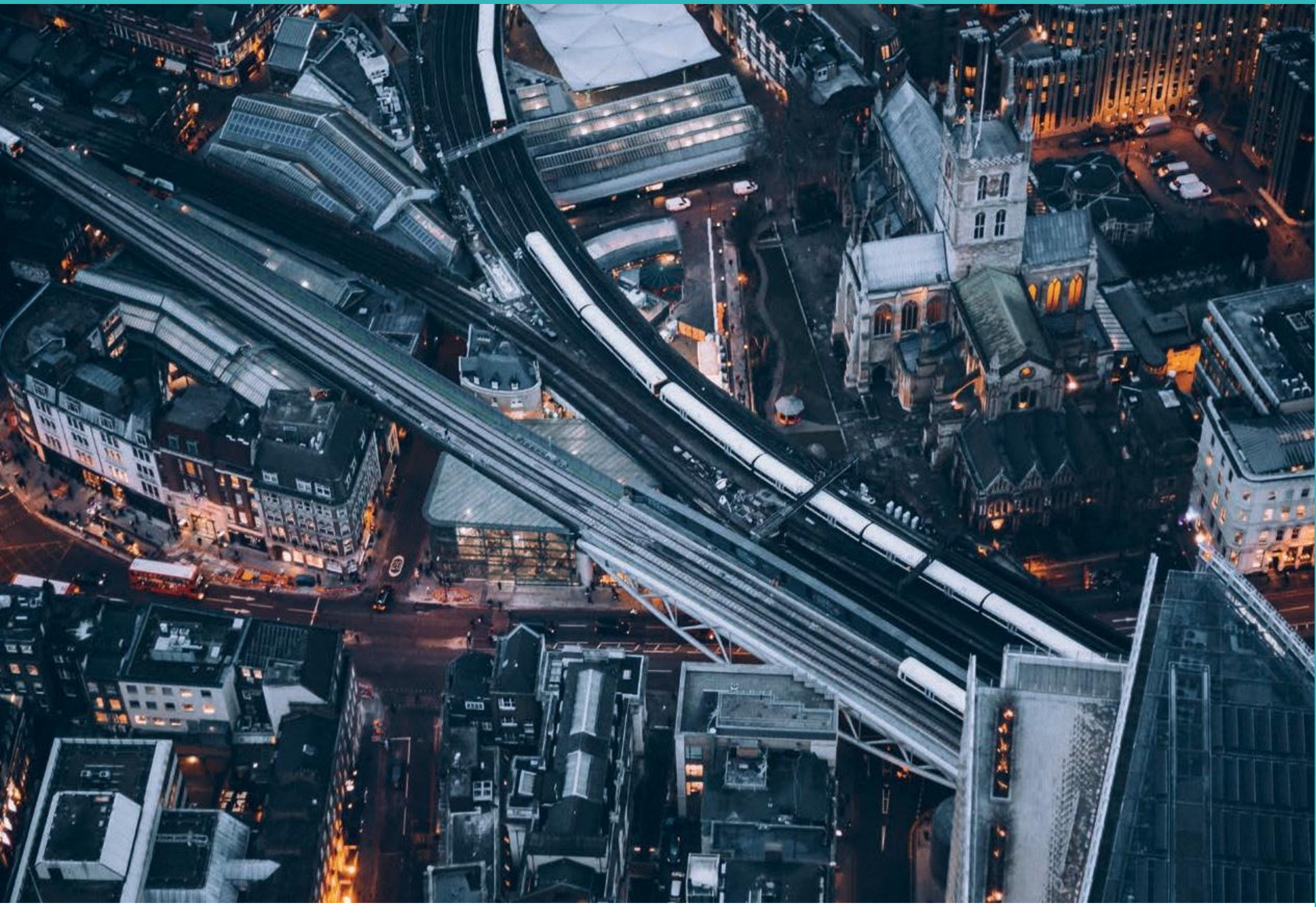

REPORT

SILVERSMITH Literature Review

Prepared for: Western Power Distribution

Report No: EA16141-TR2
Document Version: 1.3
Date: 14 February 2023

technology

Version History

Date	Version	Author(s)	Notes
22/08/2022	1.0	Sebastian Lindmark, Thomas Stone	Draft Report
01/09/2022	1.1	Sebastian Lindmark, Thomas Stone	Updated to address client comments
09/09/2023	1.2	Sebastian Lindmark, Thomas Stone	Final report
14/02/2023	1.3	Sebastian Lindmark, Thomas Stone	Removal of "Private & Confidential" labels

Final Approval

Approval Type	Date	Version	EA Technology Issue Authority
Business	22/08/2022	1.0	David Mills – Head of Net Zero Transition
Business	02/09/2022	1.1	David Mills – Head of Net Zero Transition
Business	09/09/2022	1.2	David Mills – Head of Net Zero Transition
Business	14/02/2023	1.3	David Mills – Head of Net Zero Transition

EA Technology Limited, Capenhurst Technology Park, Capenhurst, Chester, CH1 6ES;
Tel: 0151 339 4181 Fax: 0151 347 2404

http://www.eatechnology.com

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Executive Summary

The *Solving Intelligent LV - Evaluating Responsive Smart Management to Increase Total Headroom* (SILVERSMITH) project is being undertaken in order to examine the issue of extracting maximum value from the existing Low Voltage (LV) electricity network, given an uncertain future where foreseeable futures witness a vast growth in LCTs such as Electric Vehicles (EVs) and Solar PV. SILVERSMITH will assess smart and novel technologies, using the EA Technology Transform® Cost Benefit Analysis software to see which of these technologies offer value to Western Power Distribution, by increasing available headroom on the existing LV network. DIgSILENT PowerFactory will also be used to assess the impact of these smart novel technologies on a range of case study networks from dense urban, urban and rural environments.

To inform the analysis, Western Power Distribution (WPD) have asked EA Technology to conduct a literature review to identify potential technologies for consideration in the Transform Model® and PowerFactory analysis. The literature review presented in this report has considered a range of source, including innovation projects conducted by UK DNOs, as well as project carried out elsewhere around the world. Solutions covered by the literature review include direct network solutions (such as transformer cooling, phase balancing, smart transformers), market based solutions (such as DSM /DSR) and policy based solution (such as increasing voltage tolerances).

As part of the process of identifying potential solutions, a Request for Information (RfI) was published by WPD (in collaboration with EA Technology), asking potential technology providers to give information about their technologies to inform the assessment. Responses to the RfI are summarised in this report.

This report considers how technologies from the literature review and RfI processes will be incorporated into the Transform and PowerFactory studies. It collates the parameters required for each technology based on the literature review findings. This will inform the Transform and PowerFactory studies.

The conclusions from the literature review are as follows:

C1. As part of the literature review a range of solutions have been considered that have potential to provide either additional voltage or thermal capacity to the network. These solutions range from retrofit devices, physical network interventions, market solutions (encouraging consumer engagement) and policy solutions.

C2. The Request for Information received six replies from suppliers, and the relevant commercial and technical information provided have been used to update the technical and commercial parameters required for modelling.

C3. The Request for Information was limited in its range compared to the list of solutions under consideration, therefore as the project progresses further engagement with suppliers may be needed. Future responses to the RfI can still inform solutions to be deployed in the Transform and PowerFactory analysis.

C4. Where possible, the technical and commercial parameters required for modelling have been updated from previous relevant studies.

The recommendations from the literature review are as follows:

R1. Engagement with suppliers should be continued in the next stages of the project, either through leaving the RfI portal open or direct communication with suppliers, to provide further information on the listed solutions.

R2. Further consideration should be made as to how engagement from suppliers could be improved. This may include being more clear in communications on what the benefits of engaging in the project are for the suppliers.

R3. The RfI is tailored for established products and may be too technically detailed for lower TRL solutions. The focus of this project are high TRL solutions, however WPD may wish to continue engagement with low TRL solutions as they become more established.

R4. For future studies, other factors to capture could include second order benefits (i.e. environmental / social benefits) for the solutions.

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1. Definitions

Term	Definition
AC	Alternating Current
BESS	Battery Energy Storage System
DAR	Dynamic Asset Ratings
DC	Direct Current
D-FACTS	Distributed Flexible AC Transmission Systems
DNO	Distribution Network Operator
DSM	Demand Side Management
DSR	Demand Side Response
EAVC	Enhanced Automatic Voltage Control
ED-2	Electricity Distribution 2
ENA	Energy Networks Association
ER	Engineering Recommendation
EU	European Union
EV	Electric Vehicle
EVCPs	Electric Vehicle Charge Points
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
kW	Kilowatt
LCTs	Low Carbon Technologies
LV	Low Voltage
NDA	Non-Disclosure Agreement
NPg	Northern Powergrid
OEM	Original Equipment Manufacturer
OLTCs	On Load Tap Changers
PV	Photovoltaics
RfI	Request for Information
SPEN	Scottish Power Energy Networks
STATCOMs	Static Synchronous Compensators
TRL	Technology Readiness Level
UK	United Kingdom
UKPN	UK Power Network
USA	United States of America
VARs	Unit for Reactive Power
WPD	Western Power Distribution

2. Background and Introduction

Traditionally, low voltage (LV) networks have been designed using assumptions about the diversity of customer's electricity usage to drive efficiencies in the network design. The forecast growth of Low Carbon Technologies (LCTs), ranging from embedded generation (most typically solar PV), to storage technologies (e.g. battery energy storage systems) and new sources of load (most noticeably electric vehicles and heat pumps), will provide new challenges in managing the LV network. The challenge for network operators is how to ensure that they continue to provide a safe and reliable supply of electricity to consumers at best value under an uncertain future. Simultaneously, networks should be designed in a way that is equitable for both owners and non-owners of LCTs. As a result, alternative network interventions are being considered where they offer value instead of traditional asset replacement. These interventions include a range of solutions ranging from technical devices to consumer service models all aimed at ensuring better utilisation of existing network assets.

Historically, alternative network interventions have been focused towards the high voltage (HV) networks. This has mainly been driven by cost and necessity. With regards to cost, the distribution networks are planned and designed to ensure compliance with the Distribution Code, and further specific details set out in the Energy Networks Association (ENA), Engineering Recommendation (ER) P2 (currently P2/7 [1]) and P28 (currently P28/2 [2]). The former of these ENA ER focussed on designing a system to ensure security of supply for customers and the later focussed around ensuring the voltage at customer terminals remains within limits compatible with customer devices (BS EN 50160 [3]).

To comply with the requirements set out in these standards investment in HV networks have often shown greater return due to the larger number of customers that are benefitted. As a result, investment in alternative interventions on the HV network have been trialled and are becoming more widely used across the distribution networks these have typically focussed around HV network deployed solutions, such as:

- Network monitoring and modelling – The increased use of monitoring devices on the HV network allows the networks to better understand the available capacity, existing load and status of circuits on the network. Integrating this with existing modelling tools ensures investment is targeted at those areas of greatest benefit.
- Fault detection – Increased use of devices to provide real-time estimates of fault levels as well as reporting on fault situations enables networks to understand where the greatest operational risks remain. Utilising this data, the networks can intervene through network reconfiguration or upgrades to ensure the network remains operational and within appropriate safety parameters.
- Voltage regulation – Voltage regulation on the HV network has historically been provided through on-load tap changers (OLTC) and reactive power devices. This has ensured the voltage on the HV network remains within operational limits and by design maintained the LV network within regulatory limits. Increasing levels of embedded LV generation and LV demand means the direction of power flow is changing and voltage regulation at the HV network may no longer be the only option.
- Flexibility services through a range of commercial models to enable LV and HV connected customers to alter their demand or generation in response to signals and payment from the distribution network.

