as on particular network types or for particular constraints, Other Smart and Shortlisted solutions in combination is the most cost-effective intervention.

The Widening of the Design Voltage Tolerance is the solution with the greatest difference in deployment between Runs 1 and 2, not being deployed in Run 1 but being deployed 60,602 times in Run 2. This solution has become cost-effective by being combined with DSM intelligent control of charging devices, which is an ‘Other Smart solution’ not available in Run 1. This solution does not release headroom but shifts demand peaks, particularly those caused by electric vehicles. Figure 4 illustrates this clearly; the two solutions are deployed in a very similar pattern over time. This is because demand-side management combined with a widened voltage tolerance can address constraints more effectively than either solution alone. Furthermore, they are both relatively low-cost solutions, so make a cost-effective pairing compared to more expensive solutions that could solve the same kinds of constraints on their own.

Figure 4: Cumulative total number of LV interventions deployments of DSM intelligent control of charging devices (orange) and Widening of the Design Voltage Tolerance (blue) solutions in Run 2, 2021-50.



Modelling Conventional and ‘Other Smart’ Solutions

For reference, a further Transform run was performed with Conventional solutions and the Other Smart solutions that were not shortlisted. This gave an indication of how the shortlisted solutions perform compared with those which were not selected. Between 2020 and 2050[21] the cumulative discounted totex was £34.5bn, approximately £6.5bn more than the costs when all solutions are included (Run 2). However, compared with the case of conventional solutions deployed with shortlisted solutions (Run 1), this combination leads to a saving of £4.3bn. This is likely a result of the fact that there are far fewer shortlisted options than ‘Other Smart’ options. While each individual shortlisted option is generally more effective at resolving LV network constraints than the other solutions, the lower variety of options to choose from means that constraints cannot be resolved as efficiently, leading to higher overall costs.

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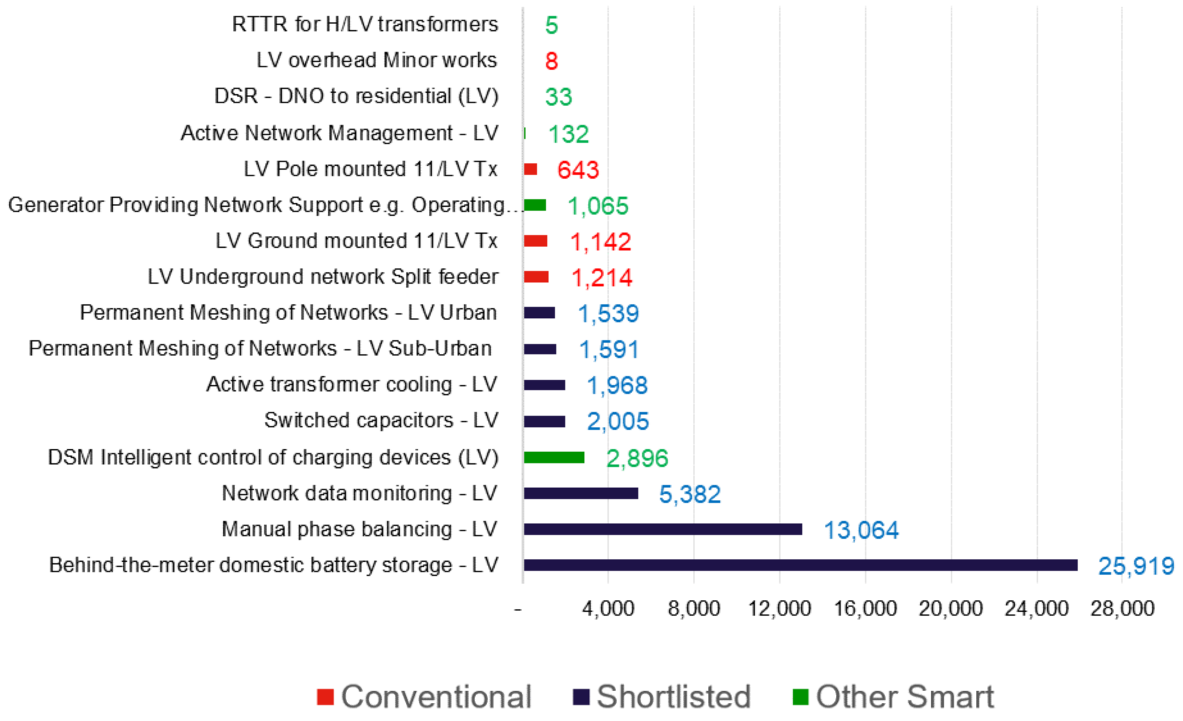
[21] The 2020-2040 cost was £25.6bn, and the 2020-2030 cost was £9.4bn.

Sensitivity: Widening the Design Voltage Tolerance Unavailability (Runs 3, 4)

This sensitivity investigated what happens in the modelling if Widening of the Design Voltage Tolerance is no longer an option. This sensitivity was intended to be run with both Run 1 and Run 2 as baselines, such that both Runs 3 and 4 would exclude Widening the Design Voltage Tolerance. However, as Run 1 yielded no deployments of the Widening the voltage tolerance solution, excluding this solution in Run 3 would have no effect and Run 3 would be effectively the same as Run 1. Therefore, the remainder of this subsection focusses only on Run 4, the case including the Other Smart solutions for comparison with Run 2. For the LV network in Run 4, the number of deployments for different solutions used to resolve constraints is shown in Figure 5.

Figure 5: Average number of LV interventions applied per year in Run 4, 2021-50.



Aside from the exclusion of Widening the Design Voltage Tolerance, the solutions selected by the model are the same as in Run 2. Run 4 shows that making the Widening of the Design Voltage Tolerance solution unavailable has a very small financial cost in the model compared to Run 2, with a totex increase of 0.038%, £11.0m. Therefore, employing the policy option of Widening the Design Voltage Tolerance to ±10% has a negligible effect on totex.

In Run 4, Network Data Monitoring is deployed more often than in Run 2, whilst Active Transformer Cooling and Switched Capacitors are both deployed less, but all with less than 2% change (101.0, 98.9, and 98.1%). This indicates that the Network Data Monitoring solution resolved voltage legroom constraints in the absence of the Widening of the Voltage Tolerance solution. In the process, Network Data Monitoring relieved both thermal constraints, reducing the need for Active Transformer Cooling, and voltage headroom constraints, reducing the need for Switched Capacitors. Network Data Monitoring has resolved constraints due to improved visibility of actual network conditions and therefore facilitates the headroom release from other technologies.

