Department for
Business, Energy
& Industrial Strategy

Low Voltage Network Capacity Study

Phase 1 Report – Qualitative Assessment of Non-Conventional Solutions

July 2022

Authors:

Alex Speakman, Consultant, Element Energy

Owen Harris, Graduate Consultant, EA Technology

Catherine Birkinshaw-Doyle, Consultant, EA Technology

David Mills, Head of Net Zero Transition, EA Technology

Reviewers:

Ian Walker, Partner, Element Energy, an ERM group company

Mark Sprawson, Director, EA Technology

Any enquiries regarding this publication should be sent to us at:
enquiries@beis.gov.uk

Contents

Executive Summary

This report explores a range of technologies that have the potential to extend LV network capacity without replacement of assets. First, we examine demand profiles based upon several key low carbon technologies to determine the timescales and magnitude of projected changes to the network. In the transition to net zero by 2050, peak demand on the LV network is expected to increase rapidly, in part due to the electrification of heat and transport, while distributed generation is also likely to place strain on the system. These effects will be offset by smart appliances and shifts in consumer behaviour, however, network reinforcement and upgrades are still likely to be required. Crucially, reinforcement expenditure is recovered through customer electricity bills, so finding ways to defer or avoid reinforcement is essential to ensure that the costs to customers is as low as possible.

We subsequently explore previous and existing methods for estimating headroom on the low voltage network, followed by a discussion of network infrastructure characteristics and changes in policy around network development. This analysis notes that networks are either thermal limited (load), voltage limited, or fault level limited, however, fault level presents little risk at LV. Networks with voltage issues are managed as and when problems arise - determining load growth that would affect them is non-trivial as it depends where load is positioned with respect to the feeding substation. Thermal headroom is determined by comparing load with ratings of the assets through which it flows.

To establish which solutions exist for releasing network capacity, and to determine where research has been focused, we conducted a literature review of over 60 studies, including innovation projects and international studies. Research was broadly divided into high, moderate and low research interest, with solutions such as dynamic asset ratings, network monitoring and energy storage having received greater levels of attention in recent years. The literature review also examined ‘cold-spots’ where limited research has been carried out, such as in widening of the design voltage tolerance, phase balancing and transformer cooling, which may represent opportunities for further investigation and investment.

This literature review was used to generate a longlist of solutions which were assessed against a number of criteria including cost, headroom release, and applicability. Using a ranking analysis we established a merit order for these solutions, from which we generated a shortlist of options to be investigated in greater depth. Where various implementation alternatives exist, we explored the costs and benefits of each option to determine which to take forward for further analysis. These included a number of network-side solutions, a customer-side solution, and a policy-based approach, listed below:

- **Network-side:**
  - **Transformer cooling**
  - **Dynamic voltage management**
  - **Network monitoring**
  - **Switched capacitors**
  - **Meshing**
  - **Phase balancing**
- **Customer-side:**
  - **Energy Storage**
- **Policy-side:**
  - **Widening of design voltage tolerance**

We explore the relative merits of each technology in the shortlist, whilst also noting any limitations and risks. Low regrets options included solutions such as transformer cooling and network monitoring, while more established solutions such as dynamic voltage management were also included for deployment in the short term. Shortlisted options were selected such that they covered a range of technology readiness levels, and therefore provide options for deployment at different timescales. Limitations in the analysis were found in the level of quantification that could be drawn from the literature since studies were not generally consistent in their how cost and headroom release was assessed. However, Phase 2 of this project will address this by using modelling each of the selected solutions to evaluate how they may be deployed and what the resulting impact on the LV network is likely to be.

Stakeholder engagement was initiated, with responses noting the synergies between some solutions such as network monitoring and meshing. Stakeholders perceived transformer cooling, network monitoring, and widening of the design voltage tolerance as priorities for further development. In the next phase, we will investigate the counterfactual case of conventional reinforcement followed by development of detailed quantitative analysis of each solution identified in this report.

Acronyms

ADMD	After Diversity Maximum Demand
ANM	Active Network Management
CCC	Committee for Climate Change
DER	Distributed Energy Resources
D-FACTS	Distributed Flexible AC Systems
DNO	Distribution Network Operator
DSO	Distribution System Operator
DSR	Demand Side Response
EAVC	Enhanced Automatic Voltage Control
EES	Electrical Energy Storage
EV	Electric Vehicle
FES	Future Energy Scenarios
HP	Heat Pump
HV	High Voltage
LCT	Low Carbon Technologies
LV	Low Voltage
NG	National Grid
PHEV	Plug in Hybrid Electric Vehicle
PV	Photovoltaic
RTTR	Real Time Thermal Ratings
ToU	Time-of-Use
TRL	Technology Readiness Level

Introduction

The transition to net zero by 2050 is expected to bring about considerable changes to the way that low voltage networks operate, as increasing levels of low carbon technologies and distributed energy resources are deployed across the UK. Rapid uptake of LV-connected technologies such as heat pumps and electric vehicles are anticipated to result in substantial increases in electricity demand, while distributed generation such as solar photovoltaics is likely to place further strain on the network. This is expected to drive a high level of load-related expenditure as a result of the reinforcement that will be required to accommodate this transition.

Conventional reinforcement typically involves upgrading and replacing assets, for example, installing higher rated conductors or transformers. It is expected that in RIIO-ED2, the next electricity price control period (2023-2028), this reinforcement will account for the majority of distribution network expenditure. The level of required investment is expected to be high in part because much of the network is buried underground, leading to significant civil engineering costs. Increased use of overhead conductors may reduce some of the initial civil engineering costs but at increased operational costs due to a number of other factors such as visual impact, asset lifetime, weather related reliability, safety and customer objection. The LV network is already the most expensive part of the network to maintain due to its size and complexity, with these costs being recovered from domestic and business customer electricity bills. Consequently, it is of interest to minimise costs to consumers, whilst still accommodating technologies that must be deployed to decarbonise the UK electricity system. Understanding of how much 'spare' capacity exists on the LV network is relatively poor, since assets have previously been connected on a 'fit and forget' basis with limited network monitoring. Hence, there is a level of uncertainty over the timing and magnitude of required reinforcements, and work is required to understand how these upgrades might be deferred or avoided by use of alternative 'smart' solutions.

This study will investigate methods for identifying and extending this spare capacity through deployment of technologies that can potentially defer costly and disruptive reinforcements. We first present an analysis of how the uptake of low carbon technologies and distributed generation is likely to change in the future, and how this might impact on the low voltage network. We reviewed several forecasts from the CCC Sixth Carbon Budget and the National Grid Future Energy Scenarios to assess a range of possible outcomes. In our analysis we focus on the CCC Balanced Net Zero Pathway which is one of the scenarios that Ofgem has encouraged DNOs to consider in their RIIO business planning. Following this, the current visibility of the LV network was evaluated through an exploration of existing and novel methods for assessing network headroom. This included consideration of After Diversity Maximum Demand (ADMD), and Debut methods, as well as a summary of legacy network characteristics.

To establish which solutions exist to extend LV network capacity, we carried out a review of existing literature, including network innovation projects and international studies. We analysed over 60 individual projects and papers, examined where research has previously been concentrated, and which DNOs or other organisations have conducted this work. Following from the literature review, a range of potential solutions were identified for expanding network capacity, which were collated to form a longlist of options.

Smart solutions included network-side technologies (e.g., dynamic voltage management), customer-side options (e.g., smart electric vehicle charging), and policy-based approaches (e.g., widening of design voltage tolerances). Smart functionality has been defined within this report 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[1]. 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[2].

We subsequently evaluated the longlist based upon a number of key criteria, including cost, headroom release (the levels of thermal and voltage capacity increase across the low voltage network), and applicability across the low voltage network. Consideration was also given to Technology Readiness Level (TRL) to ensure that diverse solutions were identified, with potential to be deployed in the short-, medium-, and long-term. Finally, through a quantitative ranking analysis, we present a shortlist of 8 low-regrets options with the highest potential to defer reinforcement at best value. Where possible quantitative and qualitative data was extracted from the literature to build up a thorough profile and explore the relative merits of each technology. In the next phase of this study we aim to build on this work, by developing a detailed quantitative understanding of the effectiveness of each smart solution at extending network capacity in different types of LV networks, for comparison with a conventional network reinforcement counterfactual. This quantitative understanding of conventional and smart solutions' impacts on the LV network across Great Britain will be developed using the TRANSFORM techno-economic model.

[1] BEIS, *Electric Vehicle Smart Charging: Government Response to the 2019 Consultation on Electric Vehicle Smart Charging, (2021)*

[2] BEIS, *PAS 1878: Energy smart appliances – System functionality and architecture – Specification, (2021)*

Demand Profiles

To gain a better understanding of the changes that may occur on low voltage networks in future, we first developed a range of demand profiles based upon uptake rates of low carbon technologies. Projections of how demand and generation will change in the future is of relevance to this study since it helps to establish when and where investment may be required, and which solutions may be most appropriate to deploy for deferring conventional reinforcements. This data will also inform work to be carried out in Phase 2 of this project, in which the Transform model will be used to quantitatively analyse the solutions selected in Phase 1. Data for this analysis is drawn from two sources: National Grid's Future Energy Scenarios and the CCC's Sixth Carbon Budget.

The scenarios within the National Grid and CCC data represent a range of possible outcomes for the UK energy system, with most achieving net zero targets through a variety of approaches. Ambitious scenarios such as NG Leading the Way and CCC Tailwinds see rapid decarbonisation, brought about through deep innovation and considerable societal change. Both sources also include slow decarbonisation scenarios, namely NG Steady Progress and CCC Headwinds. Other scenarios represent decarbonisation through a range of technological approaches. These include NG Consumer Transformation which sees high electrification across the UK, NG System Transformation which envisages a greater role for low carbon hydrogen in the decarbonisation of heat and transport, requiring less change to consumer lifestyles, and CCC Balanced Net Zero Pathways which seeks to explore a more diverse range of options to meet net zero.

The scenarios described above only take into consideration the real power requirements of the system, ignoring the potential changes in reactive power requirements as a result new demand. Electric vehicles and heat pumps are expected to introduce electricity demand with a power factor close to unity. At times of peak demand this is unlikely to significantly alter the power factor which is already high on the LV networks and provides limited option to increase capacity. However, at non-peak times of day improvements in power factor can release more capacity and if load can be shifted into those periods enable greater delivery.

For the analysis presented in this report, we focus on 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[3]. For our analysis, we have extracted information from CCC datasets for a range of technologies and flexibility measures, including those presented in this report. This data primarily includes uptake rates and peak demand/generation, but also considers changes to consumer behaviour. Details of this analysis can be found in Appendix 1, where data is presented regarding the uptake of heat pumps, electric vehicles, and distributed generation.

[3] 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).

Overall, while there is a significant level of uncertainty in these projections, peak electricity demand on the LV network is very likely to increase rapidly over the next thirty years, in part due to the electrification of heat and transport. These effects will be offset by deployment of smart appliances and changes in consumer behaviour, however, increases in demand and network loading will still be substantial. The required reinforcement that this demand necessitates is anticipated to be expensive, and solutions that are able to defer or avoid this are likely to offer considerable savings to DNOs, ultimately reducing customer electricity bills. Specifically, reinforcement costs are expected to be driven by the higher peak demand and generation on the LV network brought about by deployment of low carbon technologies. For example, electrification of heat is likely to increase the peak demand on LV networks during cold winter days, while increased solar PV penetration may place strain on the network during the summer.

In Phase 2 of this project, this year-by-year demand data will be used as an input to the Transform Model as part of a quantitative assessment of how the solutions presented in this report can improve the level of headroom on the LV network. Furthermore, we will investigate clustering to increase deployment of LCTs in particular network types to understand what the impact of an even higher electrification scenario might be. This can help to understand the highest level of reinforcement that might be required and gives an indication of how smart solutions might perform in a high electrification world.

Existing Estimates of LV Network Headroom

Electricity networks are typically limited by thermal constraints (load), voltage constraints, or fault level[4]. Networks with voltage issues are managed as and when problems arise - detemining load growth that would affect them is non-trivial as it depends where load is positioned with respect to the feeding substation. Thermal headroom is determined by comparing load with ratings of the assets through which it flows. Historically, there have been two key methods which have been used for estimating maximum demand on LV networks, and hence calculation of available headroom. These are the statistical method “Debut”, and after diversified maximum demand “ADMD”. These methods have been recommended for use since the 1987 issue of the ENA’s Engineering Recommendation P5, Design of LV underground networks for new housing estates, and both have been in common use since[5].

ADMD models each customer, or most often a group of customers, as a fixed demand, which is reflective of the customer’s diversity. Diversity is the consideration of how multiple

[4] Fault level limits presents little risk at LV.

[5] Theoretically, the maximum level of headroom on the LV network can be approximated by comparing existing peak demand with annual consumption. This allows a coarse estimation of the potential to increase the ‘load factor’ of the network through smoothing peaks and troughs in daily power demand. If current residential/domestic peak demand is supplied 24 hours a day, the energy delivered in one year can be approximately doubled (increase of 97%). For reference we take GB residential peak demand to be 21GW and annual residential consumption to be 95 TWh/y (NG FES 2021).

customers behave collectively. The maximum demand of a single domestic property, for example, may be in the evening when the resident has the oven, kettle, and TV on simultaneously, but all houses on a street will not have all their appliances on at exactly the same time as each other. ADMD generates an estimate of what the maximum demand would be per property after this diversity is taken into account.

The Debut methodology is a probabilistic method in which the probability of customer demand is modelled as being normally distributed. Maximum demand is estimated using a mean-based component, p, and a standard-deviation-based component, q. These are combined so that the calculated estimate is equivalent to the 90th percentile maximum demand which is expected to be seen on the network. This produces a reasonable worst-case estimate, resulting in the designed network being able to cope with the worst days of the year without being over-specified.

The ADMD methodology does not account for coincidence of maximum demand peaks and so can be inaccurate for networks supplying a mix of customers with unusual patterns of use. Debut accounts for this through the use of 60 half-hour covering a winter day, the worst expected day and notable worst weekend half-hours. This ensures coincidence of peaks are accounted for giving more accurate estimates for mixtures of usage patterns and allowing for demand to be calculated for each asset independently in the network. However, Debut is typically limited to analysis of radially-connected systems only whereas ADMD can be utilised for both radially and meshed networks through network reduction or nodal analysis methods. Appendix 2 includes further details and comparisons of these specific methodologies, their history and how their use in differing design policy has impacted on network headroom.

Network designers would typically use one of the two above methods, along with the properties of the proposed cables and transformer, to assess whether a potential network was suitable for purpose and within all necessary limits. Until recently, the preference was to choose the cheapest assets available which are inevitably smaller assets; lower-diameter cables and smaller transformers. More recently (those designed in the last 5-10 years) have seen a shift towards considering lifetime losses and future proofing which results in the use of higher rated assets. As a result of these changing priorities with regards to network design there is a mixture of networks with different levels of LV network headroom and limiting factors.

Literature Review

In order to find which options exist for expanding LV network headroom, we conducted a literature review covering a diverse range of studies including innovation projects and published international research in established scientific databases[6]. In total, over 60 studies were reviewed including published work from all six GB DNOs. Much of the literature was gathered from the ENA Smarter Networks Portal by conducting a focused search, filtered to low voltage networks and electricity distribution network operators. This literature was

[6] IEEE Xplore and Google Scholar were utilised to find peer reviewed, high quality international research publications.

subsequently compiled into Table 1 which illustrates which solutions have seen the most research in recent years from each DNO/author. Darker blue indicates where we found a higher density of research and lighter blue indicates where solutions may have seen less research interest[7] . For brief summaries of selected literature included in this review, the interested reader is directed to Appendix 2.

Table 1: Distribution of studies and literature across DNOs and international authors. Darker blue indicates a higher density of research and lighter blue indicates lower research interest.

Solution / DNO	UKPN	SSEN	WPD	SPEN	NPg	ENWL	Other Authors
Phase Balancing	Medium	Low	High	Medium	Low	Low	High
Dynamic Voltage Management	High	Medium	Low	Medium	Low	High	Medium
Dynamic Asset Ratings	Medium	Medium	High	Medium	High	Low	Medium
Widening of Voltage Tolerance	Low	Low	Medium	Low	Medium	Low	High
Smart Transformers	Low	Low	Low	Medium	Low	Low	Low
LV DC Networks	Medium	Low	Low	Medium	Low	Low	Medium
Microgrids	Low	Low	Low	Low	Low	Low	High
D-FACTS	Low	Low	Low	Low	Low	Low	Medium
Network Monitoring & Modelling	High	High	Low	High	High	Medium	Medium
Smart EV Charging	High	Low	High	Medium	Medium	Low	Medium
Dynamic Time of Use Tariffs	Medium	Low	Low	Low	Medium	Low	High
Energy Storage	Low	Low	High	Low	High	Medium	High

[7] Note that this table represents only the distribution of the literature examined in this study and is not an exhaustive list of all relevant projects. Limitations were found in terms of access to some studies, and for the sake of brevity, some projects have not been included in this report.

Enhanced Automatic Voltage Control	Medium	Low	Low	Low	Medium	Low	Medium
Switched Capacitors	Low	Low	Low	Low	Low	High	Medium
Generator Constraint Management	Low	Low	High	Low	Low	Low	Medium
Generator Providing Network Support	Low	Low	Low	Low	Low	Low	Medium
DSR - Commercial	Low	Medium	High	Low	Medium	Low	Medium
DSR - Residential	Low	Medium	Medium	Low	Low	Low	Medium
Meshing - Temporary	High	Low	High	Low	Low	Medium	Medium
Meshing - Permanent	Low	Low	Low	Low	Low	Low	Medium
Transformer Cooling	Low	Low	Low	Low	Low	Medium	Low

High Research Interest

Solutions which have seen high research interest include dynamic voltage management, dynamic asset ratings, network monitoring and modelling, smart EV charging, energy storage, and meshing. Key studies on dynamic voltage management include a number of interlinked projects conducted by Electricity North West[8] which investigate a range of approaches to voltage control such as distribution transformers with on-load tap changers (OLTCs) and the use of remote terminal units (RTUs) to automatically modulate substation voltage. Dynamic voltage management is also investigated through Development of an LV Management Strategy conducted for South Australia Power Networks (SAPN). Real time thermal ratings (RTTR) were investigated by NPg as a key aspect of the Customer-Led Network Revolution (CLNR) project, in which technology trials were deployed across multiple network types. This included applications to underground and overhead lines, as well as substations. Thermal ratings were calculated at resolutions of up to 5 minutes based on both environmental conditions and asset loading. These rating were used as part of an active network management system to control

[8] Electricity North West, *Voltage Management on Low Voltage Busbars (2013), Low Voltage Network Monitoring (2014), Low Voltage Integrated Automation (2013).*

the level of real power at different parts of the LV grid. WPD examine RTTR in OpenLV, in which a novel software platform is developed to control hardware on the LV network.