As the uptake of LCT grows it is expected that smart interventions to the LV network will be more commercially viable as traditional network reinforcement is not practically, technically or commercially viable at the scale required. For this reason, network operators are now considering a range of solutions that will extract additional headroom from the existing LV network, postponing the need for the network reinforcement. Some of these solutions are derivatives of tried and tested solutions on the HV network whereas other are completely novel. In both cases it is important to do a bespoke analysis of the technical and commercial viability of the solutions to the LV network and the level of effectiveness they have in releasing additional capacity from existing assets.

This report analyses technologies that have the potential to allow network operators to extract additional headroom from their existing LV networks, ensuring that they can extract maximum value from their existing assets. By evaluating alternative network interventions as well as their compatibility with WPD's network, the most promising solutions available (both now and in the next decade) to release headroom on each network archetype across the distribution network can be identified. This evaluation will also identify any gaps in the market where there is potential for a new technology to be developed that would see widescale deployment on WPD's network.

2.1 Existing HV Regulation Solutions

Historically, power has flowed in the UK distribution network from HV to LV systems. As a result it has traditionally been assumed and designed that if the HV voltage is maintained within operational requirements (for example 11 kV +/- 6%) then operational design of the LV network will ensure all customers remain within statutory limits (0.4 kV +10% / -6%).

Several options are available to the distribution network to actively maintain the HV voltage within statutory limits, some of the most typical installations being:

- On-load Tap Changers (OLTC) – These allow the tap position of the EHV/HV transformer to be changed without the need to interrupt any load. The tap changer controller (AVR) setting is established to ensure the voltage at both the closest and furthest HV/LV substation is such that the LV voltage remains within limits.
- Capacitors – The introduction of capacitance to the HV network can increase the voltage locally. These can either be static or switched to enable control of the HV voltage and are typically used during period of high demand.
- Reactors – The introduction of inductance to the HV network provides a reduction in the voltage locally. These can either be static or switched to enable control of the HV voltage and are typically used during periods of low demand or high generation.
- Generator connection agreements – Traditionally HV connected generators operate with a constant power factor and provide an export of reactive power. Alternative connection agreements can provide an option to import reactive power, reducing the impact active power export has on the network.

The specific combination of HV connected voltage regulation approach depends on the design of the HV network, variation in demand and level of embedded generation. Additionally, as demand and generation levels change set-points and operating parameters may well be altered to improve voltage compliance.

2.2 Existing LV Voltage Control Solutions

Traditionally, power flows in one direction on the majority of LV networks from the HV/LV transformer to the last customer along the LV feeder. As a result the voltage is assumed to reduce with distance along the feeder and therefore design considerations need only consider the maximum demand condition to ensure the voltage remains within statutory requirements. Figure 1 Table 1Figure 1shows an example of the voltage drop along a feeder where the HV voltage has been established such that the LV voltage remains within statutory limits (+10% / -6%) for maximum and minimum demand conditions.

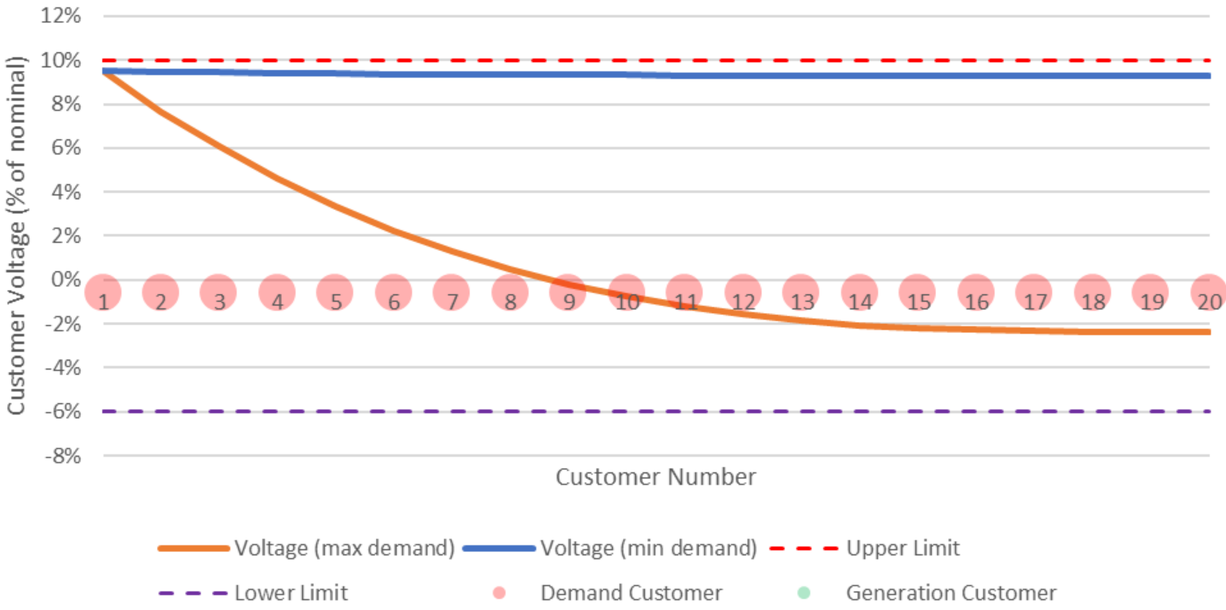

Figure 1 Example of voltage drop along LV feeder for minimum and maximum demand conditions

As the uptake of LCTs continues to increase the power flows on the LV network are anticipated to change. This being as a result of both increasing levels of demand as a result of electric vehicles and heat pumps, alongside embedded generation such as rooftop solar. As a result, it will no longer be possible to establish a target HV voltage at the HV/LV substation that can accommodate all conditions across all feeders. Figure 2 provides an example, where even after reducing the source LV voltage a single set-point cannot be achieved for both maximum and minimum demand conditions.

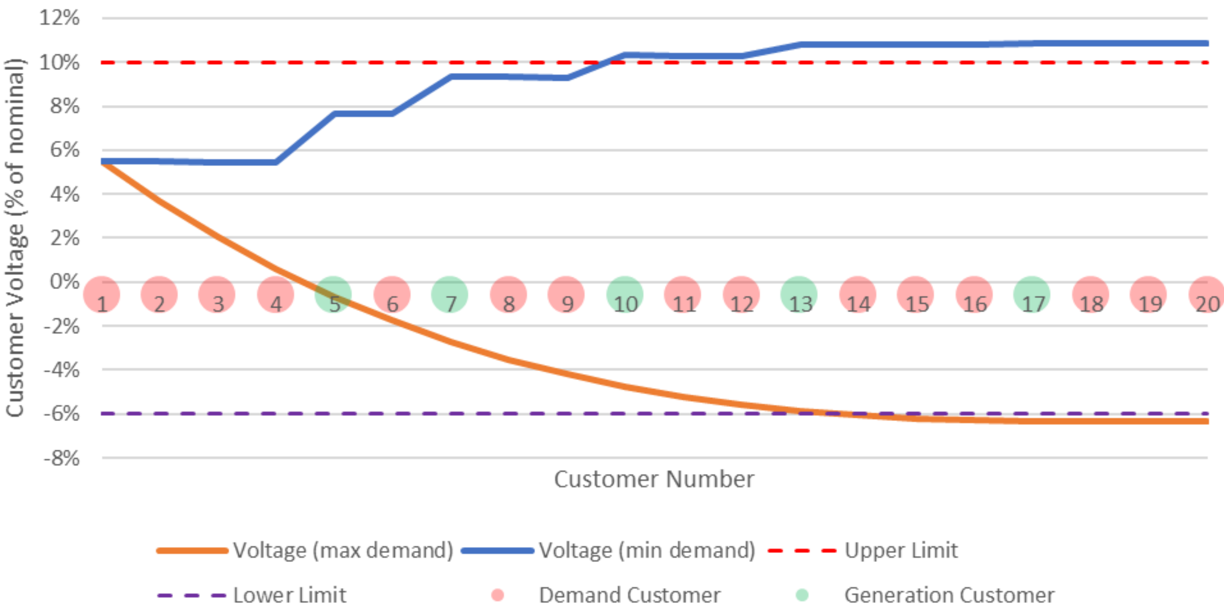

Figure 2 Example of voltage drop along LV feeder with increased levels of embedded generation

It should also be noted, that this example has only considered the impact of changing the HV voltage on this substation. That change would also have an impact on the wider HV system and consequences for other LV connected customers.

3. Literature Review of Existing Technologies

3.1 Factors to Consider

3.1.1 Transformer Thermal Loading

It is vital to consider the thermal characteristics of transformers when assessing alternative solutions to network reinforcement. Transformers, although big devices, are relatively compact and mainly consist of metallic parts. Insulation is therefore a vital factor of design to prevent conductance between different phases and limit electrical losses. Different parts of the transformer (i.e. windings and transformer wall) will require different types of insulation. The insulation, alongside the structural components of the transformer, will have thermal ratings associated to them. When these ratings are exceeded both their mechanical strength and dielectric properties deteriorate. This is the critical factor to transformer lifetime. IEEE C57.91-1995 guide [4] states that the life of the insulation is the life of the overall transformer.

With this being said, it is very common to temporarily overload a transformer beyond its name plate rating. In order to do so it is important to know it's basic limitations. According to the IEC 60076-2:2011 standard [5], power transformers ratings are set relative to the ambient temperature. According to this guide the maximum ambient temperature should not exceed 40 ^{o}C or have an average monthly ambient temperature higher than 30 ^{o}C. The temperature rise limit is the maximum differential allowed between the ambient and transformer temperature. Different parts of the transformer (i.e windings and insulating liquid) may have differing temperature rise limits, which will also vary depending on the cooling systems in place. The limiting factor (and therefore the thermal rating) is the hotspot temperature of the transformer. The IEC 60076-2:2011 standard states that the standard rated temperature is 105 ^{o}C, however this will vary dependent on the design of the transformer. It is important to note that older generation transformers may have been designed to operate under different thermal ratings, hence this may not apply for all existing assets.

The thermal rating of a transformer can be exceeded, however there is a relationship between the hot spot temperature of a transformer and the per unit of its normal life. Meaning that as the temperature increases the expected life span of the product decreases. Careful consideration of transformer temperature is therefore needed when overloading, as excessive temperatures for prolonged periods of the time will drastically accelerate the transformer degradation rate.