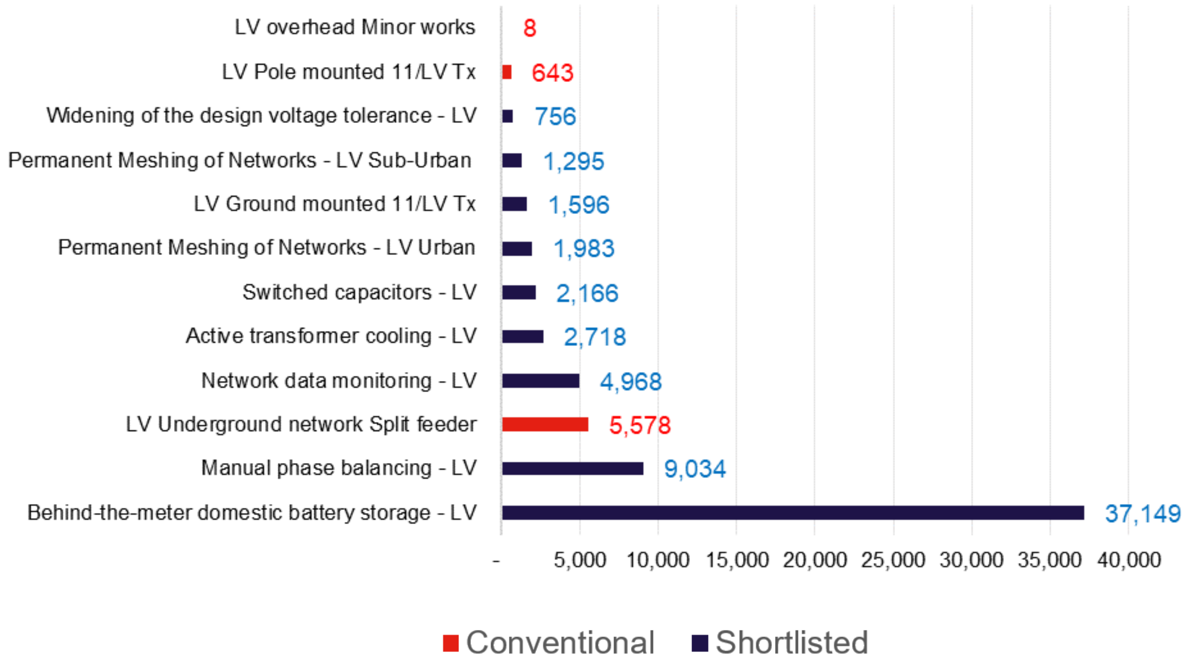
Sensitivity: Battery Storage Capacity (Runs 5 and 6)

The BtM Domestic Battery Storage for DSR sensitivity halves the capacity assumed. This consequently halves the headroom released by this solution, as well as halving the opex (as DNOs are only paying for half as much capacity) and parameters including losses[22]. This sensitivity was run with both Run 1 and Run 2 as baselines, so both Runs 5 and 6 have 50% of the storage capacity available, but Run 5 excludes the Other Smart solutions whilst Run 6 includes them.

Run 5: Run 1 with Battery Storage Capacity Sensitivity

This run includes Conventional and Shortlisted solutions, with the capacity and opex of battery storage halved compared to its previous values. For the LV network in Run 5, the number of deployments for different solutions used to resolve constraints is shown in Figure 6.

Figure 6: Average number of LV interventions applied per year in Run 5, 2021-50.



Run 5 (above, Figure 6) shows several notable differences to Run 1 (Figure 2):

- BtM Domestic Battery Storage for DSR, releasing half the headroom compared to Run 1, is deployed 42% more often. These deployments will likely be covering the same locations as in Run 1 along with some additional locations where this solution is now more cost effective. This is due to the solution's halved cost and the dynamic merit order

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[22] In reality, costs may not be directly proportional to battery capacity and opex may not exactly halve as battery capacity is halved. This is due to the battery only making up part of the total cost—there would also be costs associated with installation which may remain largely unchanged.

being calculated with a strong emphasis on totex as discussed in *The Transform Model: An Overview*.

- The Widening of the Design Voltage Tolerance solution is selected for deployment by the Transform model in Run 5 whereas it is not selected in Run 1. This implies the voltage tolerance solution is combined with BtM Battery Storage for DSR in Run 5 to resolve voltage legroom constraints, where in Run 1 this was not necessary because the battery storage solution's capacity was twice as large so yielded a 20% increase in voltage legroom, rather than 10% in Run 5.
- The Conventional solution LV underground network split feeder is deployed at 387% of what it was in Run 1, this large increase indicating that it too is often combined with BtM battery storage for DSR due to battery storage's reduced headroom-releasing capabilities in Run 5. This implies that were BtM storage to be removed as an option, there would remain a large role for splitting the feeder (see Phase 2 Extension Report for further evidence of this).
- Active Transformer Cooling and Manual Phase Balancing solutions both see significant changes, with transformer cooling deployments up 73% on Run 1 and phase balancing down 31%. This change is discussed further later in this subsection.

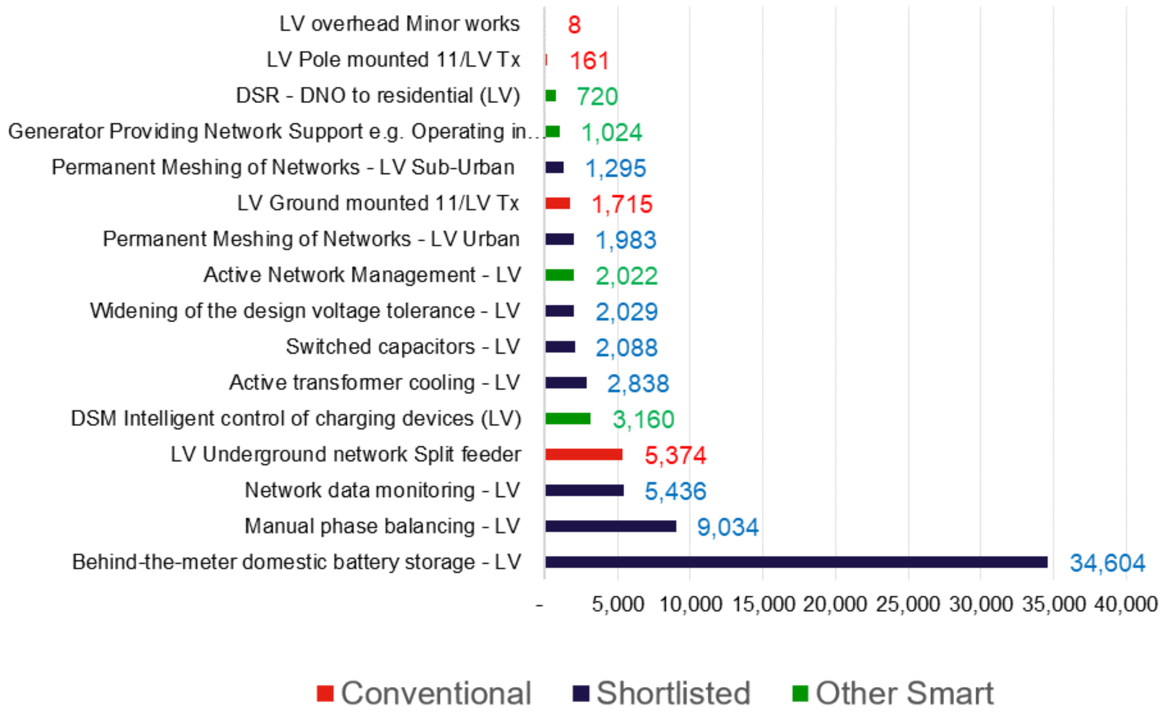
Other more subtle interactions in the model in a smaller number of cases affect yet more solutions, with Switched Capacitors being deployed 14.5% more often and Network Data Monitoring and Permanent Meshing 4.3 and 1.7% less respectively.