Network monitoring and modelling at LV level has received considerable attention from a range of DNOs, as well as in international projects. This includes NetZero Cheshire: Delivering Network Visibility in which EA Technology's VisNet® technology is being deployed at 673 LV substations to measure quantities such as network load. The CLNR project also features an element of network monitoring through the Enhanced Network Monitoring Report, which was initiated in order to better understand the impact of LCT uptake, as well as to understand the effectiveness of CLNR solutions such as RTTR, EAVC, EES, and DSR. Historic data from the CLNR project is also used in Smart Network Design Methodologies to investigate novel statistical and probabilistic modelling techniques for modelling of network voltages[9]. The specific impacts of heating decarbonisation are currently being investigated in an active study by Imperial College London[10], which aims to provide the UK's first 'map' of network capacity. The project investigates weather data to assess how heating and cooling demand may change in the future and aims to evaluate how system transitions will ultimately affect customers. Further modelling studies aimed at improving the networks' abilities to forecast the impact of heat and transport electrification on the networks include UKPN's HeatStreet and Recharge the Future projects[11].

The studies reviewed on the subject of smart EV charging reflect a number of technologies such as dynamic time-of-use tariffs, LV flexibility procurement, and energy storage. Such broad scope can be seen in Shift (UKPN) which investigates three methods for EV demand shifting, including two price signalling methods, and a method for limiting charging demand during a given peak time window. Similarly, projects such as Electric Nation (WPD) incorporate other technologies in order to achieve effective smart charging. Most significantly, monitoring is viewed as a crucial enabler for this solution, which can be used to detect charging loads on the network. Impacts on customers are a key consideration for all methods; customer lifestyles are not always equally adaptable to price signalling and social factors should therefore be considered when implementing dynamic tariffs[12]. Additional incentives have been trialled alongside smart charging schemes, such as a points system with rewards for participation[13].

The literature on the use of storage is commonly focussed on synergies with heat pumps, examining how electric heating demand can be shifted to reduce peak loading. Studies have also examined the use of storage alongside solar photovoltaics, with a view to absorbing

[9] During the literature review, limited evidence of machine learning for network modelling related to LV networks was identified suggesting that it is not currently an active area of research. Customer monitoring and smart meters were not explicitly included within the scope of this solution, however it is acknowledged that these can provide further benefit to the LV network. The focus of this solution was on monitoring of assets directly to assess scope for deferring upgrades and reinforcement.
[10] Imperial College London, *Network headroom, engineering upgrades and public acceptance (NUEPA)*, active project.
[11] UKPN, *Heat Street: Local System Planning (2021), Recharge the Future (2019).*
[12] Ozaki, R., *Follow the price signal: People's willingness to shift household practices in a dynamic time-of-use tariff trial in the United Kingdom (2018).*
[13] UKPN, *Shift (2021).*

surplus generation and reducing risks of reverse power flows on the network[14] [15]. Customers may store energy at times of low demand (from the grid or domestic generation) which may then be consumed when heat pump operation is required, thereby reducing the electricity drawn directly from the grid. Operation of storage to relieve network constraints may be incentivised using time-of-use tariffs, or through direct compensation to customers by DNOs. This solution may be implemented using thermal or electrical alternatives, however, neither of these are expected to be a 'cost optimal' solution at present. Batteries are currently the more expensive option, although in residences with high non-heating electricity consumption, their demand shifting potential may be up to three times higher. Moreover, reducing costs of battery storage mean that electrical alternatives may represent a considerable opportunity in the medium- to long-term[16].

Battery storage may be located at substation level (grid-scale) or behind-the-meter in individual customer residences and commercial premises. Research for NPg conducted by Element Energy found that where the uptake of storage is DNO driven (i.e. installed by the DNO for alleviation of network constraints), costs per kW for a domestic battery are likely to be considerably higher than for grid scale alternatives[17]. Where storage uptake was customer driven (installed by customers behind-the-meter for their own savings), benefits to the network were still seen in terms of reduced reverse power flows and peak load, however these were less significant compared the DNO driven case. Headroom release from customer driven installations may be seen as essentially free to the network, however, this capacity release is dependent on whether customers perceive the purchase of domestic energy storage as a sufficiently attractive option for reducing their savings[18]. Peak loading may be reduced further by allowing DNOs greater control over domestic storage, whereby customers are compensated for operating their storage at certain times to maximize their impact on the network. However, were DNOs to provide this compensation, it is anticipated that they may require a high degree of control over the asset in order to procure flexibility services[19]. 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).

Meshing has seen sustained research interest in recent years, with notable research conducted as part of the FUN LV and Active Response projects[20]. The focus of both projects has primarily been on temporary meshing with the use of power electronics such as soft open points and soft power bridges which are capable of transferring loads and regulating active and

---

[14] NPg, *Distributed Solar and Storage Study (2015).*
[15] BEIS, *Cost-Optimal Domestic Electrification (CODE), (2021).*
[16] Bloomberg, *A Behind the Scenes Take on Lithium-ion Battery Prices (2019), Why an Electric Car Battery Is So Expensive, For Now, (2021)*.
[17] NPg, *Distributed Solar and Storage, (2020)*. Domestic cost per unit energy = £1333/kW, Grid-scale cost per unit energy = £461/kW.
[18] For example, through increased self-consumption of locally generated energy.
[19] Estimated in the same study to be 243 days per year for 3 hours per day.
[20] UKPN, *Flexible Urban Networks – Low Voltage (2016), Active Response to Distribution Network Constraints (2021).*

reactive power control to distribute power flow across assets[21]. These devices can be integrated as part of an active network management system that is able to optimise network capacity remotely to ensure that LV assets are not overutilised or overloaded.

Moderate Research Interest

Solutions which have seen a moderate level of research include phase balancing, commercial demand side response (DSR), LV DC networks, widening of design voltage tolerances, and microgrids. Phase balancing has seen a number of studies aimed at gaining a better understanding of the existing level of phase imbalance on LV feeders, as well as studies to evaluate possible network benefits of connecting residential customers to three phase supplies. Again, this solution relies to some extent on enabler technologies such as network monitoring, which has been used to characterise the scale of imbalance across the networks[22]. While some level of imbalance is difficult to avoid, high demand customers connected to a single phase have the potential to cause significant reductions in headroom, as well as causing higher I2R losses. Some estates have also seen issues where there has been an uneven distribution of connections to each phase, leading to further imbalance. Improved monitoring across the network could enable automated detection of phase imbalance. SPEN have conducted research into the most effective methods and locations for rebalancing, which include feeder link box reconfiguration and installation of new types of transformers[23]. Energy efficiency measures have also been considered to reduce demands from large single-phase customers.

Rebalancing may also be performed in real time through the use of phase shift converters, which operate by redistributing power at the secondary distribution transformer[24]. Phases must be shifted to avoid increases in voltage levels and to maintain delivery of a 50Hz sine wave. Combining this with monitoring allows balancing to be performed in on a minute-by-minute basis, allowing transformers to utilise their maximum capacity and release headroom[25].

In parallel to phase balancing, DNOs have conducted further research into the benefits of connecting customers to three phase supplies as standard. This solution has been proposed primarily in response to anticipated high demand that can result from electric vehicles and heat pumps at individual customer residences. Consultations have been conducted by WPD to assess the merits of this option[26], and the potential to deploy this solution is acknowledged in their Electric Vehicle Strategy[27]. Further studies have investigated the potential to step up

[21] Cao, W., *Operating principle of Soft Open Points for electrical distribution network operation (2016).*
[22] SPEN, *HV and LV Phase Imbalance Assessment (2015),* Electricity North West, *Low Voltage Network Solutions (2015).*
[23] These are a “zigzag transformer to balance voltage typically used in the past on long LV overhead lines” and a “Scott transformer balancing method currently under investigation”.
[24] Zhang, J. M., et al. "Comparison study of phase-shifted full bridge ZVS converters." *2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No. 04CH37551)*. Vol. 1. IEEE, 2004.
[25] UKPN, *Phase Switch System (ongoing).*
[26] WPD, *Superfast Electricity Consultation (2020)*
[27] SPEN are planning a similar approach in ED2 for domestic connection upgrades where a single-phase cable has to be replaced.

voltage on the single-phase LV network from 230V to 400V to reduce losses, through the use of power electronic converters[28].

We identified a moderate level of research in demand side response, covering both commercial and domestic approaches. While DSR is commonly used at higher voltage levels, commercial approaches are less common at low voltage level because demand from individual customers is lower so more customers would need to be recruited to produce any significant effect. WPD has conducted a series of projects on DSR, however most are focused on 11kV and 132kV networks[29]. At a residential level LV Connect and Manage investigates how domestic load controllers (DLCs) can be used to modulate demand and generation at individual properties, including EV charging, PV generation, and electrical storage. Progress was made with regards to monitoring power flows associated with low carbon loads, however, barriers exist in terms of legislation and policy required to deploy such technology on a wide scale.

LV DC networks have also seen some research interest, however, the low technology readiness level of this solution has meant that innovation projects are limited in number. A study conducted by SPEN notes that LV DC systems may be more reliable than LV AC networks but not necessarily have greater capacity. This solution could be particularly useful for application in rural areas where security of supply is an issue[30]. It is further noted that losses from reactive power and AC-DC conversion could be eliminated. However, this work is still at a preliminary stage, with no large-scale trials identified in this review. Research is ongoing[31], however, and it is expected that this technology may be of greater relevance for long-term energy system transitions. An active WPD innovation project is currently investigating the potential of smart transformers that can deliver LVDC supply, whilst still maintaining utilisation of the existing AC network[32].

Similarly, microgrids have seen little research from DNOs, however there exists a substantial body of literature from international organisations such as NREL[33]. Some research has been conducted into costings of microgrids, which has been found to be less than that of conventional reinforcement, when factors such as reliability are considered[34]. However, this solution represents a major change to the network structure and is unlikely to be considered a low-regrets, low-cost option for deferring reinforcement. Deployment locations are very specific, however certain use cases have been successful, such as in remote rural areas, campuses, and small communities.

[28] WPD, *LV Plus (2018).*
[29] These include *FALCON (2015), Solar Yield Network Constraint (SYNC) (2018), and Entire (2019).*
[30] SPEN, *Transition to low voltage DC distribution networks – Phase 1 (2017).*
[31] SPEN, *Transition to low voltage DC distribution networks – Phase 2 (ongoing).*
[32] SPEN, *LV Engine.*
[33] e.g., *A comparative study of DC and AC microgrids in commercial buildings across different climates and operating profiles (2015), Microgrid Controllers: Expanding Their Role and Evaluating Their Performance (2017).*
[34] Parag, Y., *Sustainable microgrids: Economic, environmental, and social costs and benefits of microgrid deployment (2019).*

Dynamic time-of-use tariffs were found to have received some level of research within innovation projects[35] including studies regarding smart EV charging[36] and energy storage[37]. However, most of the research on this solution that was identified in this review was from international sources[38]. DNO research may be limited due to risks surrounding how dynamic price signals impact on customers who are less able to make changes to their energy usage patterns. Hence, difficulties exist in designing a pricing system that is fair for all customers. Altering consumer energy usage behaviour has been described as “less a technical challenge and more a matter of understanding and responding to sociocultural practices”[39]. It has been suggested that, in parallel to this approach, steps should be taken which provide tools for consumers to shift their usage patterns more easily.

In our review of literature regarding widening of the design voltage tolerance, we noted a greater level of research interest in recent years from DNOs[40]. These studies acknowledge that current tolerances were designed for an energy system in which appliances only worked within a certain voltage range, and modern appliances may be able to function with a more variable power supply. Studies point to wider voltage limits abroad, most notably in the EU[41], and highlight that appliances are now designed to operate in multiple countries. As a result, widening of design tolerances in the UK may have negligible impact on customers, and facilitate LCT growth while deferring or eliminating the requirement to reinforce the network[42]. Government studies have also placed focus on this solution, with an independent review recommending that standards be changed[43], however, in a response to this study[44] it was stated that further work is still required before implementation is possible. Specifically, work is required to evaluate the impact on distribution network losses and total distribution network power carrying capacity.

Limited Research Interest

Solutions which have seen less research interest include switched capacitors, generator constraint management, Distributed Flexible AC Transmission System (D-FACTS), generator providing network support, and enhanced automatic voltage control (EAVC). Switched capacitors have been researched as part of Electricity North West studies on dynamic voltage management and were found to release significant headroom. Various uses exist for switched

[35] e.g., UKPN, *Low Carbon London (2014).*
[36] UKPN, *Shift (2021)*.
[37] BEIS, *Cost Optimal Domestic Electrification (2021).*
[38] e.g., Ozaki, R., *Follow the price signal: People’s willingness to shift household practices in a dynamic time-of-use tariff trial in the United Kingdom (2018),* Yang, L., *Electricity time-of-use tariff with consumer behaviour consideration (2013).*
[39] Bell, S., et al, *Sociality and electricity in the United Kingdom: The influence of household dynamics on everyday consumption (2015)*
[40] Electricity North West, *Changing Standards (Statutory Voltage Limits) (2015)*, ENA and EA Technology, *Increased Voltage Range: Effects on Domestic Appliances (CEP025) (ongoing).*
[41] WPD, *LV Network Templates for a Low Carbon Future (2013).*
[42] This relates to changes in design tolerances rather than operational timescales to increase capacity. Allowing systems to be designed with a larger voltage tolerance will enable LCT growth before reinforcements are implemented.
[43] BEIS, *Electricity Engineering Standards Review (2020).*
[44] BEIS, *Independent Review of Electrical Engineering Standards: government response (2021).*

capacitors and imaginary impedance elements on LV networks, including reactive power control as well as voltage management[45]. Generator constraint management (GCM) is examined on a residential scale in LV Connect and Manage where solar PV output was controlled at an individual customer level. GCM is largely a transmission technology, but applications on the LV network have been studied, with most focus being placed on solar photovoltaics[46]. As a key form of distributed generation projected to grow significantly in the transition to net zero, management of photovoltaics requires consideration but does not necessarily increase capacity for new load. We identified research focused on EAVC within the CLNR project which investigates how automatic voltage control can be implemented closer to customers (sometimes at individual residences or business premises), such that power quality and voltage can be more precisely managed. Similar to dynamic voltage management, on-load tap changers were deployed in EAVC trials, as well as shunt capacitor banks. D-FACTS is a class of power electronic devices for impedance line matching to control reactive power flow to increase capacity and there has been some studies identified in international sources[47], however research interest on this solution appears to be lower today than in previous years. This literature notes that D-FACTS must be deployed alongside effective control and modulation technologies which give consideration of the timing of commands sent to devices installed on the network[48]. System stability is a risk if multiple commands are transmitted to devices across the network in short space of time, however, when control methods are well coordinated, system stability has the potential to see improvement. A number of transformer cooling methods have been investigated through the Celsius project, which examines how transformer temperatures may be reduced to increase thermal headroom. Results varied depending on specific cooling types, with active cooling systems releasing the highest level of spare capacity.

The list of solutions which were identified in this literature review are given below in Table 2. Table 2, which shows all variations that exist for each solution type. In the next section we briefly examine the characteristics of each solution and the various implementation alternatives that exist for each technology.

---

[45] In this literature review we primarily focus on the voltage management capabilities of this technology since reactive power compensation has limited potential for extending headroom on LV networks. The efficacy of this approach on GB LV cable networks is poor as the reactance is low with voltage change 5-10 times more effective through real power control at the critical time (unless there is an unexpected shift in load power factor).
[46] Northern Powergrid, *Distributed Storage & Solar Study (2020)*, WPD, *Solar Storage (2019).*
[47] Rogers, K. M., Overbye, T. J., *Some applications of Distributed Flexible AC Transmission System (D-FACTS) devices in power systems (2008)*
[48] Rogers, K. M., Overbye, T. J., *Some applications of Distributed Flexible AC Transmission System (D-FACTS) devices in power systems (2008).*

Table 2: Solutions identified in the literature review with potential to expand LV network headroom.

ID	Solution	Implementation Alternatives	Description
1	**Phase Balancing**	Manual	Involves manually changing which loads are connected to phases of a 3-phase supply to release headroom on overutilised phases.
2	**Phase Balancing**	Dynamic	Redistributing loads in real time through the use of devices such as phase shift converters typically located at substations
3	**Phase Balancing**	Connection to 3-phase supply	Connection of customers to all three phases of LV supply rather than just one phase.
4	**Dynamic Voltage Management**	On-load tap changers (OLTC)	Regulates the turns ratio (and voltage ratio) of a transformer without interrupting current flow.
5	**Dynamic Voltage Management**	Power electronics	Regulates the voltage ratio directly through the use of power electronic converters.
6	**Dynamic Asset Ratings**	N/A	Dynamic asset rating involves changing the rating (and hence current carrying capacity) of network assets based upon real-time environmental conditions.
7	**Widening of Design Voltage Tolerance**	N/A	Widening the voltage tolerance involves extending the current limits on voltages in the UK (230V +10% - 6%) so that a higher penetration of LCTs and DG can be accommodated.
8	**Smart Transformers**	N/A	Smart transformers are solid state devices coupled with a control system that are able to provide a range of LV functionalities such as redistribution of power flows across assets, power factor management, and DC power supply.
9	**LV DC Networks**	N/A	LV DC networks refer to the conversion of LV networks from alternating current to direct current.
10	**Microgrids**	N/A	A microgrid is a system of loads, storage and generation that can operate either as part of the grid or independently.

ID	Solution	Implementation Alternatives	Description
11	**D-FACTS**	N/A	D-FACTS stands for Distributed Flexible AC Transmission system and involves the use of the power electronics to increase the power transfer capability of the network through reactive power compensation.
12	**Network Monitoring**	Network data	Taking measurements at different points of the LV grid (e.g., substations, feeders) to gain understanding of power flow and headroom characteristics.
13	**Network Monitoring**	Customer data	Use of data directly from customers, typically using smart meters to build knowledge of LV characteristics and inform investment decisions.
14	**Smart EV Charging**	N/A	Charging can be shifted to periods of low overall network demand meaning that consumers are able to benefit from lower prices, and networks are able to flatten high demand peaks.
15	**Dynamic Time-of-Use Tariffs**	N/A	Dynamic ToU tariffs can be used to incentivise or disincentivise energy use at given times, such that demand profiles on the LV network can be flattened.
16	**Energy Storage**	Grid-scale	Storage of energy at a substation that can be used by DNOs to respond to changes in distributed generation and demand peaks.
17	**Energy Storage**	Behind-the-meter	Domestic small-scale storage that can be used to respond to changes in distributed generation and demand peaks (specifically, demand associated with heat pumps).
18	**Enhanced Automatic Voltage Control**	N/A	Involves implementing automatic voltage control close to customers (often at residences/premises) to improve power quality.
19	**Switched Capacitors**	N/A	Mechanically switched devices that may be used on low voltage networks to regulate voltage changes brought about by LCTs and DGs. They also have limited use for reactive power compensation and impedance matching.