Power losses are one of the key contributing factors to a rise in transformer temperature, where the load losses are the main source of heat in the transformer. Load losses refers to the losses associated with current running through the windings including resistance related losses and stray losses. Resistance losses dissipate heat to the surrounding area respective of the current (I^2R), whereas stray losses are caused by magnetic flux leakage and can lead to concentrated hotspot areas. Methods to improve thermal capacity, therefore, consist of solutions that either effectively cool the transformer, better insulate or reduce the heat dissipated. [6]

3.1.2 Cable Thermal Loading

Similar to transformers, cables also have thermal operating limits which impact their life expectancy. Although the metallic component of the conductor has a thermal rating, these temperatures tend to be a lot higher than the ratings for the insulation, therefore the thermal rating of the insulation dictates the rating of the cable. Cable insulation materials are chosen based on a series of properties including the dielectric strength and flexibility of the material. A range of polymers are commonly utilised due to their dielectric and elastic properties. The cable rating is therefore often reliant on the thermal properties of the polymer. Under high temperature conditions, the polymer structure begins to deteriorate, resulting in reduced dielectric strength and increased probability of electrical faults. [7]

It is therefore important to consider the thermal rating of the cable and how the associated load impacts the cable temperature. As outlined previously, resistance related power losses cause heat dissipation to the surrounding area, ultimately heating up the conductor as well as the insulator. The rate at which heat (P) dissipates is proportional to the resistance (R) of the cable and the current (I) squared, $P = I^2R$. Therefore, at higher loads the cable is expected to heat up faster. Although all polymers have different thermal characteristics, as a rule of thumb it is assumed that for every 10ºC the operating temperature of the cable is increased above its rated temperature the expected life of the cable halves. Therefore, if a cable rated at 90ºC has a life expectancy of 50 years, if the operating temperature is increased to 100ºC the life expectancy drops to 25 years. [8]

3.1.3 Voltage Headroom and Legroom

Voltage headroom and legroom dictate the upper and lower voltage limits. Voltage headroom indicates the percentage increase from the nominal voltage (230 V) that can occur on the feeder before the statutory upper voltage limit (253 V) is breached. Similarly, voltage legroom dictates the percentage decrease from the nominal voltage that can occur on the feeder before the statutory lower voltage limit (216 V) is breached. Voltage limits are placed on the LV network to ensure that the voltage of the supply to the consumers is appropriate for the voltage that appliances and devices are designed to work with. The figure below shows the busbar voltage for a single phase line on the LV monitoring, showing how voltage levels may vary throughout the day.

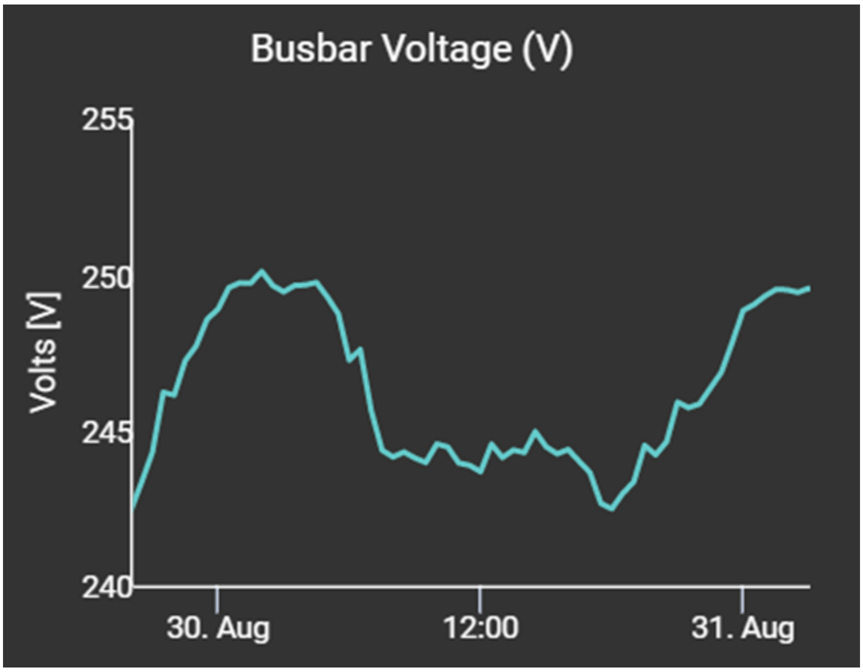

Figure 3 Example of a one phase daily voltage profile

The upper voltage limit is breached when the net export from the feeder exceeds the power that corresponds to the maximum allowable voltage rise. Similarly, the lower voltage limit is breached when the net import from the feeder exceeds the power that corresponds to the maximum allowable voltage fall. There are multiple consequences associated with exceeding these voltage limits. In example, if the voltage in a circuit is too high it can speed up electrical machinery and cause damage to components by overheating them. On the other hand if the voltage in a circuit is too low, the electrical devices may fail to start tripping a continuous inrush current which again can lead to overheating and failure of components.

3.1.4 Power Quality

Power quality refers to the voltage, current and frequency levels on the power system and their proximity to the set operating standards [9] [10]. In a scenario where there is constant power, constant impedance and constant current loads, the current and voltage waveforms are almost entirely sinusoidal. With modern power electronics this is not the case, instead we observe a higher degree of current and voltage wave distortion (see Figure 4 as an indicative example). This can have a negative effect on the distribution network, by operating outside of set boundaries, as well as for the consumer.

For distribution and transmission networks, power quality issues impact the headroom available across the network as a result of the thermal losses and heating associated with the distortion. Short term, or repetitive voltage disturbances (dips and rises) can also have unexpected consequences on system operation impacting reliability of supply. For the consumer, the power quality of their supply needs to remain within set limits to ensure the efficient operation of their devices.

Power quality related issues are becoming more relevant as modern electronics (i.e. computers, microprocessors, telecommunication devices, etc.) have more sensitive operating limits. At the same time there is an increased use of products (non-linear loads, inverter based generation, etc.) that contribute to power quality issues. AC-DC inverter are present in many LCTs, including each PV connection and EV. Existing network arrangements mean harmonic distortion and voltage disturbances cannot be treated independently at HV and LV levels. Power quality is generally of greatest concern at the HV level where limits are smaller and issues will impact HV connected commercial or industrial consumers directly. As the uptake of LCTs continues, it is expected that the LV network will begin to experience substantial power quality issues if not properly managed.

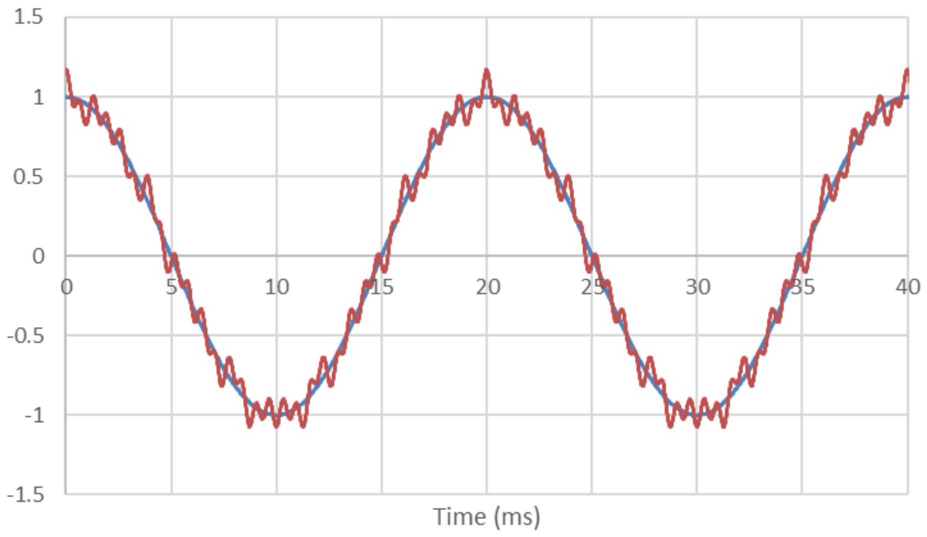

Figure 4 Example of harmonic distortion superimposed on a traditional sinusoidal waveform

3.2 Relevant Innovation Projects

The SILVERSMITH project will use knowledge from previous innovation projects to inform solutions that will be modelled in Transform and PowerFactory. SILVERSMITH will compliment these previous projects by providing an understanding of which technologies are likely to have the greatest impact on different LV network archetypes. It will also highlight any gaps in the market where technologies do not yet exit, but would provide a valuable network solution.

This project aims to identify a range of solutions that provide additional capacity to the LV distribution network. As part of the literature review, effort has been made to look at other relevant innovation projects where solutions have been trialled on the LV networks. Table 2 provides a summary of key projects where a range of innovative solutions have been developed, trialled and tested. Due to the active and ongoing work in this area of research, this table should not be considered exhaustive with many smaller or sub-projects contributing to the development of these larger scale projects.

Table 2 List of Relevant Innovation Projects

Project Name	Company Name	Date	Description	Solutions Trialled
LV-Engine [11]	SPEN	2018-2022	LV-Engine is an ongoing innovation project investigating how smart transformers and alternative network configurations can accommodate the growing demand associated with LCT uptake. The project aims to compare the transformer's ability to regulate voltage levels compared to alternative voltage control devices. As well as demonstrating the benefits of a DC connection for low carbon technologies.	Smart Transformers, LVDC networks
Faraday Grid Deployment Trial [12]	UKPN	2018-2021	Faraday Grid Limited (FGL) developed is developing a product called 'Faraday Exchanger' (FE); this is an innovative device, which occupies the position of a traditional transformer in the network. An FE provides the traditional functionality of a transformer and could potentially provide:- Voltage control over a much broader range of variation including-removal of harmonics, correction of power factor and phase-balancing. Due to insolvency, this project was not completed but the technology is being developed further by Third Equation Ltd.	Smart Transformer

OpenLV [13]	WPD	2017-2021	OpenLV developed a flexible platform that used real time data from LV monitoring to enable a series of services that helped provide additional capacity at the secondary substation. These solutions included real time dynamic asset ratings, meshed networks as well as smart charging and other flexibility services.	LV Monitoring, Dynamic Asset Rating, Meshed Networks, Smart Electric Vehicle Charging, .
Celsius [14]	ENW	2016-2020	The Celsius project looked at thermal behaviour of network assets and identified solutions to release additional thermal capacity to the network. The project monitored the temperature of 520 substation across ENW's network, used sensors to provide dynamic asset ratings and trialled a series of cooling technologies to release additional thermal capacity.	Transformer Cooling
Electric Nation [15]	WPD	2016-2019	Electric Nation was the largest home charging EV trial of its time. The project looked at identifying the key issues for network operators associated with the uptake of electric vehicles and the associated charging demand. Electric Nation looked at consumer flexibility for EV charging.	Smart Electric Vehicle Charging
Distributed Storage and Solar Study (DS3) [16]	UKPN	2016-2019	Distributed Storage and Solar Study (DS3) looked at the problems that distributed solar generation uptake may have on the network. The key concerns was around reverse power flows and voltage rises on the LV distribution network. Battery energy storage systems were explored as an alternative to traditional network reinforcement.	Energy Storage
Entire [17]	WPD	2016-2019	The Entire project builds on previous projects to develop the skills, relationships and systems required for the DNO to provide demand side response (DSR) services. The project looked at the benefits of deploying DSR schemes and it's potential to release additional capacity to the network.	DSR
Enhanced Voltage Control [18]	ENW	2015-2019	ENW had previously completed a project called CLASS (Customer Load Active System Services) looking at how effective voltage control could minimise peak demand without impacting customers. The enhanced voltage control project is a follow up project looking at new solutions, including voltage managed generation connection contracts.	Generator Constraint Management