Run 5 shows that halving the battery storage capacity has a small financial cost in the model compared to Run 1, with a totex increase of 1.87%, £742m. This means a domestic battery storage solution for DSR at half the cost of in Run 1 is selected more often by the model, but in the long term this does translate to higher cost network interventions overall.

Run 6: Run 2 with Battery Storage Capacity Sensitivity

This run includes Conventional, Shortlisted, and Other Smart solutions, with the capacity and opex of battery storage halved compared to its previous values. The number of deployments for different solutions used to resolve constraints is shown in Figure 7.

Figure 7: Average number of LV interventions applied per year in Run 6, 2021-50. (Key: Red Conventional solutions, blue Shortlisted solutions, green Other Smart solutions.)



Run 6 (above, Figure 7) shows several notable differences to Run 2 (Figure 3):

- BtM Domestic Battery Storage for DSR, releasing half the headroom to in Run 2, again sees a significant increase in deployments due to the solution's halved cost. The modified solution is deployed 34% more often by the model in Run 6.
- As in Run 5, Conventional solution LV underground network split feeder sees a very large increase, being deployed at 443% of that in Run 2.
- Also as in Run 5, the Active Transformer Cooling and Manual Phase Balancing solutions see significant changes. Transformer cooling is deployed 43% more often than in Run 2 and phase balancing 31% less. This change is discussed further below.

Other more subtle interactions in the model in a smaller number of cases affect the remaining Shortlisted solutions, with Permanent Meshing being deployed 4.7% more than in Run 2, Network Data Monitoring and Switched Capacitors both 2.0% more, and Widening of the Design Voltage Tolerance 0.5% more.

Compared to Run 5, Run 6 shows halving the battery storage capacity to be more financially detrimental compared to its baseline, with a totex increase on Run 2 of 8.71%, £2.4bn. This means that although the domestic battery storage solution for DSR is at half the cost of in Run 1, its increased deployment, together with deployment of other solutions in combination with it to resolve constraints for the 5-year time window, results in a higher overall cost of network interventions in the long-term.

As mentioned above, Active Transformer Cooling sees a 73% increase in deployments in Run 5 and 43% in Run 6, whereas Manual Phase Balancing sees a 41% decrease in deployments in both Run 5 and Run 6.

Active Transformer Cooling only relieves thermal transformer constraints. In this sensitivity Active Transformer Cooling releases almost as much thermal transformer headroom as the modified battery storage solution (22% to 25%). This implies Active Transformer Cooling is deployed alongside battery storage where battery storage alone is now insufficient to resolve thermal transformer constraints.

For voltage headroom and legroom constraints, Manual Phase Balancing releases more headroom than the modified battery storage solution (20% compared with 10%). This means Manual Phase Balancing could be expected to be deployed more often in this sensitivity, however this is not the case, and it is in fact deployed less. This is likely because battery storage is now more cost-effective for constraints requiring under 10% additional headroom or legroom due to its lower cost. Furthermore, for some constraints requiring more than 10% additional headroom or legroom, battery storage can be combined with other solutions such as Switched Capacitors or Widening of the Design Voltage Tolerance to create a more cost-effective intervention than Manual Phase Balancing, which is relatively high cost compared to many other Shortlisted solutions. This explains the increase in deployments of Switched Capacitors noted for Runs 5 and 6.

There are a number of notable differences between Runs 5 and 6. Deployments of the BtM battery storage for DSR solution increase more in Run 5 than 6 (142 to 134%). Furthermore, in Run 5 the Permanent Meshing and Network Data Monitoring solutions deployments decrease slightly (to 98%and 96% of Run 1 deployments) but increase slightly in Run 6 (to 105% and 102%). These differences are likely due to Other Smart solutions not being available in Run 5 to combine with Shortlisted solutions like Permanent Meshing and Network Monitoring.

Sensitivity: Dynamic Voltage Management Cost (Runs 7 and 8)

The dynamic voltage management sensitivity introduces a new solution in 2035, Dynamic Voltage Management using Power Electronics. This solution has lower capex and opex than Dynamic Voltage Management using OLTCs, but all other parameters remain unchanged. As with the battery storage sensitivity, this sensitivity was run with both Run 1 and Run 2 as baselines, so both Runs 7 and 8 introduce this new solution but Run 7 excludes the Other Smart solutions whereas Run 8 includes them.

In Runs 1 and 2 Dynamic Voltage Management using OLTCs was never selected for deployment. Despite capex and opex for Dynamic Voltage Management using Power Electronics in 2035 being set at half that of Dynamic Voltage Management using OLTCs in 2020, Transform still does not select this new dynamic voltage management solution in either Run 7 or Run 8. Consequently, the inclusion of this new solution makes no difference to the results of Runs 7 and 8, which remain identical to those of Runs 1 and 2.

This once again highlights the weight given by Transform’s dynamic merit order to totex, in this case dominated by high capex. Even though Dynamic Voltage Management using Power Electronics has half the capex and opex of Dynamic Voltage Management using OLTCs, it still has higher capex than all the other Shortlisted solutions. (See Appendix 3: Transform Model

Parameters for Shortlisted Solutions for all their input values.) In fact, Dynamic Voltage Management using Power Electronics' 2035 capex is 19% higher than the solutions with the next largest 2020 capex: Temporary Meshing, which was also not selected, and Permanent Meshing, which was. Furthermore, the opex of Dynamic Voltage Management using Power Electronics is the third largest, with Dynamic Voltage Management using OLTCs being the highest opex solution and BtM Domestic Battery Storage for DSR – a solution with zero capex – having the second largest opex.