ID	Solution	Implementation Alternatives	Description
20	**Generator Constraint Management**	N/A	Generator constraint management involves developing commercial contracts with generation customers, such that they reduce their export to the grid at certain times (usually low demand).
21	**Generator Providing Network Support**	Generator	Support can be provided to the LV network through connection of a three-phase generator operating in PV mode (real power and voltage) rather than PQ mode (real power and reactive power).
22	**Generator Providing Network Support**	Power electronics	Regulation of real power and voltage through the use of power electronics (rather than regulation of real and reactive power).
23	**DSR**	Commercial	Demand side response involves making arrangements with energy users to shift, reduce or increase their consumption at a given time.
24	**DSR**	Residential	Making arrangements with residential customers to turn generation or demand up or down at a given time to alleviate network constraints.
25	**Meshing**	Temporary	Through the use of meshing, customers can be supplied through more than one different pathway, therefore enabling demand to be shared across transformers and networks assets.
26	**Meshing**	Permanent	Fixed installation of a meshed LV grid, which constantly shares load across assets and cannot be operated in a traditional radial format.
27	**Meshing**	Conversion of spurs to rings	Converting LV radial networks to ringed networks allows facilitates power supply through more than one route for improved reliability.
28	**Transformer Cooling**	Active	Systems which cool transformers through active removal of heat energy. These typically draw on their own power source.
29	**Transformer Cooling**	Passive	Systems which remove heat energy from transformers without drawing power or using energy in themselves (e.g., shading of substations).

Longlisting of Solutions

The solutions identified in the literature were subsequently compiled into a longlist and assessed based upon a number of criteria. These included thermal and voltage headroom release, unit cost, and applicability. Consideration was also given to technology readiness level in order to ensure that the range of solutions identified covered short-, medium- and long-term options. Consequently, the longlist includes some solutions that are ready to deploy immediately (such as temporary meshing), and others that are at the basic research stage and are not likely to be rolled out in the near future (e.g., LV DC networks). Cross-network impacts are explored where relevant, examining potential for LV solutions to bring benefits to higher voltage networks. In general, load reduction at LV to manage an LV constraint will lower loading on the feeding HV networks, however negative impacts at HV can be seen in rare cases. The longlist covers a number of network-side solutions which apply technical approaches to expanding headroom, as well as customer-side solutions which place more focus on implementing strategies that change how customers use electricity. Policy-based solutions were also identified and included in the list, which would alter the regulations and standards governing the design and operation of LV networks (e.g. statutory voltage limits). The longlist of solutions is presented below which clarifies which implementation alternative of each solution is taken forwards, and a brief description of each approach is given in the following section.

- **Phase Balancing (manual)**
- **Dynamic Voltage Management**
- **Dynamic Asset Ratings/Real Time Thermal Ratings**
- **Widening of Design Voltage Tolerance**
- **Smart Transformers**
- **LV DC Networks**
- **Microgrids**
- **D-FACTS**
- **Network Monitoring (LV assets)**
- **Smart EV Charging**
- **Dynamic Time-of-Use Tariffs**
- **Energy Storage (for smart HP demand shifting)**
- **Enhanced Automatic Voltage Control**
- **Switched Capacitors**
- **Generator Constraint Management**
- **Generator Providing Network Support, e.g., PV Mode**
- **DSR (residential and commercial)**
- **Meshing (temporary and permanent)**
- **Transformer Cooling (Active)**

Network-Side Solutions

Phase Balancing

Connection of low carbon technologies can cause unbalancing of three phase feeders since loads on the LV network are often connected to a single phase and are not always predictable. Often this leads one phase to approach its maximum thermal capacity while the other two phases are underutilised. Redistributing loads across the feeders so that each phase is equally utilised can therefore release spare capacity and defer reinforcement. Rebalancing is typically a permanent change, however, network monitoring can help to identify where intervention is most needed[49].

Connection of residential customers to three-phase supplies has been considered alongside research into phase balancing, in order to accommodate higher individual customer demands from electric vehicles and heat pumps. Connection to three phase supplies has synergies with phase balancing since it has a secondary effect of reducing load imbalance and makes manual rebalancing for single phase supplied customers straightforward though at the risk of additional complexities with fault location and fault level management[50]. While DNOs are able to estimate expenses incurred for an individual customer connection, the overall cost and headroom release of deploying this strategy network wide is as yet unclear[51]. However, initial consultations conducted by WPD estimate installing three phase supplies for new builds or rebuilding work can be a cost-effective approach[52].

Rebalancing may also be implemented dynamically through the use of power electronics at substations. Power is redistributed between phases, which can be shifted in order to avoid voltage increases and to maintain power quality. However, this can have a significant impact on customers connected with 3-phase machinery and therefore requires careful consideration before implementation. An additional challenge is that phase imbalance can affect parts of the network not routinely monitored such as the middle and ends of feeders where installation of monitoring and power electronic devices is more difficult.

Dynamic Voltage Management

Additional demand on the network caused by low carbon technologies can cause a drop in voltage, while additional distributed generation e.g., photovoltaics, can lead to voltages exceeding threshold levels. Existing low voltage network infrastructure may not be capable of accepting these larger fluctuations in voltage, and therefore reinforcement may be needed if voltages are not managed. Dynamic voltage management aims to circumvent this

---

[49] Substation monitoring can identify high and low loaded phases allowing non-technical solutions such as 3 phase services for new loads (requires registering) or nominated phases (from monitoring) for customers with home charging and heat pump demands. Only badly affected networks with low Available Capacity Per Customer need be targeted.
[50] It is possible that provision of extra capacity can invite further demand growth however, this is not the case if properly managed. Connection of three phase supplies is assumed to only be implemented where necessary.
[51] In addition to changing supplies to three-phase, reduction in the number of looped supplies may provide further scope for phase balance. Looped supplies may inhibit connection of EVs and heat pumps and, consequently, DNOs plan to address this issue within the RIIO-ED2 period.
[52] WPD, *Superfast Electricity Consultation (2020), Electric Vehicle Strategy (2020)*

reinforcement by controlling voltages on the low voltage network to keep them within an acceptable range. This is typically achieved through the use of technologies such as on load tap changers and automatic control mechanisms with a growing use of power electronic based solutions. The implementation of dynamic voltage management needs to be coordinated to ensure it is not in conflict with an Electricity System Operator (ESO) based voltage reduction instruction (Grid Code OC6)[53].

Dynamic Asset Ratings/Real Time Thermal Ratings (RTTR)

Dynamic asset rating involves adapting the rating (and hence current carrying capacity) of network assets based upon real-time environmental conditions. Often it is possible to run an asset at a level higher than its specified rating due to environmental factors such as cold temperatures, for example. This technique can be applied to both transformers and feeders.

LV DC Networks

Converting LV networks from AC to DC removes the losses associated with skin effect[54] and AC/DC conversion. The use of DC circuits effectively reduces the resistance of a circuit for the same current carrying capacity. Additionally, the majority of new electrical loads operate on DC (such as electric vehicles and street lights) and are supplied via AC/DC converters. This in turn reduces the level of power that needs to be supplied (since the system is more efficient) and releases headroom. However, this is only possible where the DC voltage is standardised to avoid the introduction of DC/DC conversion and at sufficiently high voltages to avoid increasing DC losses. Switching to DC networks can also alleviate problems that arise from reactive power in LV circuits, since imaginary impedances from inductive loads are removed, however, power transfer is still dependent on matching of the real elements of load and supply impedances. While benefits are seen in reduced losses, infrastructure change as well as the potential replacement of appliances which use AC/DC converters are barriers to this solution. Cross-network benefits may include a lower demand at certain super grid transformer supply points[55].

Smart Transformers

Smart transformers consist of a solid-state transformer (SST) coupled with a control system that makes use of power electronics to deliver a range of functionalities that are not possible using traditional distribution transformers. For example, smart transformers may be able to recognise where demand can be shared between multiple substations[56]. It has been proposed

---

[53] Where this loading is helping manage network voltage where HV distributed generation is driving it up is one (albeit rare) event where the benefits are not connected. Lowering the voltage reduces the 'lever' available to National Grid in using the OC6 Voltage reduction instructions to reduce load. However, not all load occurs at peak times on LV networks, and we believe that in these circumstances, transition below the lower statutory limits for some customers is seen as a risk worth taking.
[54] The exact losses are dependent on frequency of AC current, resistivity of conductors, and the skin depth relative to the diameter of the cabling used. Losses can be approximated by comparing the cross-sectional area of UK cabling with the area associated with the skin depth.
[55] EA Technology for Ofgem, *Solutions Annex - Assessing the impact of low carbon technologies on Great Britain's power distribution networks (2012).*
[56] SPEN, *LV Engine (ongoing),*

that power electronics can be used to reallocate power flows to for maximization of network headroom. Provision of LVDC supply can also be incorporated into this design, as can phase balancing and voltage regulation. These approaches are also included in this longlist, however their implementation through smart transformers is regarded as a distinct solution. The cost of this solution is assumed to be high due to its low technology readiness level and the wide range of technologies that it incorporates. However, costs of this solution have been estimated to be lower than implementing smart transformer technologies separately on the network[57]. Literature identified in this study has not shown any potential for retrofitting, and it is unlikely that this is possible given that the transformer design is significantly different to traditional distribution transformers.

Microgrids

A microgrid is a system of loads, storage and generation that can operate either as part of the grid or independently. Microgrids typically operate over localised areas such as hospitals, campuses, or small communities. The ability to disconnect from the grid and operate in ‘island mode’ is seen as a key advantage of this solution since it is able to increase reliability, which is of particular use in rural areas with poor electricity security[58]. Microgrids also have the potential to balance generation and demand more efficiently, aided by integration of storage. Furthermore, novel commercial arrangements can be made possible with this system, such as involvement of local energy supply and peer-to-peer trading.

Microgrids can face a number of barriers to implementation, such as bidirectional power flows, due to the complex connection of loads and generation within the system. Interactions between energy resources can be unpredictable, leading to oscillations and power quality issues. Renewable generation in a microgrid is very dependent on local weather conditions and system inertia can present further issues with potential impacts on frequency control. From a regulatory perspective, microgrids face challenges including consumers' right to change energy provider and the fairness of how public network infrastructure charges are distributed between remaining customers. In island mode, cross network benefits are seen at HV since less power is required from centralised generation. When grid-connected, microgrids may also release headroom through the smart managements of assets and the greater degree of flexibility that they offer.

D-FACTS

D-FACTS stands for Distributed Flexible AC Transmission system and involves the use of the power electronics to increase the power transfer capability of the network through reactive power compensation. Examples of devices used to achieve this are static synchronous compensators (STATCOMs), static VAR compensators (SVCs), and static synchronous series

---

[57] Mishra et al., *A review on solid-state transformer: A breakthrough technology for future smart distribution grids (2021).*

[58] When grid connected, microgrids do still differ from other parts of the network since they possess higher levels of distributed generation, integrated storage and options for flexibility which can facilitate smarter management of the LV network and a higher penetration of LCTs. When in island mode, upstream networks see a lower demand which is also able to release headroom.

compensators (SSSRs). Typically, such devices are deployed on transmission lines where reactive power compensation has greater impact, rather than at distribution level.

Network Monitoring and Modelling

This technique involves taking measurements and gathering information about the LV grid to gain a better understanding of its characteristics. Better visibility and knowledge of the LV network can help DNOs to make choices about how to make upgrades and improvements, as well as potentially enabling a higher degree of control and more effective use of flexibility. Furthermore, monitoring and modelling techniques can provide better information regarding available LV network headroom, facilitating more efficient utilisation of assets. Customer monitoring was not included within the scope of this solution, but we do acknowledge that this may provide further network visibility and opportunity for headroom release[59]. The solution taken forward focuses on monitoring of quantities such as voltage and current on feeders and at substations.

Enhanced Automatic Voltage Control

EAVC involves extending automatic control to lower voltage areas of the network to improve the power quality seen by domestic and commercial customers. Where previous automatic voltage control has operated on the grid and at primary transformers, EAVC sees further control devices installed at individual customers' premises or businesses. EAVC is particularly useful for customers located either very close to a distribution substation (where they may see a high voltage), or those very far from a distribution substation (where they may see a low voltage). Cross network benefits are seen in that HV networks have the potential to operate outside of their statutory limits, since voltages are corrected at the point of customer connection[60].

Switched Capacitors

Switched capacitors may be used on LV circuits to manage voltage changes brought about by connection of LCTs and distributed generation. They consist of mechanically switched devices which can be introduced to LV circuits to stabilize networks under heavy load conditions. The established nature of the technology results in low cost compared to power electronic solutions such as D-FACTS. Switched capacitors may also act as a form of reactive power compensation where power transfer can be increased by providing an imaginary impedance which matches that of the supply impedance[61]. However, the effect of this approach is variable depending on the level of resistive load on the network with limited benefit seen on LV cable networks. Consequently, in this study, we primarily focus on the voltage management application of switched capacitors.

---

[59] This study considers monitoring at an LV asset level rather than through the use of smart meters, which has already seen considerable deployment and research.

[60] EA Technology for Ofgem, *Solutions Annex - Assessing the impact of low carbon technologies on Great Britain's power distribution networks (2012).*

[61] Switched capacitors address the imaginary element of impedance matching, however, real impedance elements are not addressed through this solution.

Transformer Cooling

Transformer cooling can be used to increase thermal headroom at low network substations. Various methods may be used for cooling, including using positive pressure systems to expel hot air from indoor transformers, applying solar reflective paint to outdoor transformers, and shading transformers with a covering structure[62]. All of these approaches reduce the temperature of assets and increase their current carrying capacity.

Meshing

Through the use of power electronic devices such as soft open points, customers can be supplied through more than one network pathway, therefore enabling demand to be shared across transformers and networks assets. Where the LV network is highly loaded, meshing enables power flows to be distributed to underutilised assets, thereby releasing spare capacity whilst meeting the same level of demand. It is also possible to permanently convert of networks from radial to meshed, such that loads are shared across assets[63] which can release a similar level of headroom. Power flows are distributed more equitably across assets, which relieves over-utilised substations and feeders.

Generator Providing Network Support

Support can be provided to the LV network through connection of a three-phase generator operating in PV mode (real power and voltage) rather than PQ mode (real power and reactive power). Real power is typically regulated at all times, however, generators can also regulate either voltage or reactive power. Therefore, in order to maintain a more stable voltage level (and increase voltage headroom) generators may draw reactive power from the LV network[64].

Customer-Side Solutions

During recent years, DNOs have looked to make use of customer-side solutions to manage their networks. These services are tendered by the DNO and responded to by demand side aggregators who in turn recruit LV customers with the appropriate technology (smart chargers, energy storage, etc.) to take part. The DNO (acting in this instance as a DSO) pays the aggregator for services made available / utilised and the aggregator pays the customer. The following sections provide further details on each of the common customer-side solutions.

Smart EV Charging

As electric vehicle penetration increases, flexible management of charging will become increasingly relevant to manage network demand and defer reinforcement. Charging of electric

[62] Active refrigeration was not considered in this literature review since it is likely that this would not be a cost-effective solution in comparison to the options described here.
[63] Conversion of LV spurs to rings is also possible and allows for greater reliability in the case of fault, however, this method does not typically extend capacity or release headroom.
[64] It is also possible regulate real power and voltage through the use of power electronics (rather than regulation of real and reactive power).

vehicles can be more flexible relative to other loads and as such has the potential to shift demand to flatten high network peaks. Charging times can also be matched more closely to peak supply such that EVs can make use of excess generation. There is some synergy between smart EV charging and dynamic time-of-use tariffs (see below), as consumers may be encouraged to shift the time of their charging by price signals, such that they are able to benefit from lower prices when charging at times more beneficial for the network. This method has advantages in that it still allows customers choice of when they can use electricity, although can present issues to consumers who are less able to change their usage patterns. At present, suppliers provide Time-of-Use tariffs based on wholesale market prices and do not take into consideration local DNO constraints[65]. More direct control techniques have been investigated in which customers are asked to participate in schemes that place limits on their ability to charge their vehicles. Vehicle to grid services may also be developed such that EVs effectively act as storage which can be leveraged at times of peak demand to manage LV constraints.

Power factor manipulation of EV loads is not considered here, since electric vehicles are expected to introduce electricity demand with power factor close to unity. Power factor on LV networks is already high during peak demand, so power factor manipulation is unlikely to provide much benefit. However, it is anticipated that there is potential for capacity release during non-peak times if EV demand is shifted into those periods.

Finally, at present many customers may choose to charge their vehicles outside of peak electricity demand times even without network interventions. As a result, initiation of demand shifting strategies may have less of an impact than is predicted by models which assume that most customers charge their vehicles at peak times. However, as electric vehicles are rapidly adopted (see Appendix 1), smart management of charging will become increasingly relevant. High network demands may be seen outside of typical peak times, which will require co-ordinated management in order to minimise network loading.

Energy Storage (for demand shifting heat pumps)

Energy storage may be deployed behind-the-meter at domestic or commercial premises, or at grid-scale for the management of LCT demand and distributed generation. In this study we examine energy storage with the specific aim of enabling heat pumps through the use of time-of-use tariffs. Heat pumps are one of the key low carbon technologies expected to contribute to higher peak demands on the LV network, as shown by the demand profile analysis (Appendix 1). This can be particularly problematic for LV networks due to the difficulty of shifting demand; heating demand is highly dependent on external conditions (i.e. temperature). Using storage, heat pumps can avoid drawing electricity from the grid during times of peak demand, hence reducing grid congestion and alleviating network loading. Therefore, heat pumps still draw power when required, however, network impacts are significantly reduced. Additionally, battery storage may be leveraged for absorbing generation and may find applications alongside technologies such as rooftop PV. Energy from solar panels can be stored during the day when

[65] Business drivers for ToU tariffs can be split between two key factors: capacity efficiency (smoothing peak demand over a 24-hour period) and response to renewable generation (e.g., wind). Both have relevance to the LV network since both generation and peak demand can place a strain on assets.

LV network demand is low and released in the evenings when heat pump demand may increase.

Energy storage is most likely to be implemented either thermally or electrically, with thermal storage providing the most cost-effective option in most cases (dependent on context of use)[66]. However, the demand shifting potential of electrical storage can be much higher since it is able to shift any type of electrical demand as well as heat pumps. Batteries may have the potential to shift approximately three times as much electricity at peak times, thereby offering greater capability to respond to network constraints and higher savings to consumers[67]. Moreover, costs for battery storage have reduced substantially over the past decade, and are forecast to fall further by 2030, indicating that this may represent a stronger option for demand shifting of heat pumps[68].

Time of use tariffs may be viewed as an enabler for this solution, since dynamic pricing can be used to influence when customers choose to store or consume energy from storage, and when they choose to draw energy from the grid[69]. Lower prices may incentivise drawing energy from the grid either to use directly or to store, while higher prices would be expected to result in consumers drawing from energy storage. Therefore, setting high prices during peak demand periods may relieve network loading as more customers decide to draw power from storage rather than the grid. However, as with smart EV charging, ToU tariffs are currently set by suppliers and do not typically reflect DNO constraints.