Smart Street [19]	ENW	2014-2018	The Smart Street project investigated the impact that LCTs will have on voltage levels and potential smart solutions that can help ensure that the statutory voltage limits are not exceeded. The project trialled a series of voltage regulating devices as well as developing an automation system for the LV network.	OLTC, Meshed Networks
FUN – LV [20]	UKPN	2013-2016	Flexible Urban Networks – Low Voltage (FUN – LV) looked at the potential for power electronics to help defer network reinforcement to the LV distribution network required to accommodate the uptake of LCTs. Three different methods were trialled for meshed networks and their ability to release additional capacity for the network.	Meshed Network
FALCON [21]	WPD	2011-2015	Flexible Approaches for Low Carbon Optimised Networks (FALCON) investigated new LV network solutions that would need to be deployed as a consequence of LCT uptake. The project quantified and predicted 11kV network constraints and the potential costs and benefits of potential mitigation solutions as well as actual trials of the solutions.	Dynamic Asset Rating, Meshed Networks, Energy Storage, Generation Constraint Management, Demand Side Management
Low Voltage Network Solutions [22]	ENW	2011-2014	The Low Voltage Network Solutions project was completed to gain a better understanding of the low voltage network, the thermal and voltage capacity of existing assets and the forecast increase in electricity demand attributed with the uptake of LCTs. A series of solutions were investigated and trialled to procure additional capacity from the network assets.	OLTC, Switched Capacitors, Meshed Networks, Energy Storage
Customer Led Network Revolution [23]	UKPN	2010-2014	The Customer Led Network Revolution (CLNR) was a smart grid demonstration project that investigated the impact that LCTs would have on the network, and what network and consumer interventions could help minimise the need for costly network reinforcement. Among the solutions trialled were enhanced automatic voltage control (EAVC) systems and demonstrated their potential to mitigate voltage issues related with LCT uptake.	Dynamic Asset Ratings, Energy Storage, Demand Side Response, EAVC

3.3 Identified Solutions

3.3.1 Network Monitoring & Modelling

Network monitoring and modelling consists of collating real time data from the network, providing the DNO with improved network visibility. LV monitoring is an example of this, where data is collected at a feeder level from the secondary substation. With the growing levels of LCT uptake, there is a greater need for real time data, and as a consequence a greater need for LV monitoring deployment in RIIO-ED2,. Existing LV monitoring use cases include using real-time data to predict, identify and locate faults [24]. LV monitoring can also provide a better overview of available capacity at the network that can be used to get better asset utilisation rates or facilitate flexibility services.

Figure 5 shows the phase voltage and current collected from an LV monitor, this is a publicly accessible data base where energy consumers and prosumers can also gain better awareness of the local demand profiles. [25]

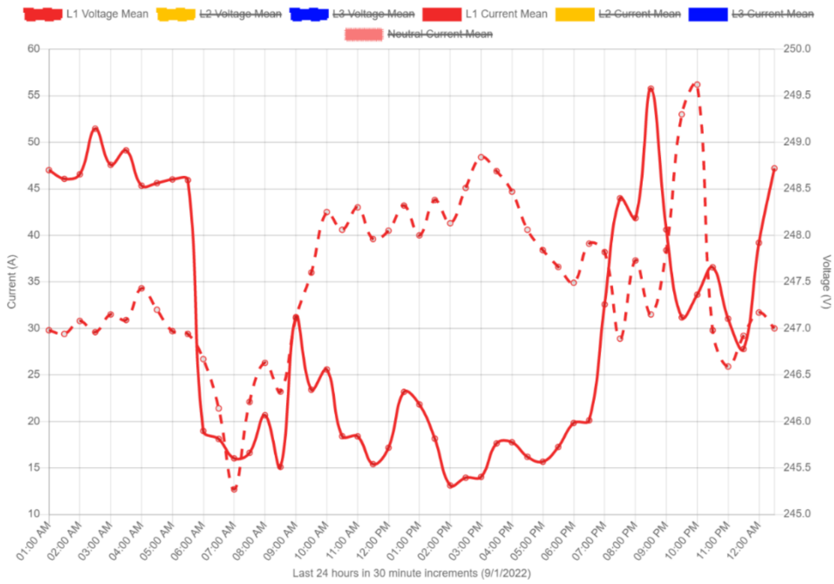

Figure 5 Voltage and Current profiles from LV monitoring, accessible through the Net Zero Cheshire website [25]

Smart meter data is the other alternative, which collects data from the consumer's site providing the DNO with valuable insight into consumer energy behaviour. Smart meter data, although it may be difficult to access by DNOs due to data security concerns, can be used to facilitate consumer led flexibility services and can also be modelled to provide an aggregated load profile at feeder or substation level. Incorporating network data with other external data sources can also be used to provide other solutions like dynamic asset ratings. Network monitoring, therefore has the potential for being a key enabler of other solutions that provide additional capacity to the network.

3.3.2 Smart EV Charging

Trials such as Electric Nation [15] have assessed whether smart electric vehicle (EV) charging could be used to alleviate potential network constraints caused by increased deployment of Electric Vehicle Charge Points (EVCPs) on the LV network. Smart charging shifts charging away from peak hours (typically during the evening peak), until times where there is capacity available on the network (typically overnight). Trials have shown that this is both technically feasible and acceptable to customers. In the UK, new EV chargers must be smart by law [26]. Smart EV chargers are sited in customer's properties, and assumed to be paid for by consumers when installing EVCPs. Often smart EV charging is controlled automatically, and incentivised by Time of Use tariffs, which allows EV owners to charge their cars more cost effectively by taking advantage of cheaper electricity rates overnight (when there is spare capacity available on the LV network). By shifting demand out of peak hour this solution is expected to provide benefits through increased network asset utilisation at times away from the current peak demand. An example is shown below in Figure 6 and Figure 7, demonstrating that shifting the EV charging demand peak to overnight, additional capacity is released.

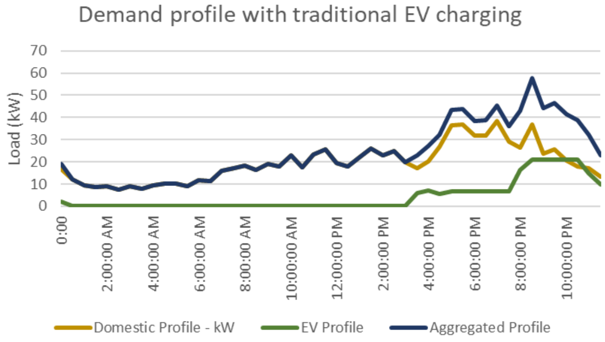

Figure 6 Example demand profile at a HV/LV substation with base domestic, EV charging and aggregated profile

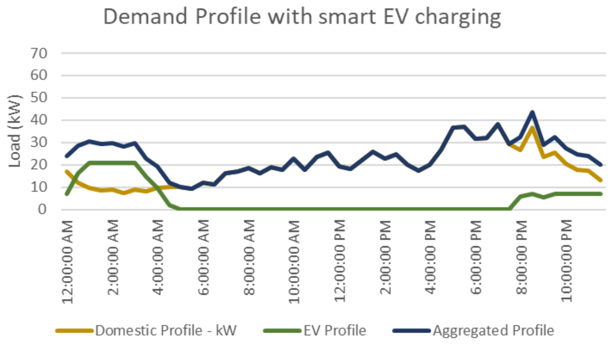

Figure 7 Base domestic, EV charging and aggregated profile with overnight (smart charging).

3.3.3 Energy Storage

Energy storage, typically provided by Battery Energy Storage Systems (BESSs), can be utilised to manage network constraints on the LV network. Battery storage can either be behind-the-meter (customer owned), sited at customer's properties. Alternatively, Battery storage can be grid connected, in which case the BESS can be positioned either in the distribution substation, or potentially at the end of feeder or some location partway along the feeder.

Energy storage can be utilised to resolve thermal constraints by either absorbing any excess generation to reduce net export by battery charging, or alternatively by discharging at the time of peak demand to reduce the strain on transformers and conductors.

Battery storage can also be used to mitigate voltage issues. If voltage drop is an issue, a battery placed sufficiently close to the section of the feeder where voltage drop exceeds statutory limits, can be used to mitigate this issue by discharging at the time where volt drop exceeds limits, charging when voltage legroom is available on the circuit. Similarly, if voltage headroom is an issue, appropriately positioned batteries can be charged during times of peak generation to absorb excess power and prevent the voltage from rising above statutory limits. Distributed Storage and Solar Study (DS3) was a study completed by Northern Powergrid (NPg), that demonstrated how energy storage systems can help facilitate the growing uptake of solar photovoltaics

(PV). The study showed that BESS can effectively mitigate reverse power and voltage rise issues associated with PV generation whilst also assessing the wider benefits of absorbing the evening peak (voltage drop and peak loading) [27].

3.3.4 Generator Constraint Management

During peak hours of generation, local generation can help alleviate some of the strain on the network. The voltage rise observed on the feeder can be reduced by the generator responding to signals under certain network conditions. By responding and ramping down generation, the generator(s) acts to release voltage headroom [28].

Generators may also provide network support by operation in PV (power and voltage) mode [28]. In this mode generators act to support network voltage by producing or absorbing reactive power (VARs) as required. This support acts to reduce reactive power on the network, reducing power losses and voltages. As the uptake of distributed generation grows this may offer a local solution to reduce circuit loading and maintain voltages within limits.

Generators positioned on the LV network can offer flexibility to network operators. Generators will typically be consumer or commercially owned and network operators may take advantage of the flexibility by entering into arrangements with providers (generator owners or via aggregators). Here the network operator offers payment to the provider in exchange for the service provided by their generator for the network. The OpenNetworks project provided the standard flexibility service framework for UK electricity network operators. [29] Arrangements may be static, based on pre-arranged operating windows, or dynamic based on when network constraints are witnessed on the network. Dynamic response requires LV network monitoring to determine when network constraints occur, and a communication protocol to signal to the providers to respond.

3.3.5 Demand Side Response

Demand Side Response (DSR) most commonly refers to agreements between the DNO and large scale energy consumers, where the consumer reduces demand at peak hours. This is now being looked into at an LV level for small scale commercial and residential customers. This solution is expected to see a higher effectiveness in increasing headroom for commercial customers where this can be managed within their operational requirements. The figure below provides an example of where a customer has provided a demand reduction, significantly reducing their demand for a period of the day and releasing spare capacity on the network.