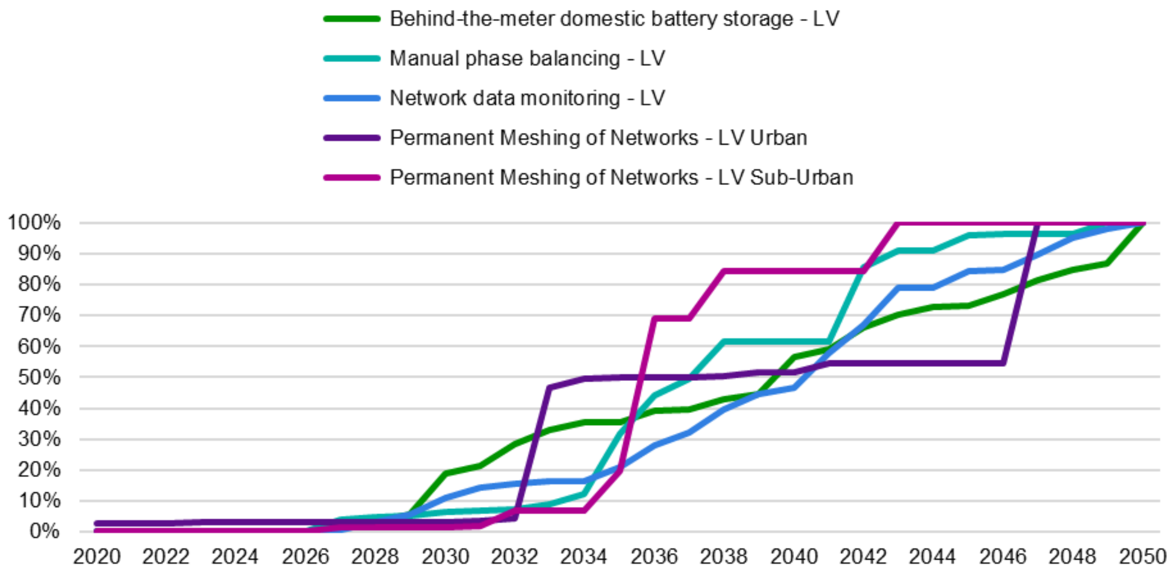
Another consideration is that all the Shortlisted and Other Smart solutions are on cost curves which are in the most pessimistic cases keeping their costs constant. However, most solutions' costs decrease over time at various rates and so in most cases the cost differences between Dynamic Voltage Management using Power Electronics and the other Shortlisted solutions will have reduced by 2035. For example, although Dynamic Voltage Management using Power Electronics is 50% of the OLTCs based solution, by 2035 it is only 63% of the cost but then continues to follow the same cost reduction curve.

Finally, the 5-year time window means that even if dynamic voltage management solutions were cost-effective over the long-term, the 5-year window and Incremental investment strategy used in this analysis means that a cheaper solution releasing less headroom will likely suffice for 5 years. Therefore, an extremely significant advancement in dynamic voltage management technology would be required to cause prices to decrease enough for such a solution to be selected by the Transform model.

Deployments Over Time for Shortlisted Solutions

For network interventions, the number of deployments required for each solution is an important consideration, which has been presented in the above subsections for each model run. Another important consideration is when these deployments are expected to be needed. Figure 8 and Figure 9 show the 'deployment curves', i.e. deployments over time divided by the total number of deployments, for each Shortlisted solution selected by Transform in Run 2. This is the Run which included the Conventional and Other Smart solutions (for brevity, the deployment curves for these Other Smart solutions are not presented in this report). Run 2 was chosen to be analysed further for this, because Run 1 excludes Other Smart solutions which are available in reality. Figure 8 shows the deployment curves of Shortlisted solutions which have significant proportions of their deployments in the short- and medium-term, up to and including the mid-2030s.

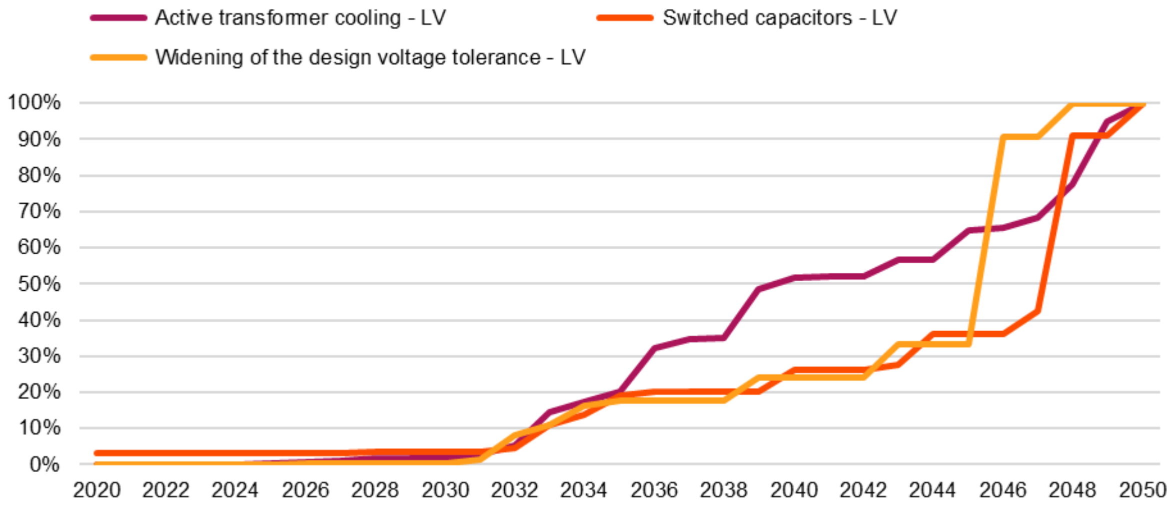
Figure 8: Deployment curves for selected Shortlisted solutions in Run 2, 2020-50, with significant deployments in the first half of the modelling period (up to the mid-2030s).



The solutions in Figure 8 are: BtM Domestic Battery Storage for DSR, Manual Phase Balancing, Network Data Monitoring, and Permanent Meshing. As a result, these are the solutions that this study's modelling indicates there would be most value focussing on in the short- to medium-term.

In the same way as Figure 8, Figure 9 shows the deployment curves of Shortlisted solutions with significant proportions of their deployments in the longer term, from the mid-2030s on.

Figure 9: Deployment curves for selected Shortlisted solutions in Run 2, 2020-50, with significant deployments in the second half of the modelling period (after the mid-2030s).



The solutions in Figure 9 are: Active Transformer Cooling, Switched Capacitors, and Widening of the Design Voltage Tolerance. These are the solutions that based on the modelling undertaken in this study, there would be most value focussing on in the longer term.

Overall Evaluation of Solutions

This subsection seeks to produce a broad ranking of the Shortlisted solutions to inform the recommendations and conclusions presented in *Conclusions and Recommendations*.