Generator Constraint Management

Generator constraint management involves developing commercial contracts with generation customers, such that they reduce their export to the grid at certain times (usually low demand times). Customers include commercial buildings such as supermarkets, and do not typically include residential properties. Signalling to generators to reduce grid exports can be designed so that it is automatic. Generator constraint management does not actively create headroom, however, and is therefore unlikely to be a key solution for deferral of LV reinforcement.

Demand Side Response

Demand side response involves making arrangements with energy users to shift, reduce or increase their consumption at a given time. We define this solution as distinct from time-of-use tariffs, placing focus on more direct forms of demand response such as direct load control or contracting flexibility that can be called upon when required. While this does still make use of economic incentives i.e. payments to commercial and business customers for the flexibility

---

[66] BEIS, *Cost Optimal Domestic Electrification (CODE), (2021)*. Thermal storage has been estimated at £500/kWh compared with £700-800/kWh in the case of battery storage. This is calculated by considering the total unit cost, and the potential duration and power of flexibility services (kW) offered to the grid.
[67] BEIS, *Cost Optimal Domestic Electrification (CODE), (2021)*. An 8kWh battery may be able to offer 7.5kWh of flexibility per day. Conversely, a 300-litre thermal store is estimated to be capable of providing 2.5kWh of flexibility per day, however this varies depending on the weather. On a colder day the demand shifting potential is higher because heat pumps operate less efficiently and therefore draw a higher power.
[68] Bloomberg, *A Behind the Scenes Take on Lithium-ion Battery Prices (2019), Why an Electric Car Battery Is So Expensive, For Now, (2021)*.
[69] NPg, *Customer-Led Network Revolution, (2015).*

they provide, we examine this solution separately to price signalling methods. Use of commercial DSR can help to flatten network peaks, increasing network headroom by reducing loading when the network experiences high levels of demand.

At a residential level, DSR might include use of smart architecture installed in customers' homes that is able to control load profiles, local storage, and LCT demand and generation. Through this approach, the loads and generation projected to necessitate network reinforcement are directly controlled in a highly localised manner, allowing networks to be controlled very precisely.

Research has also examined the potential for DSR-based approaches to smart heat pumps, where the level of demand from heat pumps is moderated during times of high network loading[70]. The primary issue with this approach is the fixed nature of heating demand, that is, dependence on ambient temperatures mean that it cannot be fully shifted to another time of day without significantly impacting consumers. Nonetheless, even small changes in heat pump usage can be significant, since the total demand from heat pumps is expected grow to markedly in future. Applications of heat pump flexibility have been found to vary considerably between locations and building stock types, since this impacts on how long heat pumps may be switched off before room temperatures drop below the comfort limit[71].

Policy-based Solutions

Widening of Design Voltage Tolerance

Current voltage limits in the UK are 230V +10%/- 6%, however, connection of LCTs on the LV network has the potential to cause these limits to be exceeded more frequently. During the planning phase additional demand from technologies such as electric vehicles and heat pumps can show significant voltage drops, while distributed generation has the reverse effect, pushing voltages above upper limits. However, if these limits can be extended, then it may be possible to accommodate higher levels of LCTs on the LV network since voltage drops and peaks will still remain inside tolerance levels. It has been proposed to reduce to lower limit to -10% as in EU states[72], as well as increasing the upper limit higher than 10% to increase tolerance to peaks. Modern appliances are designed to operate across a much wider range of power supplies[73] from different energy systems and may see little impact from wider tolerance limits. However, older appliances still in service will be particularly impacted and risks significant disruption to the quality of service.

This approach does present some challenges, the widening of design voltage tolerances would enable the increased LCT uptake but consistently operating the system towards a lower voltage tolerance would erode any headroom for emergency voltage reductions[74]. However,

[70] Fischer, D., Madani, H., *On heat pumps in smart grids: A review (2017).*
[71] BEIS, *Heat Pumps in Smart Grids, (2018)*.
[72] BEIS, Electricity Engineering Standards Review (2020), *Independent Review of Electrical Engineering Standards: government response (2021).*
[73] Modern power electronic devices typically accepting voltage inputs of 230V +15%/-20%.
[74] National Grid ESO Demand Reduction Instruction OC6

the growing use of power electronic devices supplying fixed power loads is eroding this potential and requires alternative approaches to be considered.

Shortlisting of Solutions

The longlist of solutions was subsequently shortlisted using a ranking method based upon a number of assessment criteria which are shown in Table 3. At this stage, assessment of solutions against each criterion was largely qualitative. For each criterion, solutions were categorised into tiers ranging from ‘Very Low’ to ‘Very High’. These tiers were defined based upon an initial assessment of the literature and refined as data from studies was extracted. Information from the literature was used to develop an understanding of how each solution performed against each criterion, and ultimately to decide which tiers they should be placed in. Where possible, quantitative data was used to make this assessment, however, qualitative data was equally useful in building up a picture of how solutions operated in order to categorise them.

Table 3: Criteria key for the ranking of options.

Score	Cost	Headroom Release	Applicability	TRL
1	Very High: >£100k	Very Low: <5%	Very Low: Very few locations, very large risks/barriers, minimal utilisation	Very Low: 1 - Basic technology research
2	High: £50k-100k	Low: 5-15%	Low: Minority of network locations, large risks/barriers, uneven utilisation	Low: 2-3 - Research to prove feasibility
3	Medium: £25k-50k	Medium: 15-30%	Medium: Some network locations, significant risks/barriers, moderate utilisation	Medium: 4-5 - Technology Development
4	Low: £10k-25k	High: 30-50%	High: Majority of network locations, marginal risks/barriers, almost continuous utilisation	High: 6-7 - Technology Demonstration
5	Very Low: <£10k	Very High: >50%	Very High: all network locations, minimal risks/barriers, widespread/continuous utilisation	Very High: 8-9 - System Test, Launch & Operations
1	Unknown	Unknown	Unknown	Unknown

For cost, the 'Very High' tier includes solutions with a unit cost (where a unit is a quantity appropriate to that option with cost normalised to feeder level) greater than approximately £100k (greater than £100k assumed for the counterfactual), while the 'Very Low' tier includes all solutions costing less than £10k. For the headroom criterion, 'Very Low' included any solution that was estimated to release less than 5% headroom, while the 'Very High' criterion included solutions estimated to release greater than 50% headroom. The applicability criterion was based on location (overhead, underground, substations etc.), and different characteristics of the listed solutions. As a result, applicability includes consideration of the risks and barrier associated with each solution. Risks and barriers might include legislative or regulatory issues, impacts on customer lifestyle, susceptibility to technical issues, and communication problems. Finally, technology readiness level uses the standard 1-9 scale, with 9 indicating the solution is at a 'system test, launch, and operations' phase, and 1 indicating 'basic technology research'. Since we aimed to find solutions across a range of technology readiness levels, this was defined for each solution but not used to rank the solutions. Technology readiness level was also used as a means of accounting for changes over time. Most solutions are expected to improve in how they score against the assessment criteria, as the technologies becomes more efficient and less expensive. Where solutions are score poorly against the criteria, TRL was used as a check to ensure that solutions were not disregarded if they have potential to improve with regards to performance and cost.

Categorisation in this manner was found to be an effective means of evaluating solutions, however quantification at this stage was found to have limitations. For example, in most cases a unit cost could be derived from innovation project budgets or drawn directly from information within the studies. Where costs covered installation of a number of units across multiple locations, approximations were made by finding cost per installation. In general, we present the cost incurred in relation to the scale at which the solution is deployed, however, where possible we have taken steps to assess solution costs on an even platform. This process was relatively simple for network-side solutions (such as dynamic voltage management, for example) since they typically release a specific amount of capacity at a specific location. However, assessments were more challenging for customer-side and policy-based strategies that might span across a wide area and be highly variable in the level of capacity they can release. For example, widening the voltage tolerance or implementing dynamic time-of-use tariffs are applied over much larger areas, and may have wide ranging effects depending on the context of use. Testing is less feasible at a small scale and using data from other locations (such as investigating previous deployment in overseas networks) is less reliable since the structure and operation of energy systems can vary considerably between different countries and regions. Similarly, quantifying large-scale solutions such as microgrids with the same criteria as modest interventions such as switched capacitors did present challenges. As a result, a qualitive element to the process was essential, allowing the various different characteristics of each solution to be properly captured.

In order to produce a merit order of solutions, a score ranging between 1 and 5 was attributed to each criterion tier, as shown in Table 3 and Table 4. Higher scores were associated with lower costs, higher headroom release, and higher applicability. For example, a 'Very Low' cost scores 5, while 'Very Low' headroom release scores 1, as does 'Very Low' applicability. For each solution the cost, headroom, and applicability scores were multiplied to produce an overall ranking. Headroom release is also broadly distinguished between voltage (V), thermal (T), or both (B). Following this ranking, we examined the solutions which came out with the highest scores, as well as those which fell further down the merit order. Table 4 shows that many solutions came out with the same or similar scores. Consequently, the rank order acted as a useful tool for a first approximation of solutions to take forward, after which each technology option was further inspected to build up a final version of the shortlist. For each solution we re-examined the literature to check that the scoring was appropriate and considered other factors that were not captured by the ranking exercise. We aimed to capture a range of network-side, customer-side, and policy-based solutions, as well as variation in technology readiness level.

Table 4: Solution ranking matrix used to generate the shortlist. V/T/B indicates whether headroom release is primarily voltage, thermal or both.

ID	Category	Solution	Cost Score	Headroom Score	Applicability Score	TRL	Total Score
1	Network-side	Transformer cooling	5	3	4	High	60
2	Network-side	Dynamic Voltage Management	3	5	4	Very High	60
3	Network-side	Meshing - Temporary and Permanent	4	5	3	Very High	60
4	Network-side	Meshing - Permanent	4	5	3	Very High	60
5	Network-side	Network Monitoring	5	2	5	Very High	50
6	Policy-based	Widening of Voltage Tolerance	5	2	5	Medium	50
7	Network-side	Switched Capacitors	4	3	4	High	48
8	Customer-side	Smart EV Charging	4	3	3	Very High	36
9	Customer-side	Dynamic Time of Use Tariffs	4	3	3	High	36

ID	Category	Solution	Cost Score	Headroom Score	Applicability Score	TRL	Total Score
10	Customer-side	Energy Storage	2	4	4	Very High	32
11	Network-side	Phase Balancing	3	2	4	Very High	24
12	Network-side	Dynamic Asset Ratings	4	2	3	High	24
13	Network-side	D-FACTS	3	2	4	High	24
14	Network-side	Enhanced Automatic Voltage Control	3	1	4	High	12
15	Customer-side	DSR - Commercial	2	2	3	Very High	12
16	Network-side	Generator Providing Network Support	5	2	1	Medium	10
17	Network-side	Microgrids	2	4	1	Medium	8
18	Customer-side	Generator Constraint Management	4	1	2	Medium	8
19	Customer-side	DSR - Residential	2	2	2	High	8
20	Network-side	LV DC Networks	1	3	1	Low	3
21	Network-side	Smart Transformers	1	1	1	Low	1

We also considered how solutions were interlinked and acknowledged the variation of approaches for each technology. For example, smart EV charging is strongly interconnected with energy storage and dynamic time-of-use tariffs. However, smart EV charging has already received considerable research and policy development, and ToU tariffs may be viewed as more of an enabler than a solution in its own right. As a result we decided to take forward energy storage and incorporate consideration of time-of-use tariffs in our analysis. Similarly, there exist links between dynamic voltage management and EAVC (both make use of devices such as on-load tap changers to regulate voltage) however dynamic voltage management is expected to be the stronger option due to higher headroom release per unit cost. In general, where solutions applied similar methods for headroom release, we only take forward one option to allow for variation in approaches across the shortlist. Phase 2 will also address interlinkages between solutions through application of the Transform model, which considers the interaction between different technologies when applied in parallel on the LV network.

Furthermore, we identified 'cold-spots' from Table 1 to ensure that we did not exclude solutions based upon lack of prior research interest. We included in the shortlist solutions on which fewer studies have been conducted, but which have shown high potential in the literature that was available (e.g., switched capacitors, transformer cooling). Enabler solutions were also considered, namely network monitoring and modelling. The literature review revealed this to be an important technology to facilitate and enhance the performance of all solution types, from network-side interventions, to changes in policy and regulation. Following this ranking and our subsequent sense-checking analysis, the top eight solutions that were selected for the shortlist and researched in further detail are listed below:

- **Network-side:**
    - **Transformer cooling**
    - **Dynamic voltage management**
    - **Network monitoring**
    - **Switched capacitors**
    - **Meshing**
    - **Phase balancing**
- **Customer-side:**
    - **Energy Storage**
- **Policy-side:**
    - **Widening of design voltage tolerance**

Discussion of Selected Solutions

In this section we discuss the shortlisted solutions, weighing up the benefits they bring to the LV network against associated cost, risks, and barriers. For each solution we discuss how it performs against each assessment criterion, and why solutions fall within selected tiers. For cost, the sources of expenditure are examined, though it is noted that there is potential for this to change in the coming years, particularly for lower TRL solutions. For headroom release, we investigate specifically what this means for each solution whether thermal headroom or voltage, where capacity is expanded, and by how much. For applicability, we discuss where solutions can be implemented and what barriers might exist that prevent or challenge deployment. Finally, technology readiness level is investigated for each option to gauge when a solution may be rolled out across low voltage networks and how much potential solutions have for improvement against the criteria.

Transformer cooling

Transformer cooling focuses on thermal headroom release and involves the use of active methods for reducing the temperature of substations. Those identified included active ventilation systems such as Passcomm which operates by creating a positive pressure within the substation housing, resulting in cool air being drawn in from outside to reduce transformer temperature. A similar system, Ekkosense effectively works in reverse, drawing hot air away from transformers and expelling it outside of the housing. Passive methods that were not taken forwards included the use of solar reflective paint on outdoor transformers, and the use of a covering structure to shade outdoor transformers from the solar radiation.

Costs vary between the different methods for cooling, but most fall within the ‘Very Low’ bracket of less than £10k. Data from the Electricity North West Celsius project estimates that the cost of monitoring and cooling ranges between £1500 and £6000 per substation depending on the building/enclosure type. The headroom release is similarly variable between solutions, however the most successful approaches were able to release a maximum of 30% headroom (Passcomm), therefore placing this solution in the ‘Medium’ tier for headroom release. The Ekkosense solution was found to release up to 20% capacity in some cases, but results were inconsistent between locations. This solution is applicable to substations only and has no application to overhead or underground feeders. The technology readiness level of this solution was assessed to be at level 7-8 since commercial cooling products have been deployed in demonstration projects, albeit at a small scale.

Dynamic Voltage Management

Increases in uptake of low carbon technologies such as electric vehicles and heat pumps have the potential to cause voltage drops on the network, while higher levels of distributed generation can cause the reverse problem, increasing voltages outside of statutory limits. Dynamic voltage management is a technique used to control voltages on the LV network through the use of technical installations, such as on-load tap changers, and automated control architecture.

The cost of this solution was primarily based upon data drawn from project budgets with consideration of the number of units deployed across LV substations[75]. This analysis indicated that dynamic voltage management is likely to fall within the ‘Medium’ cost tier, at between £25k and £50k. The increase in capacity delivered by this solution is potentially very significant, with Electricity North West trials indicating that deployment of on-load tap changers can deliver a ‘Very High’ level of headroom release[76]. Our review of the literature has not shown anything to suggest barriers to implementations in certain locations, provided appropriate enablers such as remote monitoring and communications were to be in place, however, limits were identified in

[75] The cost assessment for this solution was based on a number of studies, such *Voltage Management on Low Voltage Busbars (2013)*, *Low Voltage Network Solutions (2014)*, and *Low Voltage Integrated Automation (2013)*, authored by Electricity North West.
[76] Electricity North West, *Voltage Management of Low Voltage Busbars (2013).* Regulation of substation voltages using OLTCs facilitated increases in downstream feeder capacity of up to 90%.

terms of utilisation. Frequent control adjustments (e.g., tap changes) can lead to higher maintenance costs which outweigh the benefits of voltage control. To minimise costs, it may be necessary to find a balance between the length of the control cycle and the power quality delivered to the customer. The technology readiness level of dynamic voltage management was estimated to be between 8 and 9 since several projects have launched this technology successfully on the LV network.

Network Monitoring

Network monitoring refers to strategies for data gathering which can improve visibility and understanding of network characteristics. This can include monitoring at customer level (such as through the use of smart meters), however the solution brought forward focuses on monitoring at grid level. Previous studies have shown the benefits of recording voltages, power consumption and current levels at feeders and substations. While customer data is certainly of use to build profiles of demand from individual residences and demand clusters, this study focuses on monitoring of assets directly to assess their spare capacity. Costs were assessed based upon innovation project budgets, as well as contextual information from a range of studies. Network monitoring was estimated to fall within the 'Very Low' cost bracket (less than £10k unit cost), since commercial products exists for data gathering and are found to be relatively inexpensive[77]. However, it should be acknowledged that additional costs may be associated with post-processing of and data utilisation. Network monitoring does not explicitly release headroom, however, greater understanding gained from gathered data can allow network operators to utilise assets more efficiently. Work carried out by SPEN[78] estimated that thermal headroom release resulting from network monitoring averaged 8%, with some transformers seeing higher gains and some seeing no improvement at all. Network monitoring is a highly applicable, with most applications designed for substations but with potential to expand this to feeders as well. Few risks exist for this strategy; most are associated with the proper storage and organisation of collected data and communication with monitoring devices[79]. The technology readiness level of this solutions is in the 8-9 range since there have been several deployments of this technology.

Switched Capacitors

Switched capacitors are mechanically switched devices that can act as a form of low-cost voltage management on LV networks and may be used to stabilise networks under heavy load conditions. Where high levels of low carbon technologies may be connected to low voltage networks, switched capacitors can regulate voltages and therefore release voltage headroom. Uses for switched capacitors also include reactive power compensation and impedance line

[77] Commercial products are readily available but specific locations and type of monitoring depends on the individual network type and measurement location.
[78] SPEN, *Flexible Networks for a Low Carbon Future (2014).*
[79] The New Thames Valley Vision (NTVV) report Technical Guide LV Network Design and Planning Using the Network Modelling Environment (T2-LVDES-TG-002) discusses the categories of monitoring data stored in the NTVV project.

matching, however the effectiveness of this approach is expected to be limited on LV networks. Therefore, this solution is considered primarily for release of voltage headroom. Costs for this solution were drawn from existing values in EA Technology's Transform model, which estimates a CapEx cost of £10,330 and OpEx cost of £103. This modelling also indicates that headroom release for this solution is relatively low at 5% for voltage headroom and 0% for thermal headroom on both cables and transformers. However, field testing and modelling conducted by Electricity North West indicates that headroom release is potentially considerably greater[80]. Switched capacitors can be deployed at transformers as well as on feeders and therefore represent a highly applicable solution. Deploying switched capacitors on feeders also brings the benefit of regulating voltage closer to customer connections. Risks exist regarding reverse power flows that can occur when installed capacitors have a higher rating than transformers they are connected to. This strategy is also less effective when applied to networks with a higher proportion of resistive loads. The technology readiness level of this solution is estimated to be 7-8, since this technology has been demonstrated successfully on a small scale.