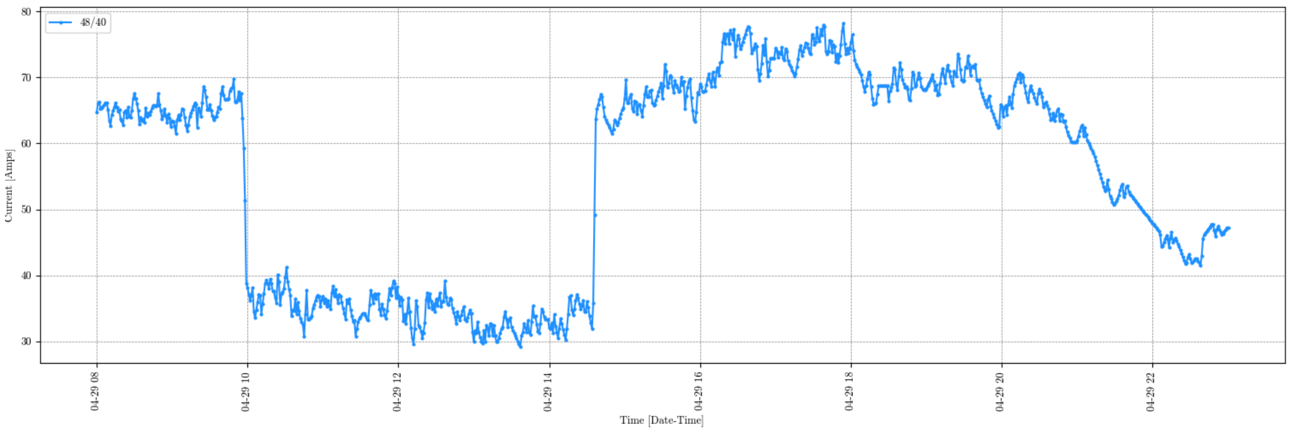

Figure 8 Example demand profile from a customer on a Demand Side Response scheme providing demand turn down

For commercial customers, DSR agreements can be made directly between the DNO and the owner of the facility, whereas for residential customers it is likely that these agreements will be made via the energy supplier or an aggregator. Octopus Energy have trialled Demand Side Response at the domestic customer level through initiatives such as The Big Switch On [30] which trialled demand turn-up and the Big Dirty Turn Down [31] which trialled demand turn-down. DSR has no physical site, instead it is associated with reduction or increases in load from existing electricity consumers on the network.

3.3.6 Demand Side Management

Demand Side Management (DSM) allows network operators direct control of particular technologies, in exchange for a payment to customers for allowing them this control. DSM of Electric Vehicle charging for example allows network operators control of Electric Vehicle charging for participants who opt in, such that they can reduce the rate of charging or stop charging entirely at times when the network is constrained.

Network operators can utilise DSM to resolve various network constraints. For example, if a transformer or conductor is thermally overloaded for a short period of time during peak hours of peak season, DSM can be utilised to resolve the constraint. This may prove more cost effective than traditional network reinforcement as network operators only have to pay DSM costs for the peak hours where the constraint occurs, which may only occur a few times a year. As with DSR, DSM has no physical site, instead its associated with reduction or increases in load from existing electricity consumers on the network.

3.3.7 Phase Balancing

Phase imbalance occurs in multiphase networks when the load on one particular phase on a feeder is consistently higher than the other phases. This means that one phase will be approaching its thermal capacity limit whereas the other phases still have additional capacity that is not being utilised. By redistributing load more equally across the phases, the network operator can ensure that the full capacity of the cable is being utilised. As LCT uptake increases, phase imbalance may become a more prevalent issue on the LV network as each property is connected to a single phase. LCT deployment in a local area is likely to cluster at particular properties, which may happen to be supplied by the same phase. Phase balancing is therefore being considered a potential solution for this study.

There are still uncertainties around the costs and level of capacity released from this solution, however based on previous network studies it is assumed that additional thermal transformer and cable headroom as well as voltage headroom and legroom capacity can be released [32]. LV monitoring can be used to identify areas of the network where phase balancing is required.

Previous studies have looked into both manual [33] and dynamic [34] phase balancing solutions. Manual phase balancing consists of physically moving connections to balance the load across the phases, whereas dynamic phase balancing consists of using power electronics connecting between phases to allow current to flow between them. There are several different proprietary technologies and approaches to achieving this.

3.3.8 Dynamic Asset Rating

The ambient temperature impacts the degree to which the cable or transformer heats up, as a consequence higher loads may be able to run through the network at lower ambient temperatures due to increased heat loss to the environment. Dynamic asset ratings (DAR) can be used to identify the maximum capacity of the network adjusted for seasonal and climatic conditions, providing information on the utilisation of network assets. This is particularly useful for the extreme climate scenarios, of high and low ambient temperatures, for example the peak maximum demand during the winter or the peak distributed generation during the summer. DAR is more commonly used at the transmission level, however studies have been completed to test DAR at a distribution level. An example of this is the WPD project FALCON (Flexible Approach for Low Carbon Optimised Networks), where DAR was trialled for overhead lines, underground cables as well as for HV/LV transformers [21]. This study found that one of the challenges with DAR is the variability across different assets. This was mainly seen for overhead lines where variability was attributed to differing wind speeds. Using live data from LV monitoring can help break down the barriers associated with DAR.

3.3.9 Smart Transformers

Smart transformers use imbedded sensors, communication devices and control systems to provide the network operator with more advanced features and functionalities than those available with traditional transformers. Smart transformers to resolve LV network issues are sited at secondary substations. Smart transformers have the potential to provide a range of different solutions to the network. Ithena, an OEM, claims that their smart transformer can provide benefits to the network operators by creating a 50% reduction in manpower needs, 80% increase in reliability and 40% increase in service quality [35]. LV Engine is a project run by SP Energy Networks (SPEN) where they are testing the benefits of using smart transformers including setting up a LV DC network [11]. Due to the variety of functionalities of the smart transformer, it may have potential to release both voltage and thermal headroom.

3.3.10 LV DC Networks

LV DC networks refer to the concept of creating retrofit LV distribution networks that feed specific loads through a DC circuit. This would remove complexities and inefficiencies associated with AC/DC converters needed for new electrical loads (i.e. EV chargers) and release more capacity on the same conductors. It's also expected that there will be an improvement in power quality and reduction in fault level. Due to the decrease in power loss in DC supply, there will also be an increase in thermal capacity of the cables. Similarly due to the improved power quality and more controllable voltage levels, there is expected to be an increase in both voltage legroom and headroom. LV DC networks are most likely to be beneficial on networks with high levels of solar PV deployment, as by having a DC network, losses in the conversion to AC by the inverter can be avoided. This concept is already being explored by other UK DNO's, with SPEN's LV Engine project being a prime example [11].

3.3.11 Microgrids

Microgrids consist of local generation, storage and demand that can run as part of the main grid or operate independently (Figure 9 provides an example). The ability to operate independently, otherwise known as in island mode, is a valuable feature for the network operator to offer greater resilience to the network (for example during power outages).

Microgrids also have the potential of operating their own local flexibility market, leveraging greater value from the local generation and storage available. Microgrids can be set up either for specific large scale buildings, i.e. hospitals or commercial sites, or in a local regional areas. Microgrids are a tried and tested solution, however they are not commonly found across the UK. Microgrids have been developed internationally for a series of different purposes, whether it is to support off-gas grid communities, improve resilience for large commercial or public buildings or integrate LCTs in constrained areas of the network [36]. Although microgrids can provide a series of benefits it is important to consider the technical and regulatory constraints, which will influence the viability of this solution for WPD's networks.

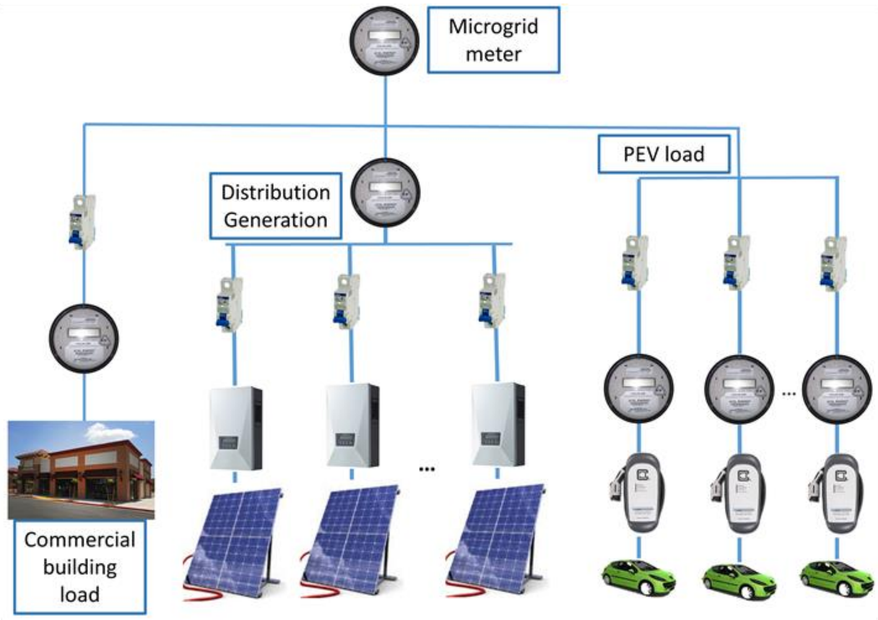

Figure 9 Example of microgrid to support a commercial vuilding alongside EV charging [37]

3.3.12 Meshing

Meshed networks allow power to be supplied from a series of directions rather than a single direction as with conventional radial networks. Meshing can either be done on a temporary or permanent basis, by either using power electronics or physically reconfiguring the network. For both cases it is assumed that a significant amount of thermal headroom will be released. Both the permanent and temporary solutions have been tried and tested across the UK, hence both approaches have high technology readiness levels. UKPN completed a project in 2016 called Flexible Urban Networks – LV (FUN–LV), looking at meshed networks and the benefits they could bring [20]. For this project a series of methods were tried for sharing capacity, this included using remote controlled circuit breakers, link box switches and back to back power inverters. Another example is a project completed by WPD called OpenLV, this project used real time thermal ratings as well as automated meshing of the network to release additional capacity from the secondary transformer [13]. This solution is dependent on monitoring and control units to be deployed, hence their spatial requirements are important to consider when evaluating this solution.

3.3.13 Transformer Cooling

Transformer cooling can be used to increase transformer thermal capacity. Transformer cooling is a solution that is implemented at the secondary substation, either directly on the transformer or in its proximity. Therefore, when selecting this solution, it is important to consider the spatial constraints. Broadly, transformer cooling falls into two categories, active transformer cooling and passive transformer cooling. Active transformer cooling involves actively forcing air past the transformer to remove heat from the transformer. Both positive (e.g. Passcomm unit) and negative pressure (e.g. Ekkosense unit) systems can be used to achieve this effect. Active transformer cooling was trialled by Electricity North West in the Celsius project [38].

Passive transformer cooling uses passive methods to reduce transformer temperature such as transformer shading or transformer painting to reduce solar gain, or additional substation ventilation to improve airflow and thus cooling. Passive transformer cooling was also trialled by Electricity North West in the Celsius project [14] and is readily used in hotter climates already.