In Run 2, the Shortlisted solutions with the most deployments were:

- BtM battery storage for DSR.
- Manual Phase Balancing.
- Network Data Monitoring.
- Permanent Meshing.
- Switched Capacitors.
- Widening of the Design Voltage Tolerance.
- Active Transformer Cooling.

The Behind-the-Meter Battery Storage for DSR solution is shown to have the most deployments, not just in Run 2 but in all runs. The battery storage capacity sensitivity further demonstrates this solution's potential, as even at lower capacities the results showed it to be deployed the most of all solutions. The modelling has clearly shown that this may be a high potential solution, that warrants further work. For example, further consideration of the economics of BtM battery storage and value proposition for building owners would be useful, as the costs assigned to this solution in this analysis are the costs to the DNO to procure services from these assets (an opex cost), but not necessarily the revenues required by building-owners to justify the investment in the asset[23].

The Manual Phase Balancing and Network Data Monitoring solutions are the top 3 solutions for each modelling run (other than the counterfactual). Therefore, the modelling shows these solutions to be significant, and to also warrant further work.

The solutions Permanent Meshing, Switched Capacitors and Active Transformer Cooling are not deployed as often as the three solutions discussed above, or the DSM Intelligent Control of Charging Devices Other Smart solution in runs where that was made available. However, they were deployed more often than all remaining Other Smart solutions and all Conventional solutions. This means these three solutions are shown to have significant roles to play in solving LV network constraints to 2050.

It is notable that of all the Shortlisted solutions selected by Transform, Permanent Meshing and Switched Capacitors were already included in the model and are solutions which are more established at higher voltage levels.

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[23] The Phase 3 extension to this study views this from a different direction and looks at what the maximum cost of behind-the-meter energy storage is before it becomes of no value to networks. This is then compared with typical capital and operating costs of a BtM storage system to see whether it is likely that costs would be recovered over the lifetime of the solution.

Although not selected in Run 1 and its sensitivities, Widening of the Design Voltage Tolerance was selected in Run 2 and its sensitivities, and analysis of Run 4 found that the inclusion of this solution did provide a very small financial benefit.

As previously noted, the following solutions were not selected in any run:

- Dynamic Voltage Management using OLTCs
- Dynamic Voltage Management using Power Electronics
- Temporary Meshing

Therefore, on the basis of our modelling in this study, these three solutions do not appear to be high priority for resolving of LV network constraints to 2050, and as such no subsequent focus on them is recommended in *Conclusions and Recommendations*.

Conclusions and Recommendations

Conclusions

In this second phase of the Low Voltage Network Capacity Study, we have presented a quantitative analysis of the shortlist of solutions that was recommended in Phase 1. This was achieved using EA Technology's proprietary TransformTM tool, which was used to investigate the level of deployment of each solution on the low voltage network, depending on their costs and capabilities to resolve constraints.

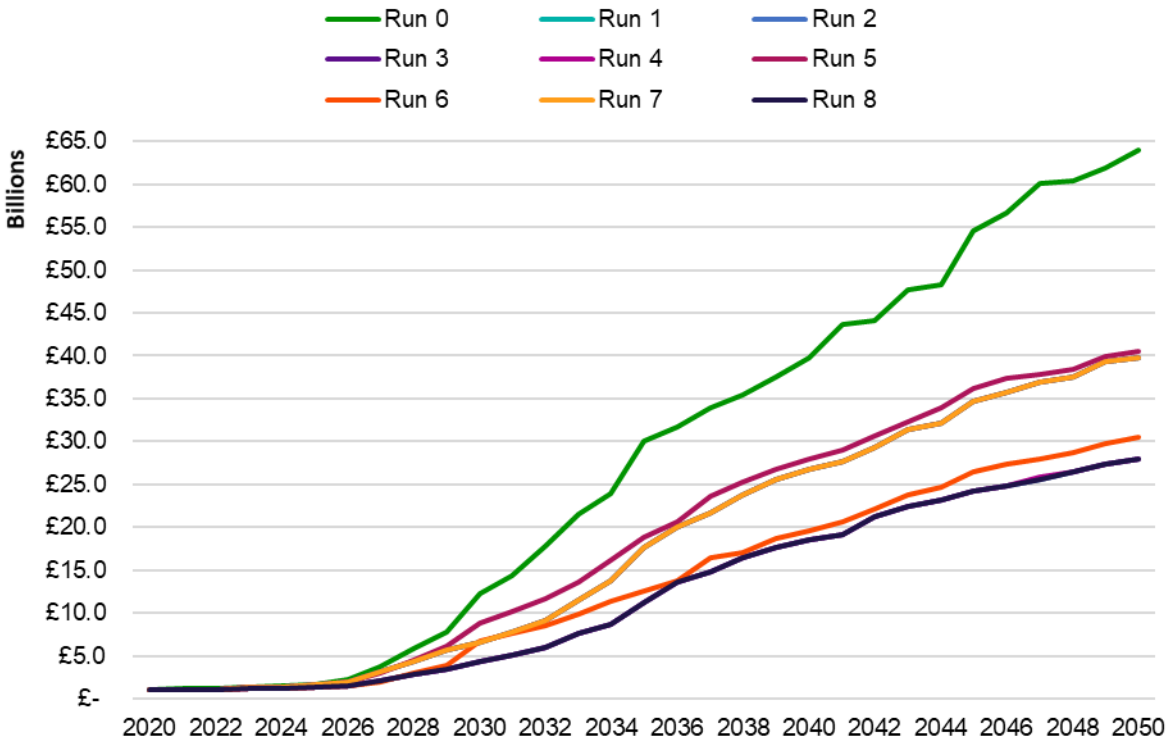
The Transform model was updated to include the Shortlisted solutions from the Phase 1 report utilising the parameters detailed in Appendix 3: Transform Model Parameters for Shortlisted Solutions. To compare the different solutions and a range of sensitivities the following runs were carried out using Transform, shown in Table 3.

Table 3: Runs of the Transform model used in this study

Sensitivity	Conventional Solutions	Shortlisted Solutions	Other Smart Solutions
None	Run 0	Run 1	Run 2
Excluding Widening of the Design Voltage Tolerance	N/A	Run 3	Run 4
Capacity of BtM storage halved	N/A	Run 5	Run 6
Including Dynamic Voltage Management using Power Electronics	N/A	Run 7	Run 8

The Transform runs showed that deployment of the smart solutions (Shortlisted and Other) when compared with the counterfactual (Run 0) created the opportunity for significant financial savings. However, in both cases (Runs 1 and 2) there was an increase in the proportion of totex earlier in the 2021 to 2050 window. The following figure shows the overall totex costs for each of the study runs with a clear saving for the use of smart solutions but also a slight flattening in expenditure rate from 2038 onwards[24].

Figure 10: Cumulative discounted totex from all runs, 2020 to 2050 (totex the same for Runs 1, 3 and 7, and for Runs 2, 4, and 8).