Meshing

Meshed networks differ from conventional radial networks in that customers can be supplied through multiple different pathways which allows demand to be distributed across substations, reducing loading on individual assets. This approach can also have benefits in terms of power quality, reducing voltage fluctuations, reducing losses and improving resilience. Costs for this solution were estimated to lie within the £10k-£25k tier ('Low'), based upon information drawn from UKPN studies[81],[82] and data from EA Technology's Transform Model which projects a CapEx cost of £20,660 and an OpEx cost of £826[83]. In the same model, voltage headroom release is estimated at 0%, while thermal headroom release is estimated at 50%. Estimates of thermal headroom release in innovation projects are slightly more conservative; the Flexible Urban Networks – Low Voltage (FUN-LV) project indicated potential to increase thermal capacity by 28% by splitting demand between substations. Where the difference between substation utilisation was previously over 50%, meshed networks enabled this to be brought below 10%.

Meshing can be implemented in the form of temporary or permanent meshing through power electronic devices or network reconfigurations, respectively. Permanent meshing is theoretically applicable across a range of network sites, with the technology readiness level of this solution very high, since it has already seen deployment in various locations across the UK. Temporary meshing has been trialled in several locations through the implementation of power electronic devices and the technology is relatively well developed. In either meshing method it is important that the load distribution profiles and increased risk of backfeeding in the event of a fault on the primary network is fully understood in order to optimise the solutions.

---

[80] Electricity North West, *Voltage Management of Low Voltage Busbars (2013).*
[81] UKPN, *Flexible Urban Networks – Low Voltage (2016).*
[82] UKPN, *Active Response to Distribution Network Constraints (2019).*
[83] The same costs are modelled in Transform for both temporary and permanent meshing.

Phase Balancing

Phase balancing involves the manual redistribution of loads on a three-phase supply so that each phase has approximately equal loading. While phase loading can vary continuously, high demand customers connected to a single phase can potentially cause long-term imbalance. Some estates have also seen issues where there has been an uneven distribution of connections to each phase, leading to further imbalance. When this occurs, feeder capacity reduces, and losses may be incurred due to higher current in the heavily loaded phase. Rebalancing loads equitably across phases means that all headroom can be maximised, and losses can be minimised. Some of this phase imbalance is due to procedures during connection of new customers which should be better managed and scrutinised. The changing usage and demand profiles is likely to compound existing issues as well as introduce new phase imbalance challenges.

Quantitative data was drawn from work conducted by SPEN, which estimates the cost of rebalancing per domestic customer to be £500 for overhead lines and £2,000 for underground cables[84]. Given the comparatively low cost of interventions on overhead lines, this method is expected to be more widely applied. However, it is acknowledged that this is only a cost per customer and application to multiple residences means that while costs are low, they are not negligible. Headroom release was found to be high, but only for a limited number of feeders – in the majority of cases phases are balanced and there is little opportunity to release spare capacity. Across the 233 feeders that were monitored, 9% of feeders were estimated to have to potential to release over 20% headroom, of which 4% had the potential to release over 30%. The technology readiness of this solution is estimated to be high since phase rebalancing is already a process that can be performed by distribution network operators.

Energy Storage (for demand shifting heat pumps)

Energy storage may be implemented at customer residences (behind-the-meter) in order to manage heat pump demand and reduce peak loading on the LV network. Heat pumps are among the key technologies that are expected to contribute markedly to increased peak demand during the low carbon transition and, therefore, shifting or reducing this demand can make a significant difference to thermal headroom on LV networks. However, heating demand can be more difficult to shift compared with other loads (such as EVs, for example) since it is strongly linked to temperature and environmental conditions. Using storage provides a means to meet heating demands when required, without placing the same strain on the LV grid. Batteries may be charged at times when grid loading is lower, which can then be drawn upon when required. Furthermore, this solution may be complemented by the deployment of dynamic time-of-use tariffs in parallel. Setting low prices during non-peak hours may incentivise battery charging, while high prices at peak demand hours can incentivise drawing on storage rather than the grid. In an Element Energy study for NPg17, it was further noted

[84] Dynamic phase rebalancing is also possible through power electronic devices at the supplying substation which would likely reduce this cost. However, phase imbalance can be an issue throughout the feeder that cannot be corrected from the source substation alone.

that "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". Hence, there exist synergies between this technology and smart EV charging, where heat pumps could potentially be powered by EV batteries.

The cost of implementing domestic electric storage has been estimated at £700-£800/kWh[85], however we also consider the potential for cost reduction, which is expected to be substantial within the next decade[86]. Thermal storage has also been investigated but was not brought forwards since, while the cheaper option at present, the potential for cost reduction is less. Furthermore, the potential to shift demand may be greater when using electrical storage since it has the capacity to shift other types of electricity demand in addition to heat pumps. Grid-scale storage options also exist as noted in the literature review, however, these are less well-suited to demand shifting of heat pumps since it represents a more centralised approach. The overall headroom release of this solution was estimated to be high, with some studies indicating a potential to reduce peak demand by up to 36%[87]. Peak demand reduction is dependent on whether storage is controlled by customers for self-consumption of locally generated energy, or whether DNOs are able to manage storage themselves to respond to network constraints. Additional benefits of this solution may be seen in reduction of reverse power flows and peak export from rooftop PV[88]. The technology readiness level of storage is very high since domestic and grid scale solutions have already been deployed across multiple locations.

Widening of Design Voltage Tolerance

Connection of low carbon technologies to the LV network in the UK has the potential to cause voltages to exceed tolerance limits, which currently specify 230V +10%/- 6%. Greater levels of electricity demand can cause a reduction in LV network voltages, whereas higher penetration of distributed generation can cause voltages to rise above specified limits. However, these limits were first implemented in the 1960s when appliances were more susceptible to voltage changes. Modern appliances are designed to operate in many countries and are therefore able to operate across a wider voltage range[89]. As a result, it is of interest to investigate what level of impact changing voltage levels will have on consumers and their appliances before making interventions on the network, since many appliances may be unaffected. If it is possible to

[85] BEIS, *Cost-Optimal Domestic Electrification (CODE), (2021).* This is calculated by accounting for the total cost of adding storage equipment, and the potential duration and power of flexibility services (kW) offered to the grid.
[86] 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.
[87] NPg, *Distributed Solar and Storage, (2020)*. A 36% reduction in winter peak was seen when batteries were operated by customers, however, when operated by DNOs to relieve network constraints peak reduction can increase to 65%. This does not refer to the specific use of storage with heat pumps, however, a similar headroom release could be expected in this case when heat pump penetration is much greater.
[88] NPg, *Distributed Solar and Storage, (2020)*. Peak export from rooftop PV was found to reduce by up to 38% and reverse power flows reduced by an average of 10kW per installation.
[89] Electricity North West, *Changing Standards (Statutory Voltage Limits) (2015).*

operate the LV network with wider tolerances such as those in the EU[90] with minimal impact to customers and businesses, reinforcement may be deferred or prevented[91].

The cost of this solution is expected to be relatively low since it does not require deployment of any significant equipment or physical apparatus. Some costs may be incurred from monitoring or research expenses, however, these are not expected to be significant. Voltage headroom is released by expanding tolerances, however thermal headroom is also impacted. The Electricity Engineering Standards Review indicates that the ampacity increase resulting from lowering voltage by 4% could be as much as 25%[92]. Studies conducted to measure impacts of overvoltages, and voltage drops have shown positive results, with customers often not perceiving significant changes to the operation of their electrical appliances. A survey conducted by Electricity North West found that 90% of customers who were supplied with voltages higher or lower than UK tolerances gave high satisfaction ratings with regards to their power quality89. This solution is potentially widely applicable, since changing tolerances would have an impact at all points of the LV network. Risks have been identified regarding the failure or reduced performance of older household appliances. In a study by EA Technology and Durham University, a failure probability of 21% was calculated for pre-1996 wet/cold appliances (of which there have been conservatively estimated to be 60,000 in GB)[93]. In 1995, voltage tolerances changed from 240V ± 10% (225.6-254.4V) to 230V +10%/-6% (216.2-253.0V). In terms of technology readiness, this solution is expected to be deployable following moderate levels of further research and testing. One area such research would need to focus on may be the effect of changing tolerances on the conditions required to blow fuses.

Stakeholder Engagement

Stakeholder engagement was conducted by gathering DNO feedback on a number of questions regarding the solutions presented in this report. A questionnaire (attached in Appendix 1) was sent to DNO working groups through the ENA to establish how network operators viewed the range of solutions that we have identified. We aimed to gauge whether any solutions had been missed and whether our assessment of solutions by cost, headroom release, applicability, and TRL was accurate. We also enquired which technologies DNOs anticipated they might deploy in ED2 and ED3, and which technologies were priorities for further research and demonstration.

Responses received from stakeholders broadly agreed with the longlist that was generated in this project, however, it was noted that some solutions could be implemented in a variety of ways and that their effectiveness was dependent on which other technologies were deployed in parallel. Stakeholders pointed out that phase balancing can be implemented either manually or dynamically, resulting in this option being expanded within the longlist. Furthermore, smart

[90] The voltage tolerance envelope in the EU is 230V ±10%.
[91] Frazer Nash for BEIS, *Electricity Engineering Standards Review (2020).*
[92] As there is a growing transition to increased use of constant power devices this voltage related load reduction is expected to reduce and at the extreme could become counter-productive.
[93] EA Technology and Durham University, *Increased Voltage Range: Effects on Domestic Appliances (CEP025) (ongoing).*

control of heating was identified as a potential area for further study, since heating may be expected to have a large impact on LV peak demand. Reactive power compensation was also seen to have more limited benefits on LV networks, leading to a reassessment of solutions which employ this approach.

It was commented that Real Time Thermal Ratings is not expected to release a high level of headroom on its own, however, combination with network monitoring could provide greater opportunities for extending capacity. Network monitoring was also seen as necessary to facilitate effective operation of solutions such as Meshing and Transformer Cooling. In general, network monitoring was perceived as a useful tool for rerating of assets and ensuring that network investment decisions are more precise (therefore mitigating costs to consumers). It was noted also that smart meter data can, in some cases, avoid physical intervention for monitoring of networks. Transformer cooling was generally seen as a low regrets option with opportunities for 'quick wins', however, consideration of noise level and ease of retrofitting was acknowledged as an important factor. Some stakeholders also noted that widening of the design voltage tolerance and smart EV charging/flexibility services would also be of interest.

Next Steps

In the next phase of the project, the counterfactual cost of network reinforcement will be calculated, based upon the load profiles detailed in this Phase 1 report. For this task, EA Technology will make use of their Transform Model which models the GB LV network using a series of network 'archetypes'. The uptake of low carbon technologies and distributed generation[94] will be assessed in terms of its impact on rural, urban, residential, commercial, and industrial areas of the network. By aggregating this data, we will evaluate where reinforcement is required, when this might take place and the magnitude of the required changes. This tool has been endorsed by Ofgem for use in all DNO planning for RIIO-ED1 and versions of the tool have also been used in Northern Ireland, Australia, and New Zealand[95].

Following calculation of the counterfactual cost, the eight solutions identified in this report will be taken forward and assessed quantitatively, again making use of the Transform model. Costings and headroom release will be broken down in detail to provide specific information such as CapEx, OpEx, as well as an appraisal of cross-network benefits. Where solutions provide benefits on the LV network, we will investigate the impact of solutions' headroom benefits on higher voltage networks. Disruption to customers will also be accounted for in Transform's parameters since solutions that have a lower impact on end users will generally be higher up the merit order of options for deployment. Stakeholder engagement will also factor into Phase 2, which will focus primarily on the results of the modelling analysis and various policy implications. Consideration will be given to the optimal network type for each solution, since it is already clear from work carried out in Phase 1 that approaches vary in terms of where they are most effective. Based on these factors, a revised ranking and evaluation of solutions will be provided to BEIS, offering recommendations for policies and priorities to be

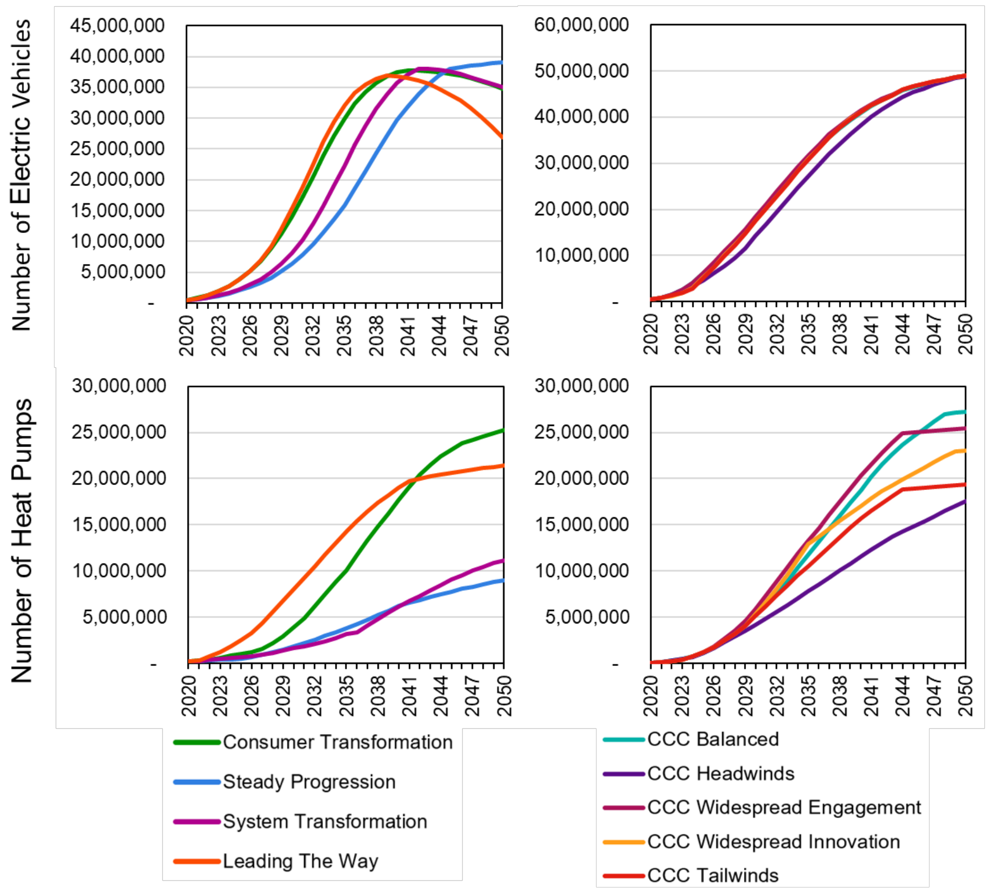
[94] This includes distributed generation such as solar PV and small onshore wind, as shown in Figure 4.
[95] This study did not identify any other similar tools that have been endorsed by Ofgem.

implemented in RIIO-ED2 and RIIO-ED3. A second report will be produced to summarise this work, and results will be disseminated through a webinar.

Appendix 1: Demand Profiles

Many forms of low carbon technologies are expected to grow markedly in future, however, we examine two examples which are likely to have a large impact on the LV network. Uptake of electric vehicles and heat pumps are shown in Figure 1, both of which see rapid increases beginning in the early 2020s and continuing steadily up to 2050[96][97]. These technologies are largely connected at the low voltage level of the distribution network, used by a mix of business and domestic customers. The CCC projections show a total stock of 50 million electric vehicles by 2050 for all scenarios, which all have similar uptake rates. Likewise, National Grid projections see an early acceleration in electric vehicle adoption, however this peaks before 2050 due to assumptions regarding uptake of "other forms of propulsion, automated self-driving vehicles and public transport". Hence, NG FES makes more conservative estimates of the total number of electric vehicles in 2050, ranging between 26 million and 39 million. However, while these scenarios vary in the extent of electric vehicle uptake, all show a very large increase in adoption from current levels, which can be expected to contribute significantly to an overall rise in electricity demand on the LV network.

Figure 1: Uptake of heat pumps and electric vehicles 2020-2050.



(a) NG *Future Energy Scenarios* projections of HP and EV uptake

(b) CCC *Sixth Carbon Budget* projections of HP and EV uptake

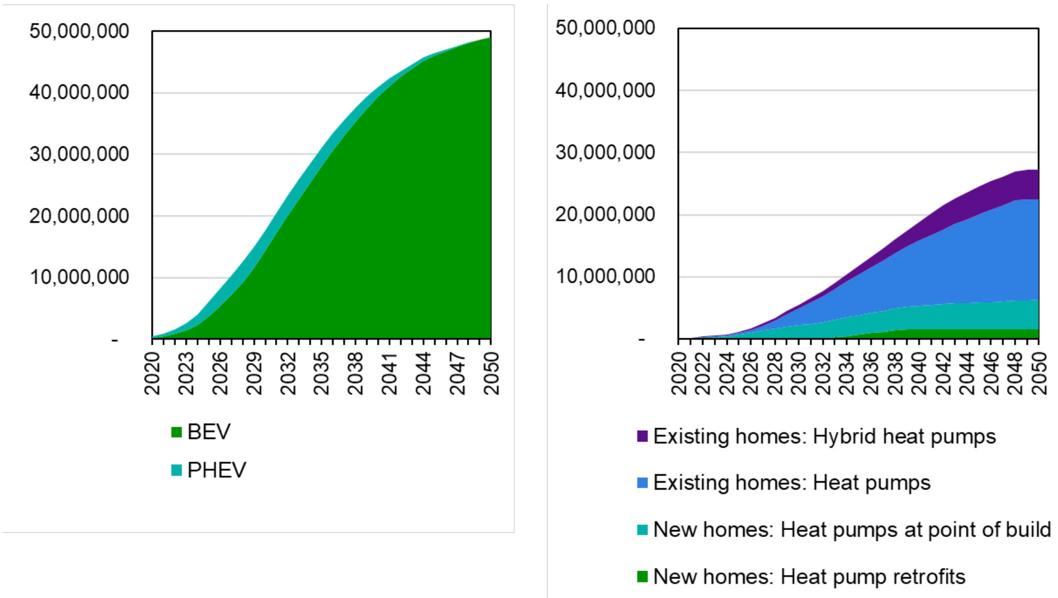
---

[96] National Grid *Future Energy Scenarios (2021).*
[97] CCC *Sixth Carbon Budget (2020).*

Similarly, heat pumps are expected to contribute significantly to demand on the low voltage network. For both datasets, the most ambitious scenarios predict 23-27 million heat pump installations by 2050. The spread of data across scenarios is greater in the case of the NG FES, with the Steady Progression scenario deploying only 5 million heat pumps by 2050. The System Transformation scenario also sees a low uptake in heat pumps, with 8 million installations by 2050, due to a greater uptake of hydrogen heating systems. However, even the more conservative estimates of heat pumps are still likely to result in substantial increases in electricity demand.