3.3.14 Widening Voltage Tolerance

In the UK the voltage of the electricity supplied is 230 V with a tolerance of -6% in legroom and +10% in headroom [39]. Widening the voltage tolerance is a policy solution that will improve the voltage headroom and legroom at the substation. For example, increasing the voltage legroom to -10% would enable greater utilisation of the existing network as more additional load (e.g. Electric Vehicle Charging Points) would be able to connect to the LV network without causing voltage levels to fall below statutory standards.

This solution could be deployed at scale across the network with a short lead time at minimal cost to the network operator. However, certain devices may operate poorly under low voltage. Examples of devices that function poorly at low voltage include motors (sufficiently high voltage is required to start motors), lighting (which may become dimmer of flicker, particularly noticeable with incandescent lighting) and electric heaters or cookers (which will take additional time to reach the required temperature at lower voltages). Additionally, some power electronic based devices do not demonstrate a linear relationship between current and voltage, as such may result in an increase in circuit load. Therefore, although quick to implement, significant research is necessary to fully understand the wider customer and equipment impact.

3.3.15 Dynamic Voltage Management

Dynamic voltage management refers to a system that can automatically respond to voltage alterations and manage voltage levels across a power system. This can be done either by using on-load tap changers (OLTCs) [40] or through power electronics. It is assumed that these solutions can enable significant increases in voltage headroom and legroom. OLTCs have been used for decades at primary substations to regulate voltage levels across the HV networks. These solutions are now being considered for the LV network applying the same principles. OLTCs typically have a control unit that is installed on the side of the transformer and is connected to the windings, this will have very little impact on the overall size of the transformer. Power electronics can also be used to control voltage levels from the windings, an example of which is included in the RfI responses in Section 4.1.1 where power electronics are used to manage voltage levels through magnetic control.

3.3.16 Enhanced Automatic Voltage Control (EAVC)

Enhanced Automatic Voltage Control (EAVC) is being proposed as a solution for network operators to actively manage voltage on the distribution network. As the name suggests EAVC is similar to traditional automatic voltage control (AVC) systems, however utilises communication and control systems to alter the voltage set points remotely. A series of EAVC solutions were tested in the, Customer Led Network Revolution (CLNR) project [23]. This included trialling EAVC systems with existing voltage control systems at the secondary substation (i.e. OLTCs and switched capacitors) as well as with new assets (LV feeder regulators) that allowed direct control over individual feeders.

EAVC systems can be implemented at the secondary substation in parallel with existing voltage control systems, along a feeder or at the consumer premise. EAVC provides a way for the network operator to respond to voltage related issues through devices located closer to the customer's premises rather than existing techniques available located at higher voltages. This improves voltage management across the system while also ensuring that different voltage control units act in harmony.

3.3.17 D-FACTS

D-FACTS (Distributed Flexible AC Transmission Systems) use power electronics, various types of static controllers, to improve reliability and power quality of the power supply. STATCOMs (static synchronous compensators) are an example, and are used to mitigate issues related to voltage flickering, providing greater stability to the network. This is done by continuously providing, or absorbing, variable reactive power in response to voltage variations. D-FACTS, due to their ability to regulate voltage levels, are expected to provide an increase in voltage headroom and legroom as well as improving power quality on the network. These solutions are typically deployed at a transmission level rather than to the distribution network. D-FACT solutions have the greatest impact closer to the point of voltage alteration (either point of demand or generation), but can also be deployed at the secondary substation which often proves more practical.

3.3.18 Switched Capacitors

Switched capacitors are mechanical switched devices used to regulate voltage levels under heavy load conditions and provide reactive power compensation. At times of maximum demand with no embedded generation, switched capacitors can generate reactive power to support voltage levels, ensuring that the voltage levels do not drop below the statutory voltage limits. Similarly at times of high generation and low demand the switched capacitor can absorb reactive power. Therefore, it expected that this solution provides additional voltage legroom and headroom as well as improved power quality. Similarly to D-FACT solutions switched capacitors are best placed close to the point of low voltage (down stream) but can also be installed at the substation in place of other dynamic voltage management devices. When evaluating this solution it is important to consider the spatial, communication and control requirements.

4. Request for Information

A Request for Information (RfI) was prepared by WPD working in collaboration with EA Technology, and issued through WPD's procurement team. The RfI was a call to providers that were developing technologies with the potential to help network operators extract headroom from their existing LV networks. Providers were asked to provide details about their solution, including practical details (spatial requirements, operating temperature, compatibility with WPD's existing substations, etc.) and technical details (headroom release, capex and opex costs, solution lifetime, lead time) required for the Transform Model® and PowerFactory analysis. Recognition was given to the fact some information requested could be commercially sensitive and thus it was made clear that blank boxes, estimates, or ballpark figures were acceptable responses for the modelling purposes required in this project.

The RfI was issued on 15th July 2022 and was open for four weeks. It was publicised on WPD's and EA Technology's social media. Direct discussions were held with multiple providers who wished for further information about the project before submitting an RfI response. The RfI closed to further responses on 15th August 2022. A summary of the respondents are provided in Table 3, whereas a more detailed description of each solution is provided later in Section 4.1. Please note that the respondents are classified by a unique "solution number", this was done to anonymise the responses.

Table 3 Participants and solution types offered by respondents to the RfI.

Solution Number	Type of Solution
1	Dynamic Voltage Management (power electronics)
2	Smart Transformer
3	D-FACTS (STATCOMs)
4	LV Monitoring
5	Dynamic Voltage Management (power electronics)
6	Dynamic Voltage Management (OLTC)

4.1 Technical Solutions and Evaluation

4.1.1 Solution number 1 – Dynamic Voltage Management (power electronics)

The first solution from the RfI response is a dynamic voltage management device. The device combines power electronics with control software to step voltage up and down at high speed and great accuracy. The device is designed to come as either a retrofit solution to existing transformers or as an integrated solution to new transformers. The technology readiness level (TRL) is assumed to be 5 today and expected to be 9 by 2030. This means that the technology is currently at a pilot stage but is expected to be fully operational by 2030.

The supplier expect that their solution can provide both thermal and voltage capacity release. By minimising voltage levels, the power is also decreased. It is estimated that their device can typically achieve a 5-8% voltage reduction, therefore assuming a linear relationship with power consumption, the supplier are confident it will release an additional 5-8% thermal capacity at the substation. At high enough penetration levels, the device will also be able to provide added benefits of power flow optimisation which will provide additional thermal capacity by minimising network losses (up to 7%). As a voltage management device it will also provide additional voltage headroom & legroom by rapidly and accurately adjusting voltage levels, facilitating a steady-state voltage modulation range of ± 7.5%. The exact level of voltage headroom / legroom released will depend on the circuit, however it is assumed that the steady-state voltage modulation range represents the increase in “voltage envelope” that the network can operate in, and hence the associated increase in voltage headroom / legroom.

The product is designed to work for implementation with 11kV/LV transformers, and is intended to be available for transformer ratings ranging from 200 kVA to 5 MVA. The supplier expects that there will be no issues integrating the solution into WPD’s networks and expects that the product will be available by 2024. Further details are provided in Table 4 and Table 5 below.

Table 4 Expected commercial parameters of solution number 1

CAPEX 2022 (£)	OPEX (£)	Cost reduction 5 years	Lead Time	Product Lifetime	Year Available
10,000	100	75%	3 months	15 years	2024

Table 5 Technical parameters of solution number 1

Size (full retrofit + transformer) [m]	Operating Temperature (°C)	Transformer Thermal Capacity Released	Cable Thermal Capacity Released	Voltage Headroom Released	Voltage Legroom Released
1 x 1 x 2	-30 to +55	5-8%	7%	+7.5%	-7.5%

4.1.2 Solution number 2 – Smart Transformer

Solution number 2 consists of a smart transformer described by the supplier as a magnetic power flow controller. The smart transformer is able to dynamically control electrical power flow in the magnetic domain in real-time. This device is an alternative solution to traditional transformers. Traditional transformers require expensive retrofits and add-ons to dynamically control voltage levels. This smart transformer has incorporated the power electronics and other add-ons required for dynamic voltage control, limiting the need for future retrofit. The device is self-powered, autonomous, and installed just like any transformer into an existing electricity network. It can connect into any supervisory control system and provide valuable information and actions to maintain grid stability and optimise the electricity system. The technology readiness level of the system is currently between a 4 and 5, since they are starting the piloting phase of their product in 2023. They expect however that by 2030 the technology readiness level will be 9, meaning that it is a fully operational solution.

It is expected that the smart transformer functionalities may provide additional thermal capacity to the transformer, but mainly it will provide additional voltage headroom and legroom. The thermal capacity of the transformer will depend on electromagnetic core and the rating of the transformer, but it is expected that additional capacity for a network can be unlocked with proper compensation/correction of power factor, increasing the amount of active power transfer. The extent to which it can provide additional thermal capacity is unknown, and it is not expected that there will be any additional thermal capacity release in the cables. The device is able to control voltage independently on each phase, ±10% at a millisecond level. This is done continuously with exact precision (not discrete setpoints), meaning that the device can operate dynamically to changing voltage levels. This provides maximum network flexibility and ultimate control of voltage headroom/legroom; as the LV network voltage fluctuations and total harmonic distortions are minimised, there is additional room for stable/constant voltage for consumers. The product is designed to work in UK secondary substations stepping from 11kV to 0.4kV, and the initial device capacity will range from 50kVA to 1MVA. The supplier is also working in other markets (EU and USA), on primary side voltages (13.3-66 kV) and plan to be able to develop primary substation transformers (up to 132kV) and higher rated transformers (50MVA). The supplier expects there to be no issues in integrating these solutions to WPD's network and will have pilot ready products by 2023. Further details are provided in Table 6 and Table 7 below.

Table 6 Commercial parameters of solution number 2

CAPEX 2022 (£)	OPEX (£)	Cost reduction 5-10 years	Lead Time	Product Lifetime	Year Available (for pilot)
See note [1]	800	20-30%	10-18 weeks	40-50 years	2023

Table 7 Technical parameters of solution number 2

Size (m)	Operating Temperature (°C)	Transformer Thermal Capacity	Cable Thermal Capacity	Voltage Headroom	Voltage Legroom
2 x 1.8 x 1.1	See note [2]	N/a	0	+10%	-10%

[1] The supplier is exploring a series of commercial models for the transformers – the initial pilot devices have a premium (ranging from 50-100%) on traditional transformers. Meaning that for a traditional £20k transformer the smart transformer equivalent will be £30-40k depending on the specifications chosen.

[2] Electromagnetic core has a 105 °C maximum, this is considering a maximum ambient temperature of 40 °C, 60°C oil temperature and 65 °C windings rise. The power electronics are rated between -20 to 70 °C.

4.1.3 Solution number 3 – D-FACTS (STATCOMs)

The third RfI response consists of a distribution suited D-STATCOM device, introducing technology to the LV distribution network that is commonly used across the HV distribution and transmission network to stabilise voltages, reduce power loss and harmonics. The device works by using a 3-phase inverter consisting of the latest Silicone Carbide and polypropylene capacitor technology. The technology readiness level of this technology is 8 as it has not been tested in the UK market. The product, however, is currently available internationally and fully expected to be compatible with WPD's network, hence will have a TRL of 9 by 2030.