Carrying out the Transform runs shows a significant preference towards low capex solutions for resolving constraints on the LV networks. The shortlisted solution shown to dominate deployment of solutions to resolve network constraints across the LV system is Behind-the-Meter Domestic Storage, which has zero capex cost. Conversely, dynamic voltage management options (using OLTCs or power electronics) have relatively high capex costs and therefore are never chosen as solutions.

Widening of the Design Voltage Tolerance only appears as a solution when considered in combination with the Other Smart solutions (Run 2). This only becomes viable as a solution when it is considered in combination with DSM intelligent control of charging devices. The sensitivity study, Run 4, investigating the impact of this shortlisted solution (Widening of the

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[24] As in Phase 1 this assumes the demand profile of the CCC Balanced Net Zero Pathway, which gives details of the pathway and timescales for decarbonisation in different sectors such as heat and transport.

Design Voltage Tolerance) did find a slight increase in overall totex when it was not available as an option, however this was negligible.

The most dominant solution across all study runs was the deployment of BtM domestic storage. This solution has no capex costs associated with it following the expectation that the networks would incur an opex cost to domestic consumers for utilisation of their domestic storage. The capex costs for the installation of the domestic storage is assumed to be met by the consumers or by other means. As a sensitivity, the assumed capacity of this domestic storage was halved (runs 5 and 6), halving the opex in the process, which was found to increase the uptake of BtM storage for DSR further still. This sensitivity also showed that other solutions became increasing viable when coupled with this reduced capacity storage:

- Widening of the Design Voltage Tolerances – with a reduced BtM domestic storage capacity there is now, while small, an increased benefit in the Widening of the Design Voltage Tolerances, allowing for an increase in the voltage legroom that can be released.
- Active Transformer Cooling – with a reduced BtM domestic storage capacity there is a need for further capacity release through Active Transformer Cooling

While battery storage clearly had the highest uptake when implemented behind-the-meter, this was not unexpected given that it is the only solution which does not have a capex paid by the DNO. The practicality of this uptake is tested further in an extension to this report, which investigates the cost at which battery storage is no longer deployed by the Transform model. Ultimately the capex paid by the consumer should be repaid by compensation payments from the DNO, or by revenue stacking through alternative mechanisms that help support balancing of the energy system (for example, supplier position balancing, market arbitrage). We also examine the relative merits of grid-scale storage, which is typically lower cost, however, may include further constraints surrounding installation and the ability to balance heat pump demand.

One of the Shortlisted solutions detailed in the Phase 1 report considers the potential for power electronic devices to be used for dynamic voltage management across the LV network. Review of the literature[25] suggested that this technology is not yet ready for deployment and therefore the sensitivity study (Runs 7 and 8) considered it as being deployed from 2035 onwards. The results show that even though this solution has significantly lower totex (capex and opex) compared with the use of OLTCs it is still not a favourable solution.

A review of all shortlisted solutions and their deployment based on Run 2 resulted in the following ranking of shortlisted solutions:

- **Behind-the-meter battery storage for DSR.**
- **Manual Phase Balancing.**

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[25] E.g., Chen, N. and Jonsson, L.E. *A new Hybrid power electronics on-load tap changer for power transformer*, (2015), Zhou, H. et al, *A review on voltage control using on-load voltage transformer for the power grid* (2019), Kruschel, W. et al, *Power electronic voltage regulator for increasing the distributed generation capacity in low voltage networks* (2013)

- **Network Data Monitoring.**
- Permanent Meshing.
- Switched Capacitors.
- Widening of the Design Voltage Tolerance.
- Active Transformer Cooling.

The following shortlisted solutions were not deployed during any of the study runs due to alternative smart solutions being more favourable:

- Dynamic Voltage Management using OLTCs.
- Dynamic Voltage Management using Power Electronics.
- Temporary Meshing.

The analysis that has been carried out utilising the Transform model has shown a significant dominance in the top 3 ranked solutions even when considering additional sensitivities in terms of cost, capacity release and combinations across solutions.

In addition to calculating the level of uptake of each solution and the associated cost, our modelling revealed valuable insights into the timescales of deployment. Most smart solutions saw deployment in the short- and medium-term, with most uptake occurring between 2030 and 2040. These solutions included Battery Storage, Network Monitoring, Permanent Meshing, and Manual Phase Balancing. The remaining solutions saw greater deployment in the period after 2040, which included Active Transformer Cooling, Widening of the Design Voltage Tolerance, and Switched Capacitors. Modelling found that these solutions were more appropriate to solving network constraints in the long-term, and therefore could be a priority for research and development in the future.

Recommendations

Based on the modelling and analysis presented in this report, we have set-out a number of recommendations for consideration by BEIS as to the priority solutions for resolving constraints on the LV networks. These recommendations relate specifically to targeted focus during the RIIO-ED2 and RIIO-ED3 price controls.

- The analysis showed that the LV network archetype with the most money being spent on it is terraced streets. Additionally, behind-the-meter domestic energy storage for DSR showed the most significant opportunity, but would require sufficient engagement with consumers to encourage and facilitate uptake in potentially difficult to install environments.
- Although the studies have shown that BtM domestic energy storage is the dominant solution the actual technology has not been explicitly considered. Based on the latest research it is expected that this will take the form of battery storage. With the anticipated continued growth in electric vehicles for those where domestic charging is

possible, a similar solution could be to link EV charging with intelligent controls, e.g. the solution DSM intelligent control of smart charging devices, to maximise benefit.

- Manual Phase Balancing has demonstrated some capacity release and can be considered as relatively static solutions, operating as a fit-and-forget type approach. To maximise the benefit of this solution there would be value in a coordinated education piece amongst the DNOs to ensure a clear understanding of optimum deployment and best practice that can be achieved.
- Network Data Monitoring comes up as a solution that releases capacity through better knowledge of the actual load and capacity on the network. However, there are additional benefits to this in that it also an enabler of many other solutions and improved asset management. DNOs as part of their RIIO-ED2 submission are preparing Network Visibility Strategies including monitoring roll-out targets and justification.
- Cost reductions seen as a result solutions examined in this study are likely to have impacts on the advantages of decarbonisation of heat by electrification relative to hydrogen. Previous studies have found that network reinforcement may represent a large proportion of the costs associated with decarbonisation of heat by electrification[26]. Deploying the solutions that have been investigated within this study are likely to reduce the impact of network reinforcement on electricity prices, meaning that the consumer cost of operating heat pumps and electric heating technologies may be less than has previously been forecast.