Figure 2 presents a breakdown of how electric vehicle and heat pump uptake is forecast to evolve for this scenario, with details of how the uptake of variants of each technology changes over time. In the electric vehicles sector, pure EVs are expected to dominate, with the uptake of hybrid vehicles projected to decline towards 2050. Similarly, hybrid heat pumps are set to experience considerable growth in the future, however, non-hybrid heat pumps are projected to see a much higher uptake.

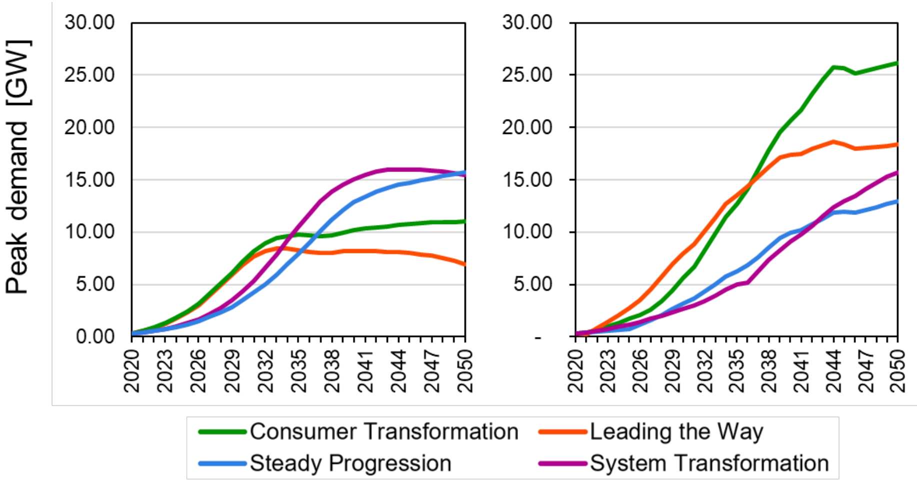
Figure 2: Detailed breakdown of electric vehicle and heat pump uptake the CCC Balanced Net Zero Pathway.



(a) Electric vehicle uptake **(b) Heat pump uptake**

The rapid uptake of these technologies will lead to higher peak demands on the LV network, which is the primary driver of reinforcement expenditure. The impacts of these two technologies are shown in Figure 3, which illustrates how heat pumps and electric vehicles could add up to 26 GW and 15 GW to peak demand, respectively. Electrification of heat may cause higher peaks during cold winter periods, while electrification of transport may result in the emergence of high network loading year-round and possibly outside of typical peak periods. Therefore, smart management of both technologies is crucial for deferral of reinforcement and minimisation of energy costs to consumers.

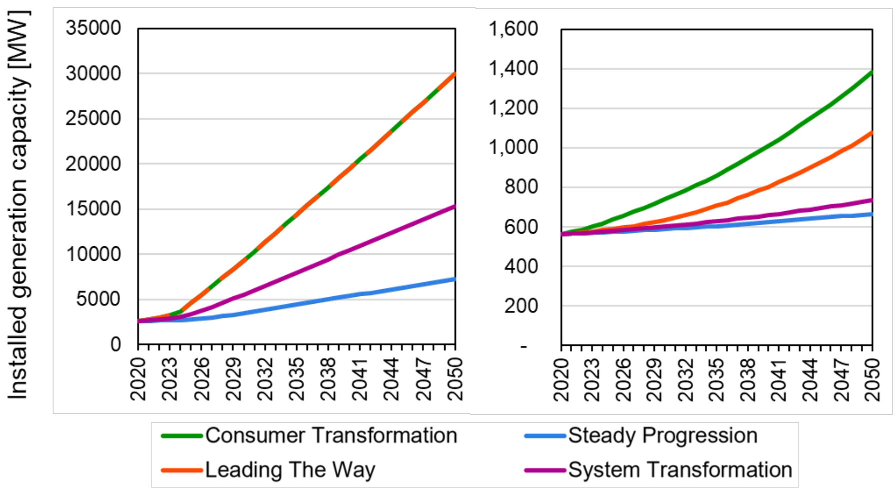
Figure 3: Peak demand resulting from electric vehicles and heat pumps



(a) Electric vehicles (b) Heat pumps (hybrid and non-hybrid)

In addition to higher electricity demand, increases in distributed generation are expected to trigger reinforcement on the network, due to higher levels of renewable energy systems generating at times of low demand[98]. The uptake of small-scale generation likely to be deployed on the LV network is shown in Figure 4, which shows projections of how domestic solar photovoltaics and small-scale wind (<1MW capacity), both of which see a sharp and sustained rise out to 2050. Consumer Transformation and Leading the Way both anticipate a ten-fold increase in installed capacity, from circa 4,000 MW in 2020 to over 40,000 MW by 2050. Such increases in distributed generation may cause issues for low voltage networks such as voltage rise and reverse power flows and can be expected to contribute to the need for reinforcement and upgrades[99].

Figure 4: Uptake of distributed generation that may be connected to the LV network 2020-2050.



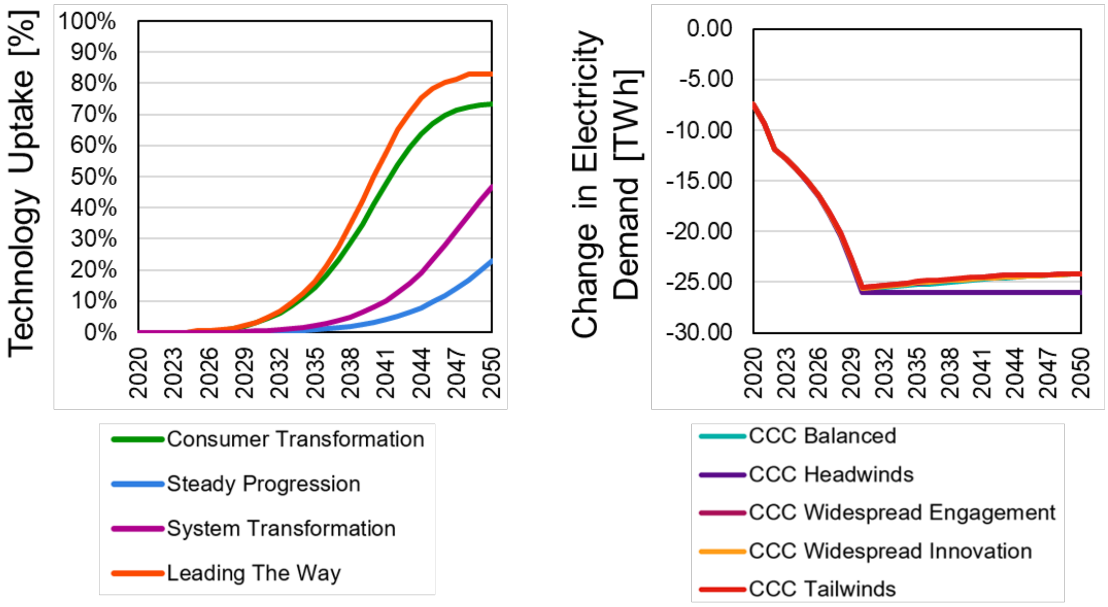
(a) Uptake of domestic solar PV capacity (b) Uptake of onshore wind generation (<1MW)

[98] Northern Powergrid, *Distributed Storage & Solar Study (2020).*

[99] Installed capacity shows the maximum potential generation, which is not expected to be seen on the network at all times due to low load factors of wind and solar. However, installed capacity gives an indication of peak generation which is the primary constraint driving LV network reinforcement.

It is acknowledged that some changes will take place in the transition to net zero that may offset the increases in demand on the LV network. Figure 5a shows how smart white good appliances may be adopted over the next thirty years, while Figure 5b illustrates the electricity savings that may occur due to efficiency improvements in lighting and appliances. Changes in consumer behaviour and appliance performance such as these can have a considerable impact and may go some way to offsetting increases in electricity demand. Smart white good appliances are able to reduce peak demand on the network by altering usage patterns so that appliances are not used during peak times, but rather when demand is low. Meanwhile efficiency improvements allow consumers to use less electricity for the same tasks. However, even when flexibility and efficiency improvements are accounted for, increases in low carbon technology deployment and distributed generation are still expected to be the dominant drivers of change on the LV network and as a result, low voltage networks are likely to see at least a doubling in electricity demand by 2050[100].

Figure 5: Offsetting demand increases through flexibility and efficiency measures[101].



(a) Smart White Good Appliance Uptake in Homes

(b) Demand decrease due to lighting and appliance efficiency

[100] CCC *Sixth Carbon Budget (2020).* This refers to peak demand (MW), however, both peak demand and energy consumption (TWh) are expected to increase substantially over this period.

[101] NG *System Transformation* and *Consumer Transformation* scenarios follow the same pathway for smart white good appliance uptake.

Appendix 2: Existing Estimates of LV Network Headroom

After Diversity Maximum Demand (ADMD)

After Diversity Maximum Demand models each customer, or most often a group of customers, as a fixed demand, which is reflective of the customer's diversity. Diversity is the consideration of how multiple customers behave collectively. The maximum demand of a single domestic property, for example, may be in the evening when the resident has the oven, kettle, and TV on simultaneously, but all houses on a street will not have all their appliances on at exactly the same time as each other. ADMD generates an estimate of what the maximum demand would be per property after this diversity is taken into account. It produces a reasonable worst-case estimate of demand on the network overall, which does not require dedicated software to calculate the total demand of many customers.

The ADMD methodology is explained in ACE Report No.105 (1986), Report on the Design of Low Voltage Underground Networks for New Housing. Historically, this approach was a simple linear model to allow for the fact that computers were not yet commonplace. This would be represented by aN+P, where a is the ADMD per customer, N is the number of customers, and P is a fixed value to account for the lack of diversity in small numbers of customers. Many DNOs[102] still use a version of this simple method, as it is fast and useful for initial ballpark estimates. ADMD in general also does not account for coincidence of maximum demand peaks (except for if DNOs use separate day/night figures to account for Economy7 customers), so can be inaccurate for networks with a mix of customers with unusual patterns of use.

For example, Western Power Distribution's standard techniques refer to a fixed ADMD for each type of customer, including different sources of heating plus a baseline demand if the number of connections is small. Similarly, SP Energy Networks[103] and Electricity North West[104] use a constant baseline demand, plus a variable demand dependent on the number of properties present and the type of property. UK Power Networks[105] have flat ADMDs for each customer type, both for daytime and night-time to account for the differing peaks of electrically and gas heated properties.

Northern Powergrid have updated the methodology to better suit modern domestic demand as a result of data obtained as part of their Customer-Led Network Revolution project[106]. They have adopted an exponential equation into their code of practice, again based on the number

[102] SSE do not have publicly-available documentation on the use of ADMDs in LV network design.
[103] ESDD-02-012, SPEN *Framework for Design & Planning of LV Housing Developments,* Issue 7 *(2019)*.
[104] ES281, Electricity North West, *Design and Planning Specification for New Low Voltage Installations for Housing Developments, Issue 3, (2020).*
[105] EDS 08-2000, UKPN, *LV Network Design, Version 3.1 (2017).*
[106] IMP001911, Northern Powergrid *Code of Practice for the Economic Development of the LV System Version 6 (2018).*

of and type of properties. This new method has the benefit of improved estimate of demand for all levels of customer numbers.

The below table illustrates ADMDs for a typical gas-heated property, using the method which is standard practice for each DNO. It is evident there is a lot of variation between the various methods used across the different DNOs and standardisation of these approaches is non-trivial due to differences in network configuration.

Table 5: ADMD data generated by different DNOs.

DNO	ADMD for single property (kW)	Total ADMD for 10 properties (kW)	Total ADMD for 100 properties (kW)
WPD	11.4	42	170
UKPN	1.2 (day), 0.3 (night)	12 (day), 3 (night)	120[107]
ENW	10.8	22	148
SPEN	9.5	23	158
NPG	4.6	33.4	211

Debut

The Debut methodology, also known as the p-q approach, is a probabilistic method based on the 1981 ACE Report No.49: Statistical method for calculating demands and voltage regulations on LV radial distribution systems. This report sets out a methodology in which the probability of customer demand is modelled as being normally distributed. Maximum demand is estimated using a mean-based component, p, and a standard-deviation-based component, q. These are combined so that the calculated estimate is equivalent to the 90th percentile maximum demand which is expected to be seen on the network. This produces a reasonable worst-case estimate, resulting in the designed network being able to cope with the worst days of the year without being over-specified. It is generally lower than the equivalent ADMD for the same property type.

Each customer type has its own profile, made of a series of p and q values, which defines the shape of demand across the day. The scale of the profile can also be changed to reflect either an individual customer's expected maximum demand or its estimated annual consumption. Customers are often placed in categories indicative of their level of consumption (e.g., there are 3 models of house available: high, medium, and low consumption), their heating type, or

[107] ADMD is lower here than for other DNOs; there is limited data on whether this leads to higher fault levels. However, it is assumed that this is unlikely since there is capacity left in most circuits as a result of discrete asset sizes, particularly in modern networks where the number of customers (<75), cable thickness (>95mm2), and transformers are large.

other aspects. These different categories are created to reflect the differing profile shapes of each consumer type.

Debut has two notable advantages over ADMD[108]. Debut considers 60 half-hour periods (24hrs of a winter weekday, the worst expected day, plus 12 notable weekend half-hours to fully model all worst half-hours). This allows the typical coincidence of the time of each customer type's peak demand to be considered, resulting in more accurate estimates for networks with a mix of customer types. Debut also calculates demand independently for each asset in the network, reflecting the diversity level seen by that asset i.e. transformers will be estimated to have demand reflecting the diversity of all connected customers, and service cables will only see the maximum demand of the customer they are servicing. Debut does have one of the same drawbacks as ADMD: for low numbers of connections, particularly for small numbers of customers, demand can be under-estimated.

Debut also requires the use of dedicated software. The Debut method is usually implemented using EA Technology's specialist software "WinDebut"[109], and its successor "Connect", which is the preferred method of network design by many of UK DNOs, as well as ICPs and other network providers. This software allows the user to draw a model of the network, then WinDebut will calculate the expected demand across each asset and whether any values are out of limits. Each DNO has their preferred settings for the scale of each customer type, but the variation between these input values is far less than there is for the equivalent ADMD. For a typical gas-heated property, WinDebut uses a model which has approximately 2.4kW peak demand for a solo customer, and 1.5kW per-customer peak demand when accounting for the diversity of over a hundred customers.

Historic Design Policy Implications on Headroom

It is to be noted that the default profiles used within WinDebut are based on older data. These profiles have been kept static throughout WinDebut's lifetime, and most DNOs use these default profiles. Engineering Recommendation P5 Issue 6 (2017) includes updated domestic profiles for WinDebut which reflect the fact that modern consumers generally use less electricity and have a lower peak demand than in previous years. A side-by-side comparison of the new and old domestic profiles suggests that as a result of more efficient lighting and appliances the maximum demand has decreased by around 0.4kW per customer, about a sixth of the magnitude of the old profile. This suggests that there is a sizeable amount of hidden spare capacity due to underlying load on existing networks, as they have been designed to larger demands than they are experiencing in reality.

[108] A comparative assessment of these methods may identify additional LV headroom available as a result of historic ADMD overdesign, however, it is anticipated that this would be limited. The effect of this would be most notable on mixed-customer-type networks, as these would be the ones that ADMD is prone to slightly over-estimate. It is further noted that this would not be possible on meshed networks.
[109] WinDebut is unique in its use of the Debut method and there are not any other commercially available providers of Debut.

For example, an existing network designed using the old profiles to supply 100 domestic customers could have around 40kW more spare capacity than would have initially been expected. For a 315kVA substation, this would free approximately an eighth of its rated capacity. However, this extra headroom could only be expected of majority-domestic networks with gas heating; new profiles have not been created for non-domestic consumers or traditionally electrically-heated properties, as these are not expected to have their maximum demand to have significantly changed.

Network designers would typically use one of the two above methods, along with the properties of the proposed cables and transformer, to assess whether a potential network was suitable for purpose and within all necessary limits. Until recently, the preference was to choose the cheapest assets available. This functionality was even built into software like WinDebut to automatically choose the cheapest suitable cables, factoring expected lifetime losses.

Cheaper assets are inevitably smaller assets; lower-diameter cables and smaller transformers. This creates a set of historic networks, a proportion of which are inherently “at risk” by design, where any increase in demand is likely to break them. This proportion of at-risk networks are those that have had their ADMD, or Debut analysis of demand calculated to be close to the limit of the deployed assets, but not over limits. Similar networks with a slightly higher maximum demand would have instead gone to the next asset size up and have plenty of headroom available. The complication is in identifying which historic networks fall into each category, and whether they are still as close to limits as when they were designed. Since 2005, the average domestic property demand has been observed to have decreased. So, while it is possible that these networks have some available headroom, they represent the marginal cases for capacity to accommodate new load. Some level of headroom visibility has been delivered through studies commissioned by network operators which have aimed to develop ‘templates’ of network loading and voltage profiles to better understand LV capacity[110]. As part of this research, the impacts of low carbon loads were investigated, in addition to an exploration of the potential to widen voltage limits to accommodate higher numbers of LCTs.

Modern networks, those designed within the last 5-10 years, are less susceptible to this issue. Within this period a further focus on the lifetime losses of these long-lived assets (cables/ transformers) has led to a trend of oversizing them thermally (lager-rating assets have less losses for a given throughput of demand). The additional costs of these ‘fatter’ assets have been somewhat ameliorated by procurement advantages in only stocking the larger sized components that are then bought in larger quantities. New networks are designed with demand growth and futureproofing in mind, primarily using larger cable and transformer sizes, and so are less likely to be at risk by design.

Additionally, legacy networks have often been designed with a much larger earth loop impedance than modern standards would allow, as they were built before ACE105, which recommended the 250milliohm cap on impedance. Though most network operators own policies and design statements allowed for up to 350 mΩ on most networks, the majority of network operators now design to the more stringent limits. The use of the ‘fatter’ cables for reduced lifetime losses allowing similar lengths of networks to be maintained but with reduced

[110] WPD, *LV Network Templates for a Low Carbon Future (2013).*

loop impedance (and therefore probability of voltage problems) for those at the end. These older, longer networks are much more susceptible to voltage drop, as the voltage headroom would decrease a lot faster for increasing demand at the end of a long network than for a short one. Again, many of these historic networks are difficult to identify quickly due to limited availability of consistently digitised data enabling feeders to be mapped in terms of their geographical and electrical connections along with the customer locations and circuit impedance.

Appendix 3: Stakeholder Engagement Questionnaire

1. Below is a longlist of smart solutions that we intend to assess and evaluate in our work. Are there any technologies that you believe we have missed that should be included? Are there any technologies that you believe should be omitted?