The D-STATCOM device is expected to release both thermal and voltage capacity to the network, however there are several caveats to consider. The capacity released will depend on the specific LV configuration, network loads, existing cabling infrastructure, physical location and quantum of embedded generation and EV charging etc. The RfI response states that the device has been known to regulate the voltage levels within a 4-6% envelope over the rated voltage limits, furthermore it also states that case studies have shown that the use of the device allowed a PV penetration of up to 129% of the rated transformer capacity. These values will therefore be assumed for the transformer thermal capacity release as well as the voltage headroom/legroom release.

The device is readily available across all network archetypes (rural, urban, underground and OHL), and is fully compatible to WPD's network. The LV device is designed to operate for a 3-phase network rated between 400-480 VAC, however it can also work across a single phase if necessary. As for other D-FACTs, the device can be installed at the substation however provides greater benefits out on the feeder closer to the point of generation/demand. The device can also be used to operate a battery controller with a DC input range of 650-1000 V. Further details are provided in Table 8 and Table 9 below.

Table 8 Commercial parameters of solution number 3

CAPEX 2022 (£)	OPEX (£)	Cost reduction 5-10-15 years	Lead Time	Product Lifetime	Year Available
9,000	700	5-10-15 %	6 months	20 years	2022

Table 9 Technical Parameters of the solution number 3

Size (m)	Operating Temperature (°C)	Transformer Thermal Capacity	Cable Thermal Capacity	Voltage Headroom	Voltage Legroom
0.49 x 0.28 x 0.6	-20 to +75°C	29%	0%	+6%	-6%

Solution number 4 – LV monitoring

This LV monitoring device is a highly optimised and integrated grid edge data acquisition, edge compute and synchronized gateway device that provides near real time monitoring and grid edge analytics for a variety of use cases such as grid monitoring, congestion analysis, fault detection, power quality and control. Grid edge technology facilitate the interaction between the smart grid and consumer, enabling solutions such as demand side response, smart EV charging or other flexibility services.

The LV monitoring unit can provide valuable insights on the network which allows the DNO to accurately control voltage and loading levels. Integrating LV monitoring data with control units enables the DNO to maintain stable voltage levels, whilst also optimising the capacity available on the existing network. This can include sending signals to generation, storage or controllable loads to either turn up or down depending on the network constraints. For example during peak hours of demand, the LV monitoring unit can detect the drop in voltage levels and signal to local generation sites to turn up their supply to the grid. Similarly LV monitoring units can also be used to identify the thermal capacity of both the transformer and connected feeders, and signal when these temperatures ratings are likely to be exceeded. These signals can either go to consumers on DSR schemes to turn down their demand, or allow the network operator to remotely turn down demand through DSM schemes. The interface between the LV monitoring device and the controllable assets can be done either directly via a LV monitoring connection, for example to the DERs inverter, through a third-party API or via DSO's Active Network Management systems. Although LV monitoring units can enable solutions that provide additional capacity, they do not directly provide any additional thermal or voltage capacity. This technology is readily available and a key part of GB DNO's investment plans for ED-2. For this reason the TRL is currently a 9 and will be the same in 2030.

The LV monitoring device is attached and collects data from the LV network (400V), however it monitors both the LV network and through digital modelling of the transformer the HV grid up to 40kV. The LV monitoring solution is available and in operational deployment today. The LV monitoring device measures parameters from the LV side of the transformer in the secondary substation but through building a digital twin of the transformer can detect and localise HV faults. The device is compatible for deployment for indoor, outdoor, urban, rural, underground and overhead line surroundings. As stated in note 3, the supplier offers a competing solution to a solution provided by EA Technology, therefore some commercially sensitive information has been excluded from their RfI response. Further details are provided in Table 10 and Table 11 below.

Table 10 Commercial parameters of solution number 4

CAPEX 2022(£)	OPEX (£)	Cost reduction 5 years (£)	Lead Time	Product Lifetime	Year Available
See note[3]	See note[3]	See note	4 months	10 years	2022

Table 11 Technical parameters of solution number 4

Size (m)	Operating Temperature (°C)	Transformer Thermal Capacity	Cable Thermal Capacity	Voltage Headroom	Voltage Legroom
348x 249 x 0.065	-20 to +75°C	N/a	N/a	N/a	N/a

[3] The listed LV monitoring device is a direct competitor to EA Technology products, for this reason the supplier was not able to release commercial information relating to their product. Their RfI response indicates a willingness to provide these details under an NDA or as a discussion separate from SILVERSMITH. To facilitate the Transform modelling, CAPEX, OPEX and Cost reduction curves will be assumed based on previous Transform modelling of LV monitoring solutions.

4.1.4 Solution number 5 – Dynamic Voltage Management (power electronics)

This solution consists of a new dynamic voltage management device that uses power electronics in place of on load tap changers (OLTCs). This is a concept design which is now ready for pilots (TRL 5), where they plan on using back-back AC inverter on the control windings of a transformer instead of OLTCs. This aims to create a more compact, efficient and cost effective solution for dynamic voltage management on the distribution network.

It is expected that this solution provides benefit to the DNO by providing additional voltage headroom and legroom capacity with the RfI response stating that the device should be able to provide up to 20% additional release of voltage headroom and legroom. The RfI response was limited on providing technical functionalities of the solution, however it is also stated that the solution will be able to provide power quality improvements, through reduced harmonic distortion, as well as balancing current and voltage levels across phases.

The product is currently designed for LV networks, but could be developed to suit higher voltages as well. There should also be no concerns relating to WPD compatibility, as the physical aspect ratio and connection locations should be readily adjustable to suit WPD's standards. There is a risk that in underground scenarios of overheating / cooling issues. The solution has a TRL of 5 and, with sufficient commercial interest, the solution should be available by 2024. Further details are provided in Table 12 and Table 13 below.

Table 12 Commercial parameters of solution number 5

CAPEX 2022 (£)	OPEX (£)	Cost reduction-10 years (£)	Lead Time	Product Lifetime	Year Available
N/a	0.25% CAPEX	25%	12 months	15	2024

Table 13 Technical parameters of solution number 5

Size (full retrofit + transformer)	Operating Temperature (°C)	Transformer Thermal Capacity	Cable Thermal Capacity	Voltage Headroom	Voltage Legroom
N/a	-40 to + 85	N/a	N/a	+20 %	-20%

4.1.5 Solution number 6 - Dynamic Voltage Management (OLTC)

This supplier is a European manufacturing company that specialises in on-load tap changers (OLTCs). The device in question, is a very compact high-speed resistor type on-load tap-changer (OLTC), especially designed for the use in distribution transformers. The OLTC allows to design voltage regulating distribution transformers (VRDT) that have the same footprint as a non-regulated distribution transformer of the same rating. The principle has been applied and well established for decades in power transformers in primary substations. Being a vacuum type OLTC, it is long lasting and maintenance free over the life-time. This solution is readily available and has a technology readiness level of 9.

By changing the number of effective turns on the HV side and hence the ratio of the secondary substation transformer, the device provides voltage regulation. The measurement of the voltage, the voltage regulation and the actuation of the OLTC is being provided by a compact control unit. By means of safety checks and an integrated energy accumulator (super caps) it provides a safe and reliable operation, even in the event of a supply voltage loss during a switching operation. The control unit is supplied from the secondary side of the transformer. By measuring this voltage and regulating it according to adjustable parameters is can provide a stable voltage band of approx. +/-2% around the set-point, which enables a much greater voltage drop and voltage rise along the LV feeders. By regulating the bus bar voltage, it allows increased voltage drop and rise on two feeders at the same time. It is estimated that the solution will provide an additional 8% voltage headroom/legroom, however will have no impact on the thermal capacity of the transformer or cables.

The product is designed to operate at 11kV and 33kV, both at single and 3 phase and is available for both LV and HV networks. The solution is compatible with UK standard transformers design and only increases the height of a transformer with no impact on the footprint and therefore no impact on the existing civil works. Further details are provided in Table 14 and Table 15 below.

Table 14 Commercial parameters of solution number 6

CAPEX 2022 (£)	OPEX (£)	Cost reduction-5 years (£)	Lead Time	Product Lifetime	Year Available
3,500 – 7,000	See note[4]	0	4 weeks	20 years	2022

Table 15 Technical parameters of solution number 6

Size (full retrofit + transformer)	Transformer Thermal Capacity	Cable Thermal Capacity	Voltage Headroom	Voltage Legroom
See note[5]	0	0	+10%	-10%

[4] Identical to non-regulated transformers. Electricity consumption of the control: 7,5 W Control unit replacement after 20 years: current list price: 942 EUR

[5] The device consists of two parts, the voltage regulator and the control unit. The sizes of which depend on the rating of the device. The following are the quoted sizes from the supplier for a 24 kV three phase unit:
785 x 188 x 134 mm (w x h x d) OLTC installed in the transformer; 317 x 130 x 147 (w x h x d) motor drive installed on the transformer cover and the control unit: 100 x 144 x 341 mm (w x h x d).

5. Technical Parameters

5.1 Transform Overview

Transform presents a parametric model of an entire electricity distribution network. This model builds on data from a number of sources, which includes:

- A range of hosting capacities from prototypical representations of different feeder categories
- A range of solutions for improving hosting capacity that a network operator may employ. (This includes network led solutions such as new transformers and non-network solutions such as tariffs or customer storage)
- Electricity consumption profiles of different customers classes
- Generation profiles of varying solar PV, battery storage and electric vehicle behaviour
- Installation rates for different DER (such as PV generation and battery storage)

Transform then overlays the anticipated future demand that will be placed upon the network from various low carbon technologies onto the existing network. In instances where network feeders are taken beyond acceptable network quality standards, the Transform simulates the technical and economic choices that a network owner will have to make to maintain an acceptable service.

Transform utilises so called solutions to resolve network constraints. Each solution is represented by critical parameters such as the Capex and Opex costs of the solution, its lifetime and lead time for deployment, and the thermal and voltage headrooms offered by the solution. Table 16 shows the parameters that will be used to represent each solution in Transform. These parameters have been drawn from the literature review [41], or are established traditional solutions modelled by default in the Transform. The outputs from Transform informs which of the solutions should be deployed for the representative feeders.

Note that DSM/ DSR and Time of Use tariffs are modelled differently to other solutions in Transform.

5.2 PowerFactory Overview

PowerFactory is a load flow engine, performing load flow calculations on specific examples. For this study, case studies that load flow assessments will be performed on will come from a dense urban, urban and rural network. Each solution to network constraints are modelled separately in Power Factory. Instead of using parameters like Transform, instead the effect of each solution has to be considered and modelled. How this is done depends on the solution, but could range from altering profiles, changing voltages, or the addition of new devices such as storage technologies.