The Transform model was operated in this study with a planning timescale of five years, in line with the length of price control periods for DNOs. Extending this timescale would likely reduce overall investment costs but could result in a higher expenditure early on. It is likely that higher cost solutions which release a large amount of capacity could be deployed early since these resolve network constraints over a longer period. Therefore, solutions such as dynamic voltage management, which was not deployed in this study, may see some level of implementation. However, while overall costs may reduce, this does not realistically reflect how current network investment decisions are made. Furthermore, it reduces the flexibility of the DNO to solve constraints in different ways as technologies evolve, and it relies on the accuracy of demand forecasts which are increasingly uncertain in the longer-term.

Following our review of all the smart solutions we recommend that the following are prioritised for further consideration and investigation, to understand how deployment can be cost-effectively accelerated to maximise benefits:

- **Behind-the-meter battery storage for DSR.**
- **Manual Phase Balancing.**
- **Network Data Monitoring.**
- Permanent Meshing.
- Switched Capacitors.

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[26] Element Energy and E4Tech for the National Infrastructure Commission, *Cost analysis of future heat infrastructure options,* (2018)

- Widening of the Design Voltage Tolerance.
- Active Transformer Cooling.

Conversely, the following solutions have been found to offer very little benefit or contribution to improve the capacity of the LV system and therefore are not recommended for any further consideration at this time:

- Dynamic Voltage Management using OLTCs.
- Dynamic Voltage Management using Power Electronics.
- Temporary Meshing.

Appendix 1: Solutions in the Transform Model

Table 4: Solutions in the Transform model, after the addition of new smart solutions shortlisted in Phase 1, and their categorisation for the modelling runs used in this study[27].

Solution Category	Solution
Conventional	EHV overhead Major works
	EHV overhead Minor works
	EHV overhead network Split feeder
	EHV overhead New Split feeder
	EHV underground Major works
	EHV underground Minor works
	EHV underground network Split feeder
	EHV underground New Split feeder
	HV overhead Major works
	HV overhead Minor works
	HV overhead network Split feeder
	HV overhead New Split feeder
	HV underground Major works
	HV underground Minor works
	HV underground network Split feeder
	HV underground New Split feeder
	Large 33/11 Tx
	Small 33/11 Tx

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[27] In this table ”Split feeder” refers to splitting an existing feeder to supply either end of the feeder from different points. ”New Split feeder” relates to installing a new feeder to supply some of the load and therefore incurs a longer lead time and cost but with a greater capacity release.

Solution Category	Solution
Conventional	LV Ground mounted 11/LV Tx
	LV New Split feeder
	LV overhead Major works
	LV overhead Minor works
	LV overhead network New Split feeder
	LV overhead network Split feeder
	LV Pole mounted 11/LV Tx
	LV underground Major works
	LV underground Minor works
	LV Underground network Split feeder
Shortlisted	Active Transformer Cooling - LV
	Behind-the-Meter Domestic Battery Storage - LV
	Dynamic Voltage Management using OLTCs - LV
	Dynamic Voltage Management using Power Electronics - LV
	Manual Phase Balancing - LV
	Network Data Monitoring - LV
	Permanent Meshing of Networks - LV Sub-Urban
	Permanent Meshing of Networks - LV Urban
	Switched Capacitors - LV
	Temporary Meshing (soft open point) - LV
	Widening of the Design Voltage Tolerance - LV

Solution Category	Solution
Other Smart	Dynamic Network Reconfiguration - EHV
	D-FACTS - EHV connected STATCOM
	Distribution Flexible AC Transmission Systems (D-FACTS) - EHV
	DSR_DNO to aggregator led EHV connected commercial DSR
	DSR_DNO to EHV connected commercial DSR
	Electrical Energy Storage_EHV connected EES - large
	Electrical Energy Storage_EHV connected EES - medium
	Electrical Energy Storage_EHV connected EES - small
	Embedded DC Networks_Embedded DC@EHV
	EAVC - EHV circuit voltage regulators
	Fault Current Limiters_EHV Non-superconducting fault current limiters
	Fault Current Limiters_EHV Superconducting fault current limiters
	Generator Constraint Management GSR - EHV connected generation
	Generator Providing Network Support e.g. Operating in PV Mode - EHV
	New Types Of Circuit Infrastructure_Novel EHV tower and insulator structures
	New Types Of Circuit Infrastructure_Novel EHV underground cable
	Permanent Meshing of Networks - EHV
	RTTR for EHV Overhead Lines
	RTTR for EHV Underground Cables
	Switched Capacitors - EHV
	Temporary Meshing (soft open point) - EHV
	Active Network Management - EHV
	Dynamic Network Reconfiguration - HV
	D-FACTS - HV connected STATCOM

Solution Category	Solution
Other Snart	Distribution Flexible AC Transmission Systems (D-FACTS) - HV
	DSR_DNO to aggregetor led HV commercial DSR
	DSR_DNO to HV commercial DSR
	Electrical Energy Storage_HV Central Business District (commercial building level)
	Electrical Energy Storage_HV connected EES - large
	Electrical Energy Storage_HV connected EES - medium
	Electrical Energy Storage_HV connected EES - small
	Embedded DC Networks_Embedded DC@HV
	EAVC - HV circuit voltage regulators
	Fault Current Limiters_HV reactors - mid circuit
	Fault Current Limiters_HV Non-superconducting fault current limiters
	Fault Current Limiters_HV Superconducting fault current limiters
	Generator Constraint Management GSR - HV connected generation
	Generator Providing Network Support e.g. Operating in PV Mode - HV
	New Types Of Circuit Infrastructure_Novel HV tower and insulator structures
	New Types Of Circuit Infrastructure_Novel HV underground cable
	Permanent Meshing of Networks - HV
	RTTR for E/HV transformers
	RTTR for HV Overhead Lines
	RTTR for HV Underground Cables
	Switched Capacitors - HV
	Temporary Meshing (soft open point) - HV

Solution Category	Solution
	Active Network Management - HV
	Dynamic Network Reconfiguration - LV
	D-FACTS - LV connected STATCOM
	Distribution Flexible AC Transmission Systems (D-FACTS) - LV
	DSR_DNO to Central business District DSR (LV)
	DSR - DNO to residential (LV)
	Electrical Energy Storage_LV connected EES - large
	Electrical Energy Storage_LV connected EES - medium
	Electrical Energy Storage_LV connected EES - small
	Embedded DC Networks_Embedded DC@LV
	EAVC - HV/LV Transformer Voltage Control
	EAVC - LV circuit voltage regulators
	EAVC - LV PoC voltage regulators
	Generator Constraint Management GSR - LV connected generation
	Generator Providing Network Support e.g. Operating in PV Mode - LV
	DSM Intelligent control of charging devices (LV)
	RTTR for H/LV transformers
	RTTR for LV Overhead Lines
	RTTR for LV Underground Cables
	Active Network Management - LV
	Local smart EV charging infrastructure_Intelligent control devices (LV)

Appendix 2: Location of Battery Energy Storage

Battery Energy Storage Systems (BESS) can have varying effects on the LV network depending on their placement. In this report we examine behind-the-meter storage, however, it is possible to locate 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[28] than behind-the-meter storage it was ultimately not taken forward due to its limited functionality in managing heat pump demand[29]. Conversely, behind-the-meter storage offers a much 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 discharge during certain hours, thereby flattening demand profiles and alleviating network loading.