- Phase Balancing
- Dynamic Voltage Management
- Dynamic Asset Ratings/Real Time Thermal Ratings
- Widening of Voltage Tolerance
- Smart Transformers
- LV DC Networks
- Microgrids
- D-FACTS
- Network Monitoring
- Smart EV Charging
- Dynamic Time of Use Tariffs
- Energy Storage
- Enhanced Automatic Voltage Control
- Switched Capacitors
- Generator Constraint Management/ Generator Side Response
- Generator Providing Network Support, e.g., PV Mode
- DSR - Commercial
- DSR - Residential
- Meshing - Temporary
- Meshing - Permanent
- Transformer Cooling

2. Below is our shortlist of solutions that we intend to assess in depth. We have selected these prioritized solutions by scoring the long-list on the basis of cost, headroom release, and applicability. For reference, the decision matrix used to generate this list is included as an appendix to this questionnaire.

   Are there solutions that you believe should or should not be present in this list? Examining the decision matrix, are there any solutions that should be in a different cost/headroom/applicability bracket?

   Based on your knowledge of these technologies, which would be the most/least promising options for releasing capacity on the LV network in a cost-effective manner?

- Transformer cooling
- Dynamic Voltage Management
- Switched Capacitors
- Meshing - Temporary
- Meshing - Permanent
- Widening of Voltage Tolerance
- Network Monitoring
- Phase Balancing
- Smart EV Charging
- Dynamic Time of Use Tariffs
- Energy Storage
- Dynamic Asset Ratings/Real Time Thermal Ratings
- D-FACTS

3. Do you have any further comments on any of the solutions we have included? For example, this might be regarding costs, headroom release, applicability, risks, and barriers to implementation (or any other relevant details).
4. Which technologies do you expect to be deploying on your networks to increase LV network capacity in ED2 (e.g., top 3 solutions you expect to deploy)?
5. What do you see as the most promising technologies for managing LV constraints in the longer term (ED3 and beyond)?
6. Which technologies are priorities for further research and demonstration?

Appendix 4: Focused Literature Review

This appendix provides a more detailed assessment of some of the literature that we believe is of particular relevance to this project. For each study we have assessed the project background, its objectives, the methodology employed, and the outcomes relevant to our work. Note that these summaries only capture the key points of each project and parts of some projects may be omitted for brevity or lack of relevance to this study. The interested reader is directed to the original studies, the majority of which are publicly available online. The documents included are listed below:

- Assessing the impact of low carbon technologies on Great Britain's power distribution networks
- Celsius
- Customer Led Network Revolution
- Development of LV Management Strategy
- Distributed Storage & Solar Study
- Electric Nation
- Electricity time-of-use tariff with consumer behaviour consideration
- Entire
- Flexible Urban Networks - Low Voltage
- Increased Voltage Range – Effects on Domestic Appliances
- Low Voltage Integrated Automation (LoVIA)
- Low Voltage Network Solutions
- LV Connect & Manage
- Network headroom, engineering upgrades and public acceptance (NEUPA)
- NetZero Cheshire: Delivering Network Visibility
- New Thames Valley Vision
- OpenLV
- Shift
- Solar Storage
- Sustainable microgrids: Economic, environmental, and social costs and benefits of microgrid deployment
- Transition to low voltage DC distribution networks – Phase 1
- Voltage Management on Low Voltage Busbars

In addition to the studies briefly summarized here, which focus on innovation projects carried out by UK DNOs, we also reviewed a wider range of literature from international studies which we list below:

- SSEN, 11kV power electronics providing reactive compensation for voltage control
- NREL, A comparative study of DC and AC microgrids in commercial buildings across different climates and operating profiles
- SPEN, A Transition to LVDC - Phase 2
- UKPN, Active Response to Distribution Network Constraints
- NPg, After Diversity Maximum Demand (ADMD)
- L. Jenkins, Application of dynamic asset rating on the UK LV and 11 kV underground power distribution network
- SPEN, Ashton Hayes Microgrid
- NPg, Autodesign: LV Connections Self-Service Tool
- NPg, Boston Spa Energy Efficiency Trial
- ENWL, Changing Standards (Statutory Voltage Limits)
- SPEN, Charge
- UKPN, Constellation
- SSEN, Distribution Dynamic Line Rating
- BEIS, Electricity Engineering Standards Review
- NPg, Enhanced Automatic Voltage Control
- SPEN, Flexible Networks for a Low Carbon Future
- UKPN, Flexible Plug and Play
- R. Ozaki, Follow the price signal: People's willingness to shift household practices in a dynamic time-of-use tariff trial in the United Kingdom
- WPD, Future Flex
- UKPN, FutureLink
- UKPN, Heat Street: Local System Planning
- SPEN, HV and LV Phase Imbalance
- NPg, Impact of LCTs on the design of the LV networks*
- ENWL, Intelligent Network meshing switch
- WPD, Investigating Balancing of LV Networks
- UKPN, Low Voltage Automation
- SPEN, LV Engine
- WPD, LV Plus

- NREL, Making microgrids work
- NREL, Microgrid Controllers: Expanding Their Role and Evaluating Their Performance
- Jin, M., MOD-DR: Microgrid optimal dispatch with demand response
- WPD, Peak Heat
- Kai Wang, Phase balancing algorithms
- UKPN, Phase Switch System
- WPD, Project FALCON Dynamic Asset Rating Cables
- UKPN, Recharge the Future
- National Grid, Smart Grid Forum Work Stream 7
- NPg, Smart Network Design Methodologies
- WPD, Solar Yield Network Constraint (SYNC)
- K. M. Rogers, T. J. Overbye, Some applications of Distributed Flexible AC Transmission System (D-FACTS) devices in power systems
- UKPN, Timed Connection Software Development
- SSEN, Transition
- Olivares, D., E., Trends in Microgrid Control
- WPD, Voltage Reduction Analysis
- WPD, Superfast Electricity Consultation
- WPD, Electric Vehicle Strategy

Name:	Assessing the impact of low carbon technologies on Great Britain's power distribution networks
ID:	1
Authors:	EA
Proposed Solution:	Multiple Solution Review
Funding	-
Start/End Date	– 03/08/2012
Background:	Project initiated due to anticipated increases in electricity demand across the network, specifically at the low voltage level. These demand increases are expected due to higher levels of low carbon technology (LCT) penetration, such as electric vehicles, heat pumps and photovoltaics. Non-uniformity of demands is acknowledged as a critical aspect of this challenge, and consequently solutions need to be diverse and targeted.
Objectives:	To propose a set of solutions to the various network challenges, and estimate the impact, cost, and applicability of each option. The project aims to develop a model ('Transform') which can assess solutions against various criteria and evaluate investment decisions.
Methodology:	A number of network 'archetypes' are created, which represent typical networks in different scenarios e.g., rural, urban residential, commercial etc. These are then applied to relevant areas across the UK. The uptake of LCTs is estimated in order to determine the level of demand increase and how that demand may be distributed across network archetypes. This allows a quantification of network headroom. Where additional headroom is required, the model deploys appropriate solutions and estimates the level of investment required.
Relevant Outcomes:	The most cost-effective solution is likely to be a combination of smart grid options and conventional reinforcements. The model also indicates that a top-down rather than incremental approach would be most economical. Therefore, investment in enabler technologies would be in the long-term interest of customers. In 2050, D-FACTS, permanent meshing, smart EV charging and DSR are identified as key technologies to deploy. Energy storage, generation constraint management, generation in PV mode, new types of infrastructure, and switched capacitors are not selected.

Name:	Celsius
ID:	2
Authors:	Electricity Northwest
Proposed Solution:	Transformer Cooling, Dynamic Asset Ratings
Funding	NIC
Start/End Date	01/01/2016 - 01/03/2020
Background:	Substation monitoring may be useful for LV networks to provide additional visibility regarding the level of transformer headroom. Cooling may then be applied through various methods to increase this headroom further and defer conventional reinforcement.
Objectives:	To monitor the real time thermal ratings of transformers and to apply cooling techniques to release headroom at substations.
Methodology:	Various methods are used for cooling, including using positive pressure to expel hot air from indoor transformers, applying solar reflective paint to outdoor transformers, and shading transformers with a gazebo structure.
Relevant Outcomes:	Cost benefit analysis of the Celsius project estimates that the cost of monitoring and cooling ranges between £1500 and £6000 per substation depending on the building/enclosure type. The most effective cooling technology, the Passcool system saw an average capacity increase of 14%. In some cases, capacity increase reached 30%. The Ekkosense solution provided a 12% average improvement in transformer ratings. Steps should be taken to avoid cyclical loading of transformers. The effects of this are largely unknown but could potentially cause damage to older assets.

Name:	Customer Led Network Revolution (CLNR)
ID:	3
Authors:	NPg
Proposed Solution:	Network Monitoring
Funding	LCN Fund Tier 2
Start/End Date	01/01/2011 - 01/12/2014

Background:	Customer Led Network Revolution was a large-scale smart grid demonstration that aimed to develop innovative solutions to the challenge of decarbonising the energy system. This brought together customers, suppliers and distributers as well as academic teams from Newcastle and Durham Universities. Also involved were British Gas, the largest unaffiliated energy retailer, and network consultants, EA technology.
Objectives:	CLNR investigated a wide range of customer-side and network-side approaches to expanding network capacity and aimed to develop a roadmap for the application of various technologies. The project sought to develop a deeper understanding of energy networks, their constraints, and methods for overcoming potential obstacles that may be presented by the low carbon transition.
Methodology:	Working with over 13,000 domestic, SME, industrial & commercial customers and distributed generators, the CLNR project deployed a range of network-side and customer-side technologies to assess the potential for expanding network capacity and responding to existing and future changes to the network.
Relevant Outcomes:	The project found that domestic customers were “inherently flexible” and that their contribution to network peak demand was less than previously assumed. Industrial and commercial demand side response was found to be a viable option for BAU deployment, however, only a small number of customers were willing and able to participate in the service. A number of novel solutions and advanced modelling techniques were developed by Newcastle University to “predict, validate, and scale-up the learnings from our trials”. The CLNR project undertook circa 200 trials of electrical energy storage (EES), enhanced automatic voltage control (EAVC), real-time thermal rating (RTTR) and demand side response (DSR). These interventions were deployed both in isolation and in combinations through the use of an active network management system.

Name:	**Development of LV Management Strategy**
ID:	4
Authors:	EA for SAPN
Proposed Solution:	Multiple Solution Review
Funding	-
Start/End Date	- 23/11/2018
Background:	SAPN commissioned this project in order to develop a better understanding of how demands on their LV network will change in the future. This requires an

	understanding of which technologies are likely to impact on the network, and how much of a risk this poses.
Objectives:	To develop a number of solutions that are able to respond to increases in network demand, and quantify investment required. The goal of this study was not to provide a single definitive answer to which solutions SAPN should choose, but rather to provide a framework for decision making
Methodology:	This study utilises the Transform model developed by EA technology to identify solutions, and evaluate them based upon headroom expansion, cost, and applicability.
Relevant Outcomes:	The Transform model outputs a network investment profile detailing the level and timing of expenditure required to respond to connection of distributed energy resources. Network solutions include rebalancing and retapping, reactive power support, non-network solutions, feeder reconfiguration, and substation upgrades.

Name:	**Distributed Storage & Solar Study (DS3)**
ID:	5
Authors:	NPg
Proposed Solution:	Energy Storage
Funding	NIA
Start/End Date	01/08/2016 - 01/11/2019
Background:	While traditional networks have been designed to cope with morning and evening demand peaks, clustered PV can cause pressure on the LV network due to generation throughout the day. Peak generation occurs during the middle of the day, when demand is lowest, which can lead to strain on assets. Battery storage can alleviate this pressure, by storing the energy generated by rooftop PV. Charged batteries can then help provide electricity for evening loads.
Objectives:	This project seeks to find out more about clustered domestic solar panels, battery storage and household demand. Furthermore, the study aims to assess whether it is better in the long term to use smaller batteries at individual residences, or larger storage facilities at substations.
Methodology:	DS3 monitors the behaviour of 27 solar panels and 40 batteries. Monitoring equipment is installed at substations and at properties to investigate how the two technologies interact.

Relevant Outcomes:	DS3 found that peak demand could be reduced by up to 65% using battery storage. Peak export from rooftop PV was also found to reduce by up to 38%. Additional benefits are seen in reduction of reverse power flows; DS3 finds that this falls by an average of 10kW per installation. It was noted that some battery users struggled to operate the technology.

Name:	**Electric Nation**
ID:	6
Authors:	WPD
Proposed Solution:	Smart EV Charging
Funding	Network Innovation Allowance
Start/End Date	01/04/2016 - 01/10/2019
Background:	As EVs are adopted in clusters, demands of the LV network are forecast to increase. It is predicted that 30% of the LV network will need reinforcement by 2050 if EV uptake is widespread. This will result in a large cost to the consumer if alternative solutions are not found to increase headroom. At the time of starting, there was no quantitative tool to identify the level and location of reinforcement needed to respond to increases in EV penetration in WPD license areas.
Objectives:	To collect real data on EV charging patterns and identify pinch points of high demand. To formulate a model to evaluate whether EV demand control services can alleviate network peaks. To provide tools for distribution operators to monitor EV demand and deploy demand control services.
Methodology:	The project is split into three sections: monitoring, mitigation, and modelling. The monitoring phase develops a system for identifying EV demands on a network. The mitigation phase focused on gathering a small set of trial results from EV users to investigate how and when they charged their vehicles. The modelling phase involved development of a Network Assessment Tool (NAT) which is able to determine the network impacts of EVs and simulate the impacts of various solutions.
Relevant Outcomes:	Monitoring through the use of smart EV chargers allowed WPD to develop demand profiles from users, improving visibility of how EVs affect the LV network. An algorithm was developed alongside Lucy Gridkey which can detect the presence of EV charging with >95% accuracy. In the modelling phase, the NAT predicted that the use of smart charging and dynamic time-of-use tariffs can be appropriate solutions to network peaks caused by EVs. The study also identifies a number of technical challenges that face smart EV charging. These include "ensuring secure and reliable

	communications between the charger and control services; providing customers with information about the charging of their PIV [plug-in vehicle]; allowing the customer to state preference as to when they are charged (ensuring the control is as “fair” as possible to all); and investigating what, if any, compensation or incentives customers require to participate in PIV demand control."

Name:	**Electricity time-of-use tariff with consumer behaviour consideration**
ID:	7
Authors:	L. Yang
Proposed Solution:	Dynamic Time-of-Use Tariffs
Funding	-
Start/End Date	- 01/12/2013
Background:	Dynamic time-of-use (ToU) tariffs are increasingly being investigated as a means to create a more efficient energy system that can deal with projected demand increases over coming decades. Dynamic ToU tariffs involve adjusting electricity prices in response to demand as a means of reducing network peaks. Increased prices disincentivise customer electricity usage at peak, encouraging customers to change consumption habits.
Objectives:	The study looks into how dynamic ToU tariffs can be optimised and what kind of benefits they can bring to the different stakeholders acting within the electricity system. An optimal tariff scheme is developed for a range of environments and tested to assess its impact on costs to consumers and profits for producers.
Methodology:	The study applies a ‘two-level’ model to dynamic time-of-use tariffs. In the first level, the tariff is designed by the producer through consideration of consumer behaviour. In the second level, consumers respond to this tariff and shift their electricity consumption accordingly. This shift is seen from the peak period to the ‘base period’, when electricity demand is otherwise relatively low.
Relevant Outcomes:	The paper finds that adoption of the tariff developed in the study results in a ‘win-win’ situation for both consumers and producers. Consumers are able to reduce electricity costs and producers are able to increase profits. The study also presents useful data from other literature. Use of DToU tariffs after California's 2000-2001 energy crisis led to reductions in peak demands in the range of 7.6 - 27% [Faruqui and George, 2005]. Peak demand reductions up to 41% have been seen in Florida's Gulf Power Select Program. Trials in Norway have seen reductions in the range of 8-9%. In general, studies show that this strategy can have

	varying impacts depending on the location and means of implementation, however, it is reasonable to expect headroom release in the 10-30% range.

Name:	**Entire**
ID:	8
Authors:	WPD
Proposed Solution:	Demand Side Response
Funding	Network Innovation Allowance
Start/End Date	01/06/2016 - 01/04/2019
Background:	Expanding on previous trials such as FALCON and SYNC, Entire looks to develop DNO-led flexibility services, including demand-side response (DSR).
Objectives:	To identify the key obstacles facing DNOs when implementing DSR strategies. To create a roadmap for other license areas and DNOs to deploy DSR and deliver increased value to customers. As the name 'Entire' suggests, this study aims to find a more comprehensive method of DSR than previous projects (in which sample sizes have been relatively small) where multiple customers can be recruited across a wide area.
Methodology:	The first step of the project is an audit of generation connected to the LV network to identify all possible DSR participants. Following this, policies, processes, and systems were identified that can facilitate the deployment of DSR. A business model is subsequently developed which demonstrates enhanced value to customers.
Relevant Outcomes:	Though 69 sites engaged with the program, amounting to 120MW of capacity, very few actually committed to operational trials. This poor response was attributed to "the potential time bound nature of potential returns". Costs are likely to be incurred from identifying capacity that can participate in DSR strategies, and payments made to customers in exchange for their cooperation in the scheme. This has been estimated at between £150/MWh and £600/MWh

Name:	**Flexible Urban Networks - Low Voltage**
ID:	9
Authors:	UKPN

Proposed Solution:	Meshed Networks
Funding	LCN Fund Tier 2
Start/End Date	01/01/2014 - 01/12/2016
Background:	While LCTs are very likely to cause higher peaks on distribution networks in the near future, it may not be the case that sustained load growth occurs. As a result, flexibility is the key characteristic that must be introduced to LV networks, to deal with the higher variability in demand that LCTs bring about. Customers on the distribution network are typically fed through a single source of supply in a ‘radial’ configuration. Some urban networks have more than one possible supply route, however, usually only one route is used at a time. Meshed networks involve supplying customers through multiple routes on the LV network, allowing demand to be shared across substations thereby releasing spare capacity.
Objectives:	To explore the use of power electronics in meshed networks, with the ultimate goal of deferring LV reinforcement and facilitating the connection of LCTs. Particular focus is placed on meshing of existing networks, rather than creating new meshed networks.
Methodology:	The project examines existing LV networks to identify issues and areas where meshing could potentially drive improvements. Following this, power electronics are deployed and monitored to assess their benefits to network headroom. The use of power electronics to provide ‘soft open points’ (SOPs) is investigated which facilitate modulation of load sharing between substations. The project was broken down into the following stages: Monitoring of candidate LV networks and identification of network issues. Identification of how these networks would conventionally have been reinforced. Identification of where power electronics solutions can be used to address network issues. Deployment and evaluation of power electronics applications in LV networks, compared to conventional reinforcement.
Relevant Outcomes:	Load sharing across substations was enabled by all three power electronic systems tested. It was shown that network meshing using power electronics has significant potential to increase LV headroom. Application of meshing was able to bring load utilisation of neighbouring substations to within 10% of one another where previously this had been over 50%. For example, in a trial of the technology in Loughborough two substations had utilisations of 78% and 20%, respectively. After application of meshing, this was brought to 50% and 48%, hence releasing 28% of headroom on the first substation.