However, another option exists for managing LV network constraints through storage, that is placing batteries along or at the end of the feeder. 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 drops, 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[30].

However, it has been noted in energy storage trials that space constraints can be a significant issue for this type of implementation[31] as a result of the number of additional systems required, 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 this study’s modelling highlighting 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 (on customers’

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[28] This refers to absolute cost of grid-scale vs behind-the-meter storage, rather than that seen by the DNO or the customer. In 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.

[29] 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).

[30] SSEN, *New Thames Valley Vision Learning Outcome Report, LV Network Storage – ESMU Trials*, (2017)

[31] Northern Powergrid, *Customer Led Network Revolution Lessons Learned Report: Electrical Energy Storage*, (2014)

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.

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. Consequently, some of the modelled uptake of end of feeder battery storage may in practice lead to deployment of substations where they are cheaper. Substations are also a more reliable means of increasing headroom, owing to the additional systems required for storage noted above increasing solution complexity, and because battery solutions need to spend some of the time charging so are not always available for network support.

Appendix 3: Transform Model Parameters for Shortlisted Solutions

Table 5: Transform model parameters for Shortlisted 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
Active Transformer Cooling	3,872	66	15	1.3	1.3	1	0	3	6	2
Behind-the-Meter Domestic Battery Storage	-	1,920 [32]	10	1.3	1.3	2	1	3	6	5
Behind-the-Meter Domestic Battery Storage*	-	960	10	1.3	1.3	2	1	3	6	5

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[32] Opex costs obtained from NPg project, DS3 - Distributed storage and solar study with the Transform 3.5% discount rate applied. This is the compensation that a DNO might be expected to pay customers for use of behind-the-meter storage systems.

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
Dynamic Voltage Management using OLTCs	49,125	3,375	20	1.3	1.3	2	1	2	18	3
Dynamic Voltage Management using Power Electronics*	24,563	1,688	20	1.5	1.5	3	1	2	18	3
Manual Phase Balancing	20,000	-	45	1.5	1.5	3	0	2	18	2
Network Data Monitoring	2,347	94	20	1.2	1.2	1	0	5	12	4

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
Permanent Meshing, sub-urban	20,660	826	45	1.1	1.1	2	-1	2	6	2
Permanent Meshing, urban	20,660	826	45	1.1	1.1	2	-1	2	6	2
Switched Capacitors	10,330	103	30	1.1	1.1	2	1	2	18	2
Temporary Meshing	20,660	826	25	1.5	1.5	2	0	4	6	3
Widening of design voltage tolerance	64	-	60	1.5	1.5	1	0	1	3	3

Table 6: Transform model parameters for Shortlisted solutions, input into the ‘Solution Headrooms’ tab.

Solution	Thermal Transformer	Thermal Cable	Voltage Headroom	Voltage Legroom	Power Quality	Fault Level
Active Transformer Cooling	22	0	0	0	0	0
Behind-the-Meter Domestic Battery Storage	50	50	20	20	10	-5
Behind-the-Meter Domestic Battery Storage*	25	25	10	10	5	-3
Dynamic Voltage Management using OLTCs	0	0	90	0	5	5
Dynamic Voltage Management using Power Electronics*	0	0	90	0	5	5
Manual Phase Balancing	20	20	20	20	10	5
Network Data Monitoring	8	8	0	0	0	0
Permanent Meshing, sub-urban	5	50	0	2	20	-33
Permanent Meshing, urban	10	50	0	2	20	-33
Switched Capacitors	0	0	5	5	10	0
Temporary Meshing	5	50	0	2	10	-33
Widening of design voltage tolerance	0	0	0	5	-10	0

Table 7: Transform model parameters for Shortlisted solutions, input into the 'Solution Misc. Settings' tab[33].

Solution	Effect On Copper Losses (%)	Effect on Iron Losses (%)	Effect On Interruptions (%)	Year Available (yr)	Year Unavailable (yr)	Enable DSM? (T/F)	Feederised Solution [T/F]	Underground Solution? (T/F)	Overhead Solution? (T/F)
Active Transformer Cooling	-10	0	5	2020	2080	FALSE	TRUE	FALSE	FALSE
Behind-the-Meter Domestic Battery Storage	-5	0	0	2020	2080	TRUE	FALSE	FALSE	FALSE
Behind-the-Meter Domestic Battery Storage*	-3	0	0	2020	2080	TRUE	FALSE	FALSE	FALSE
Dynamic Voltage Management using OLTCs	17	-8	0	2020	2080	FALSE	TRUE	FALSE	FALSE

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[33] Columns *Enable DSM*, *Feederised Solution*, *Underground Solution*, *Overground Solution* are used by Transform to understand when solutions can be deployed together (enablers) and when they are not compatible. Battery storage options also included parameters describing their capacity in kW and kWh. For Runs 1-2 this was 14kW and 72kWh, for the sensitivity this was 7kW and 36kWh.

Solution	Effect On Copper Losses (%)	Effect on Iron Losses (%)	Effect On Interruptions (%)	Year Available (yr)	Year Unavailable (yr)	Enable DSM? (T/F)	Feederised Solution [T/F]	Underground Solution? (T/F)	Overhead Solution? (T/F)
Dynamic Voltage Management using Power Electronics*	17	-8	0	2035	2080	FALSE	TRUE	FALSE	FALSE
Manual Phase Balancing	-20	0	5	2020	2080	FALSE	FALSE	FALSE	TRUE
Network Data Monitoring	0	0	0	2020	2080	FALSE	TRUE	FALSE	FALSE
Permanent Meshing, sub-urban	-10	0	30	2020	2080	FALSE	FALSE	FALSE	FALSE
Permanent Meshing, urban	-10	0	30	2020	2080	FALSE	FALSE	FALSE	FALSE
Switched Capacitors	0	5	0	2020	2080	FALSE	FALSE	FALSE	FALSE

Solution	Effect On Copper Losses (%)	Effect on Iron Losses (%)	Effect On Interruptions (%)	Year Available (yr)	Year Unavailable (yr)	Enable DSM? (T/F)	Feederised Solution [T/F]	Underground Solution? (T/F)	Overhead Solution? (T/F)
Temporary Meshing	-5	0	30	2020	2080	FALSE	FALSE	FALSE	FALSE
Widening of design voltage tolerance	0	0	0	2020	2080	FALSE	FALSE	FALSE	FALSE