Name:	**Increased Voltage Range – Effects on Domestic Appliances**
ID:	10
Authors:	EA Technology and Durham University
Proposed Solution:	Widening of Design Voltage Tolerance
Funding	Funded by the Energy Networks Association (ENA)
Start/End Date	2/04/2020 - 15/04/2021
Background:	"The general consensus amongst industry reports and studies was that a wider tolerance will allow greater flexibility to the DNOs for voltage optimisation and renewable generation integration. Academic sources for the most part dwell on details of specific appliances and population statistics. They point to specific effects of voltage fluctuations from an engineering perspective and estimate how many appliances could be affected."
Objectives:	"The project investigated the effects of transitioning UK low voltage statutory limits from the existing 230 V -6%, +10%. (216.2 V to 253.0 V) to 230 V -10%, +10%. (207.0 V to 253.0 V). The project is focused on studying the effects of the statutory voltage limits change on resistive, inductive and/or non-linear loads, mainly on cold and wet domestic appliances that are 20 years or older. The appliances included in this study are Washing Machines, Dishwashers, and Refrigerators, Freezers and Fridge-Freezers."
Methodology:	"Using the learning from the literature, a testing regime was developed, a test rig designed to fully comprehend the extent of effect adopting the European voltage limits of 230V +/-10%. The testing methodology included safety, comfort and performance tests for all domestic goods, testing them both mechanically and electrically. British standards (for individual appliances) were followed in the testing of each appliance and its various parts where applicable. An evaluation method was utilised to analyse the results, then these were extrapolated for a wider understanding of the effects of increased voltage range."
Relevant Outcomes:	"There is a low chance (below 33%) of experiencing an impact leading to an appliance failure. In most cases however there is a higher chance (33- 66%) of experiencing some alterations in the operation of the appliance (e.g., reduced efficiency, prolonged cycles, etc). […] This means that out of the appliances impacted by a reduced voltage, majority would result in slight loss in performance and mild discomfort to user but will mostly remain safe to use. […] on average […] there will be a 21% chance that a similar appliance exhibits a similar failure given the similar operating conditions […]. [T]his refers to 21% of the population of usable appliances in the UK that are older than 24 years (i.e. the rest of the appliances in the UK that

	are of the same conditions, and in the same age group as those tested). Based on a conservative estimate the total number of appliances falling within this category (wet/cold appliances) is estimated to be at around 60,000 appliances.”

Name:	**Low Voltage Integrated Automation (LoVIA)**
ID:	11
Authors:	Electricity Northwest
Proposed Solution:	Dynamic Voltage Management
Funding	LCN Fund Tier 2
Start/End Date	01/03/2013 - 01/03/2013
Background:	LoVIA builds on learnings from Voltage Management on Low Voltage Busbars and Low Voltage Network Solutions which deployed and tested OLTCs, automatic voltage control and asset monitoring. Specifically, LoVIA introduced a method of remote measuring of voltages and automatic controlling voltages such that they remain within given limits.
Objectives:	To develop a more efficient and low-cost method for measuring voltages on the LV network and automatically making adjustments to keep voltages within a given range.
Methodology:	GPRS was used for as the communication method for remote voltage management and OLTC control.
Relevant Outcomes:	The project developed an algorithm driven by remote voltage measurements to regulate and control voltages at LV substations. This was found to be a successful method of voltage control and is anticipated to be a useful technique for dealing with voltage fluctuations caused by LCT uptake on the LV network. To minimise costs, it may be necessary to find a balance between the length of the control cycle and the power quality delivered to the customer. Frequent control adjustments (e.g., using a tap changer) can lead to higher maintenance costs which outweigh the benefits of voltage control.

Name:	**Low Voltage Network Solutions**
ID:	12
Authors:	Electricity Northwest

Proposed Solution:	Network Monitoring
Funding	LCN Fund Tier 1
Start/End Date	01/04/2011 - 01/03/2014
Background:	Monitoring of LV networks enables DNOs to gain greater visibility of the state of their assets and to understand the level of spare capacity at various points of the network. LVNS aims to assess the voltage and thermal headroom at LV substations and quantitatively evaluate how this can be extended through the use of smart solutions.
Objectives:	To assess the thermal and voltage headroom at a number of substations and evaluate how implementation of smart network solutions can defer reinforcement. Solutions were assessed by the additional LCT penetration that they enable the LV network to accommodate. For example, the use of OLTCs allows the network to accommodate 60% PV penetration rather than 40% without OLTCs.
Methodology:	200 substations were monitored, covering over 1,000 feeders resulting in the collection of over 10,000 days of data. Monitoring was particularly focused on areas with high levels of PV deployment. Data was recorded on transformer utilisation, substation busbar voltages, the voltage unbalance factor across phases, power factor, neutral currents, and indicative values of total harmonic distortion. A Monte Carlo method was developed to assess the level of headroom at each substation and estimate the level of LCT connection possible before voltage and thermal issues would arise.
Relevant Outcomes:	The total project cost for Low Voltage Network Solutions was £1,680,000 for monitoring at 200 substations. Unit cost can be estimated as the cost per substation, which is £8,400. Where the Smart Grid Forum examines the % headroom released by each solution, LVNS gives the % LCT penetration at which headroom issues arise. For example, deployment of meshing was found to defer network problems from occurring at 40% PV penetration, to 70% PV penetration.

Name:	**LV Connect & Manage**
ID:	13
Authors:	WPD
Proposed Solution:	Demand Side Response/Generator Constraint Management (Referred to as ‘Active Network Management’ or ANM)
Funding	Network Innovation Allowance

Start/End Date	01/04/2016 - 01/04/2019
Background:	Prior to this project, WPD had a limited understanding of how active network management techniques could extend to LV networks. Specifically, this involved extending communications and controls to customer's homes and the ability to deal with bidirectional power flows.
Objectives:	The project aims to investigate whether Active Network Management is an effective measure for mitigating negative impacts caused by future LCT connections. Furthermore, the project developed a novel business process for the deployment of ANM in real LV networks.
Methodology:	LV Connect & Manage develops a solution architecture to control the level of demand from various low carbon technologies in consumers' homes. Domestic Load Controller (DLC) boxes were used in order to control loads such as EV charging as well as PV generation and storage.
Relevant Outcomes:	The project developed the capability to monitor the power flows associated with low carbon loads and generation in consumers' residences and built an active network management system that was able to automatically control LCTs to reduce network impact. It was concluded that this solution was an appropriate means of deferring conventional network reinforcement. The study points out that the use of this solution would be aided by the introduction of legislation and policy can be brought in to allows DNOs greater scope to make network interventions in customers' homes. Barriers are also presented by the control interfaces of LCTs; currently there exist many forms of communication with LCTs and standardisation would greatly benefit this strategy.

Name:	**Network headroom, engineering upgrades and public acceptance (NEUPA)**
ID:	14
Authors:	Imperial College London
Proposed Solution:	LV modelling (enabler not solution)
Funding	EPSRC
Start/End Date	01/07/2020-30/06/2023
Background:	"Recent work on heat decarbonisation is strong with respect to assessment of end use technology options and on supply energy vectors. However, it is weak on engineering, economic and social assessment of infrastructure needs and trade-offs -

	particularly for distribution network infrastructures that bring energy services to homes and businesses. This project is explicitly focused on this 'last mile' and combines engineering evaluation and constraint modelling with social science insights from public engagement with proposed heating solutions and their associated disruptions"
Objectives:	"The project will provide the UK's first 'map' of network capacity and headroom and consider case studies in different parts of the UK in detail. It will also assess how heat and cooling demand might change in future using weather data. Based on all this the project will evaluate the nature of potential disruption in local communities created by heat system decarbonisation. It will engage with citizens to investigate their perceptions and expectations of heat system change"
Methodology:	"The project sets out to [evaluate] what is known about distribution network condition based upon information reported by network companies and through interviews and surveys involving industry participants. […] The project will use deliberative social science research to explore the expectations of citizens to the changes and disruption to local environments that might be associated with competing alternatives for delivering low carbon heating"
Relevant Outcomes:	NEUPA "will provide information about the capacity of local networks to provide low carbon heating and cooling, recognising operational characteristics of technologies, service choices made by consumers, and policy goals. It will disseminate new information about disruption to local neighbourhoods for particular technology mixes, alongside in-depth understanding of how local communities are likely to view such changes. […] The project aims to identify those technologies which have commercial potential."

Name:	**NetZero Cheshire: Delivering Network Visibility**
ID:	15
Authors:	EA Technology
Proposed Solution:	Network Monitoring (enabler not solution)
Funding	Jointly funded by Cheshire & Warrington Local Enterprise Partnership (C&W LEP) and EA Technology
Start/End Date	1/05/2020-30/06/2021
Background:	EA Technology's VisNet® technology can be installed into a LV substation and measure many parameters, including network load. In addition to network operators' desire for greater visibility of their LV networks, this data may also be of interest to other parties, as it can signpost present capacity, identify opportunities for new

	connections, and facilitate new business models. Cheshire's Energy Innovation District (EID) is an energy intensive region and C&W LEP aims to support the local energy industry.
Objectives:	To show that LV monitoring can be deployed at scale, collected data made available, and that there is commercial interest and demonstrable value in such data.
Methodology:	For the project, VisNet® devices are being installed in 673 of SP Energy Networks' ground-mounted LV substations in the EID. These will collect near real-time data from monitored substations. This data will then be available to interested parties via a web portal, on an open access or commercial basis depending on the time delay and granularity required.
Relevant Outcomes:	Data is not yet fully available, but the relevant outcome will be whether comprehensive LV monitoring at scale removes a large portion of the uncertainty around which options to increase network capacity would be most suitable.

Name:	**New Thames Valley Vision**
ID:	16
Authors:	SSEN
Proposed Solution:	Multiple Solution Review
Funding	LCN Fund Tier 2
Start/End Date	01/01/2012 - 31/3/2017
Background:	Low carbon technologies are likely to increase electricity demand on the LV network. Distribution Network Operators (DNOs) must ensure that network constraints are not exceeded and that the network is not overloaded.
Objectives:	To investigate the LCT impacts on the LV network in the Bracknell area. The project has a particular focus on photovoltaics (PV), heat pumps (HPs), electric vehicles (EVs), and energy efficiency (EE) devices
Methodology:	The report investigates existing predictions of LCT uptake and applies them to the Bracknell area. Uptake scenarios are developed for 2020 and 2030. The study uses a forecasting model to allocate LCT distribution to individual households based on a clustered distribution and calculates the resulting changes in demand. 11 different substations in the Bracknell area are investigated.
Relevant Outcomes:	The study finds that LCTs, in particular PV technologies have a significant impact on LV networks. The risks identified are over-voltages, reverse power flows and

	exceeding thermal limits. For the model developed in this study, when >25% of households are assigned an EV, simulations show that LV networks are likely to be overloaded. Reverse power flows are predicted to occur when PV penetration exceeds 25% uptake, and over-voltages are seen at PV penetrations of 15% and above.

Name:	**OpenLV (project report, brochure, videos etc.)**
ID:	17
Authors:	EA Technology
Proposed Solution:	Distributed intelligence platform (enabler not solution)
Funding	NIC
Start/End Date	01/01/2017 - 31/12/2020
Background:	New solutions are starting to appear on otherwise passive LV networks. However, each solution is built on a different proprietary platform. There is a risk of lots of competing systems being deployed, each addressing its own, highly specific purpose, resulting in inefficiency, higher in capital and deployment costs, and stranded assets.
Objectives:	The OpenLV Solution (LV-CAP®) is a software platform, operating on off-the-shelf commodity hardware. It will sit as an interface between the HV/LV substation assets and the customers it serves. This Solution is analogous to a smartphone. The growth in smartphone Apps, shows the importance of having an open Operating System (OS) that can be deployed on multiple vendors' hardware, and the ability to have a central system or store to deploy Apps and make them available to new users. Whilst the platforms are common, the Apps used are highly tailored to suit the unique nature of a user's own needs – no two phones are identical, as no users are identical. OpenLV, will trial a similar, open platform, but for a substation.
Methodology:	LV Network Capacity Uplift will demonstrate the capability of the OpenLV platform to perform measurements and control from within a HV/LV substation. This Method is innovative as it will test the ability for control signals to be sent via a highly distributed architecture. It will also be the first NIC project to implement automated meshing of LV networks in conjunction with RTTR (Real Time Thermal Rating) of the local HV/LV transformer.
Relevant Outcomes:	OpenLV installed LV-CAP® in 50 substations and demonstrated how the platform can benefit the local electricity network by: Monitoring the network

	Performing calculations on the data received locally, reducing data transmission requirements Calculate real-time updates on the state of network assets, including remaining local capacity Predict the future status of the network based on historical performance Enact changes to the local network in response to current and predicted network status

Name:	**Shift**
ID:	18
Authors:	UKPN
Proposed Solution:	Smart EV Charging
Funding	NIA
Start/End Date	01/01/2019 - 01/05/2021
Background:	UKPN's forecasts predict that the number of EVs on their network will increase from 100k to 3.6M within the next ten years. UKPN are keen to ensure this transition is as smooth as possible.
Objectives:	Project Shift aims to understand how customers may be encouraged to take up smart charging of their electric vehicles. Additionally, the study aims to quantify the extent to which peak demand can be reduced through this method and how smart charging interacts with other network solutions.
Methodology:	Three mechanisms were tested to incentivise smart EV charging, including dynamic pricing systems, and managing the power drawn by certain customers during peak demand hours.
Relevant Outcomes:	The UKPN shift project sees peak demand reductions of 24-26% at a household level from demand management. Peak demand reductions were also seen as a result of dynamic pricing systems. One risk observed from these trials was secondary peaks that can be caused by demand shifting.

Name:	**Sustainable microgrids: Economic, environmental, and social costs and benefits of microgrid deployment**
ID:	19

Authors:	Parag, Y.
Proposed Solution:	Microgrids
Funding	Israeli Ministry of Energy
Start/End Date	- 01/10/2019
Background:	Microgrids are assessed within the context of Israel's energy system. In recent years Israel has seen a lack of investment in energy, making microgrids an attractive alternative, especially in light of the high level of expected LCT connections.
Objectives:	This research article aims to assess the costs and benefits of microgrids in comparison to the counterfactual of conventional reinforcements and grid development. Existing tools for assessing the cost-benefit of various network reinforcements are biased against microgrids; this paper therefore aims to develop a new and 'fair' assessment framework
Methodology:	Microgrids are assessed on a number of factors including environmental, deferral of investment costs and reliability of supply. Previous methods of network asset evaluation do not take into account all of these factors, largely because they can be hard to quantify. This paper aims to tackle this issue and value microgrids more effectively.
Relevant Outcomes:	Costs for setting up a microgrid are likely to be very high since they involve multiple installations, monitoring equipment and maintenance costs. However, comparing this with conventional upgrades on the same scale show that microgrids are still the less expensive option. For 10MW of generation capacity, microgrids save $260,000 compared to the counterfactual

Name:	**Transition to low voltage DC distribution networks – Phase 1**
ID:	20
Authors:	SPEN
Proposed Solution:	LV DC Networks
Funding	Network Innovation Allowance
Start/End Date	01/01/2017 - 01/10/2017
Background:	DC networks represent an opportunity to transfer higher power in existing cables, since it can eliminate losses associated with inductive loads and AC-DC power

	conversion. These systems have already seen utility scale application in high voltage networks (HVDC) and, with advancements in power electronics, are being investigated at the distribution level.
Objectives:	To provide a business case to demonstrate whether low voltage DC networks are financially and technologically competitive with conventional reinforcements. To develop an understanding of LV DC networks in order to determine requirements for their deployment and installation. To highlight some potential applications and give estimates of costs.
Methodology:	A literature review was carried out prior to any modelling to find out about existing LVDC research or projects and extract any relevant information. Following this, desktop modelling was carried out to assess theoretical potential for DC networks to increase capacity. Finally, technical specifications for DC cable testing were generated, to be used in a second phase of the project.
Relevant Outcomes:	LV DC systems have the potential to increase cable capacity and may be less costly than conventional reinforcements. However, it is noted that additional energy is dissipated during DC faults, known as 'thermal shocks'. LVDC networks can be more reliable than LVAC and may be useful for application in rural areas where security of supply is an issue. The study also reports that this system is better at managing local generation and loads than equivalent AC networks. In urban areas the main advantages of this system are increases in capacity and reduced reinforcement costs. The main obstacles facing this technology are power losses from power-electronic interfaces and DC protection requirements.

Name:	**Voltage Management on Low Voltage Busbars**
ID:	21
Authors:	Electricity Northwest
Proposed Solution:	Dynamic Voltage Management
Funding	LCN Fund Tier 1
Start/End Date	01/04/2011 - 01/10/2013
Background:	The rapid uptake of low carbon technologies in the near future is likely to lead to significant variations in line voltages on LV networks, which could lead to voltage tolerances being exceeded and deterioration of power quality. It is expected the demand in increase caused by electrification of heat and transport will lead to a fall in line voltages if remedial measures are not introduced. Furthermore, distribution-connected generation also poses the risk of raising line voltages outside of normal

	limits. As a result, it will likely be necessary to control voltages throughout the LV network, rather than just at 11kV busbars.
Objectives:	To deploy a range of voltage management strategies across 15 substations and monitor their ability to regulate line voltage in real time. The ability of solutions to correct poor power factor was also evaluated. The study acknowledges that the LV network will likely see problems associated with thermal headroom, however the focus of this investigation is mainly regarding voltage issues.
Methodology:	The following solutions were deployed: distribution transformers with on-load tap changers, a 'powerPerfector Plus' (voltage optimiser), active harmonic filters and LV capacitors. The devices were monitored in real time and results post-processed to evaluate the merits of each solution. Modelling was also carried out by the University of Manchester for both solutions deployed in the field and technologies that were not physically deployed.
Relevant Outcomes:	On-load tap changers showed the best results in terms of raising headroom, however, it is acknowledged that the location and number of feeders have a significant effect on this and that, in some circumstances, storage or capacitors may be a more favourable option. It was found that larger capacitors increase network headroom, however, above a certain rated capacity, reverse power flows start to occur. For the setup detailed in the report, capacitors rated at 100kVAr and 250kVAr increased headroom, but those rated at 400kVAr were less effective due to reverse power flows. Furthermore, the study also notes that this strategy is less effective for networks with more resistive loads rather than inductive loads.

This publication is available from: www.gov.uk/beis [replace with direct URL if known]

If you need a version of this document in a more accessible format, please email enquiries@beis.gov.uk. Please tell us what format you need. It will help us if you say what assistive technology you use.