5.3 Modelling Solutions

5.3.1 Transform Specific

Transform represents LV management technologies with what are known in Transform as solutions. Each solution is represented by a set of parameters. All solutions are modelled using the same parameters, which are shown in Table 16. A small number of LV management technologies or strategies are modelled slightly differently to solutions. These are outlined later in Section 5.3.1. The solution parameters representative headroom released by each solution, across thermal, voltage, power quality and fault level capacities. Transform is designed to perform a Cost Benefit Analysis. Transform will select the solution that solves the network constraint at the cheapest possible cost to the consumer. The parametric nature of Transform means that it knows future deployment rates of traditional loads and LCTs until 2050. To reflect the uncertainty faced by network operators in the real world, it selects the cheapest solution for the five years immediately following when a network constraint is first encountered, even if an alternative solution would be cheaper long term (as it resolves future network constraints more cost effectively).

The values in Table 16 and Table 17Table 17 are used based on previous studies including the *Low Voltage Network Capacity Study,* completed for BEIS in July 2022 [32] as well as other previous studies including the 2012 OFGEM study *Assessing the Impact of Low Carbon Technologies on Great Britain's Power Distribution Networks* [42].

In Transform, the voltage rise or fall on a feeder is calculated by the net export (for voltage rise) or net import (for voltage fall) multiplied by the kW/% parameter, which represents the number of kW of load or generation required to cause a 1% decrease of increase in voltage respectively.

DSM and DSR solutions are modelled differently. These solutions are not modelled by capacity release, but instead are implemented when network constraints are encountered on the network to ensure that network constraints are not breeched, but instead the net import or export is capped at the network limit. Customers are compensated by the network operator for use of DSM at a rate known in Transform as the Inconvenience Cost (£/kWh). If the price required to utilise DSM is a cheaper method to resolve the network constraint than traditional network reinforcement, then this DSM will be deployed.

Time of Use tariffs are not modelled by solutions at all, but rather by additional profiles. For example, to model EVs charging on a Time of Use tariff, a new EV Time of Use tariff profile is introduced into Transform. In addition, the uptake rate of EVs on Time of Use tariffs are input separately to EVs on standard tariffs.

Table 16 Assumed Capacity Release by Solutions for use in Transform Modelling.

Solution	Capex 2022 (£)	Opex (£/year)	Duration / Lifetime (Years)	Lead Time (months)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)	Power Quality Capacity Release (%)	Fault Level Capacity Release (%)
Phase Balancing (Manual)	20,000	0	45	18	20	20	20	20	10	5
Dynamic Voltage Management (On Load Tap Changers)	8,500	3,375	20	18	0	0	8	8	0	0
Dynamic Voltage Management (Power Electronics)	10,000	100	15	12	8	7	7.5	7.5	0	0
Dynamic Asset Rating (OHL feeders)	4,980	0	15	18	0	20	0	0	0	0
Dynamic Asset Rating (UG feeders)	16,600	0	15	18	0	8	0	0	0	0
Dynamic Asset Rating (Transformer)	4,980	0	15	18	10	0	0	0	0	0
Widening of Voltage Tolerance	64	0	60	0	0	0	0	5	-10	0
Smart Transformers	N/a[6]	800	50	4	0	0	10	10	N/a[7]	0
LV DC Networks	125,000	5,000	30	12	20	0	10	10	50	50
D-FACTS (dSTATCOM)	9,000	700	20	6	29	0	6	6	20	5

[6] Based on the RfI response, it is expected that a smart transformer will have a 50-100% premium on a traditional transformer, therefore the cost will vary depending on the size of the transformer and the type of configurations chosen.
[7] It is expected that there will be improvements on power quality, however there is no reference to quantifications of this impact

Solution	Capex 2022 (£)	Opex (£/year)	Duration / Lifetime (Years)	Lead Time (months)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)	Power Quality Capacity Release (%)	Fault Level Capacity Release (%)
Network Monitoring & Modelling (Network Data)	2,100	500	20	18	8	0	0	0	0	0
Smart EV Charging	15,495	1,550	25	18	5	10	0	5	0	0
Dynamic Time of Use tariffs [8]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Energy Storage (Grid [Feeder] Scale)	309,900	10,000	20	6	See Note [9]	0	0	0	0	-8
Energy Storage (Behind the meter)	0	1,920	10	6	50	50	20	20	10	-5
Enhanced Automatic Voltage Control (EAVC) - LV Circuit Voltage Regulators	12,000	480	20	12	0	0	10	10	0	0
Enhanced Automatic Voltage Control (EAVC) - LV PoC Voltage Regulators	1,000	400	15	12	0	0	2	2	0	0
Switched Capacitors	10,330	103	30	18	0	0	5	5	10	0
Generator Constraint Management	20,000	2,000	5	6	10	10	3	3	0	0

[8] Time of Use tariffs are modelled by separate profiles and uptake rates in Transform. For example, EVs on a Time of Use tariff would be given a separate profile and uptake rate to an EV on a standard tariff. Time of Use tariffs are considered a market solution with no cost to the DNO.
[9] Grid Scale energy storage solutions are modelled slightly differently in Transform to other solutions. Instead of headroom release per se, headroom is capture by Storage (kW) and Storage (kWh) parameters which inform the model as to whether the solution can be used to mitigate a network constraint.

Solution	Capex 2022 (£)	Opex (£/year)	Duration / Lifetime (Years)	Lead Time (months)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)	Power Quality Capacity Release (%)	Fault Level Capacity Release (%)
DSR - Commercial[10]	0	0	5	6	0	0	0	0	0	0
DSR - Residential	0	0	5	6	0	0	0	0	0	0
DSM - EV Charging	0	0	5	6	0	0	0	0	0	0
DSM - PV Curtailment	0	0	5	6	0	0	0	0	0	0
Meshing - Temporary	8,000	500	25	6	5	50	0	2	20	-33
Meshing - Permanent (Sub-Urban)	8,000	500	45	6	5	50	0	2	20	-33
Meshing - Permanent (Urban)	8,000	500	45	6	10	50	0	2	20	-33
Transformer Cooling - Active	3,872	66	15	6	22	0	0	0	0	0

[10] DSR / DSM is modelled in Transform by solution with zero Opex and Capex cost. Separate solutions are provided that are applied to different types of load. Transform allows the user to define the availability window of DSM (time of day DSM can be applied), as well as the percentage of potential providers participating in DSM (e.g. Number of EV owners allowing DSM of EV charging in exchange for payment). Instead, the cost is captured by a so called "Inconvenience cost". This represents the value (£/kWh) that the network operator pays the demand response provider for shifting their electricity consumption.

5.3.2 PowerFactory Specifics

The PowerFactory model will run load flow studies to establish when network parameters are breached by the operation of Low Carbon Technologies within the LV networks being studied. These studies will be undertaken at specific time intervals reflecting future uptake scenarios. For some of the proposed solutions such as demand side management the effect of the proposed mitigation can be explored using variations in the demand/export profile. The extent of demand reduction that is expected needs to be agreed.

For other interventions which require new plant or equipment to be installed in the network it will be necessary to understand the available capacity that the device provides, where it can be or needs to be installed and what input signals drive the operation.

Some of the voltage and network control devices are expected to be able to be modelled using default devices within the PowerFactory system. Whilst some such as dynamic phase balancing do not exist within the suite of devices in PowerFactory's library and more details of the means by which the balancing of the phases is achieved will be required to inform attempts to develop a suitable model.

Meshing between feeders from the same transformer will likely not release any additional thermal capacity in the transformer, there may however, be an increase in the thermal capacity of one feeder but this will inevitably come at the expense of some thermal capacity within the other meshed feeder now picking up some of the load from the first feeder. This may or may not be an issue depending upon the loading already applied to the second feeder. Variations in the deployment of new LCTs in differing scenarios may highlight these effects. The voltage profile of the network may be improved by the paralleling of these feeders and this will be established by the studies.

Meshing with adjacent substations cannot readily be studied as the current plan is to model only a single substation's worth of circuits for each archetype. Connecting networks together at LV needs to consider the effects at HV which will vary according to the relationship between the HV feeding substations and where they are fed from.

5.3.3 Other Technical Parameters

There are other technical parameters to consider for each of the specified solutions Section 3.3 provided a qualitative review of how these solutions work and example use cases. This section provides an overview of the physical dimensions, technology readiness level (TRL) and technology compatibility.

Table 17 Other Technical Parameters of listed solutions

Solution	Type of Solution	Dimensions (width x length x depth [m])	Operating Temperature Range (ºC)	TRL today	TRL 2030	Year Available	Device Location
Phase Balancing (Manual)	Physical Intervention	N/a	N/a	9	9	2022	N/a
Dynamic Voltage Management (On Load Tap Changers)	Technical Device	Multiple devices see RfI	-25 to +50	9	9	2022	Multiple locations see RfI
Dynamic Voltage Management (Power Electronics)	Technical Device	1 x 1 x 2	-30 to +55	6	9	2024	Secondary Substation
Widening of Voltage Tolerance	Policy change	N/a	N/a	9	9	2022	N/a
Smart Transformers	Technical Device	2 x 1.8 x 1.1	Transformer core : +105, Power Electronics -25 to +70	4	9	2023	Secondary Substation
LV DC Networks	Technical / policy change	N/a	N/a	7	9	2022	N/a
D-FACTS	Technical Device	0.28 x 0.49 x 0.6	-20 to +70	8	9	2022	Secondary Substation
Network Monitoring & Modelling (Network Data)	Technical Device	0.25 x 0.4 x 0.07	-25 to +70	9	9	2022	Secondary Substation
Smart EV Charging	Commercial Model	N/a	Normal Ambient Temperatures	9	9	2022	Consumer Property
Dynamic Time of Use tariffs	Commercial Model	N/a	N/A	9	9	2022	N/a
Energy Storage (Grid [Feeder] Scale)	Technical Device	Various (depends on manufacturer, battery technology and storage capacity)	-20 to +60 for Li Ion Batteries -5 to +45 for Vanadium Flow Batteries	8	9	2022	Secondary Substation / Cabinet at End of Feeder / Cabinet at Other Location along Feeder

Solution	Type of Solution	Dimensions (width x length x depth [m])	Operating Temperature Range (ºC)	TRL today	TRL 2030	Year Available	Device Location
Energy Storage (Behind the meter)	Commercial Model	N/a (Consumer Site)	-20 to +60 for Li Ion Batteries -5 to +45 for Vanadium Flow Batteries	9	9	2022	Consumer Property
Enhanced Automatic Voltage Control (EAVC) - LV Circuit Voltage Regulators	Technical Device	N/a (Consumer Site)	-20 to +70	9	9	2022	Consumer Property
Enhanced Automatic Voltage Control (EAVC) - LV PoC Voltage Regulators	Technical Device	N/a (Consumer Site)	-20 to +70	9	9	2022	Consumer Property
Switched Capacitors	Technical Device	N/a	N/a				Secondary Substation
Generator Constraint Management	Commercial Model	N/a	N/a	9	9	2022	Consumer Property
DSR - Commercial	Commercial Model	N/a	N/a	9	9	2022	N/a
DSR - Residential	Commercial Model	N/a	N/a	9	9	2022	N/a
DSM - EV Charging	Commercial Model	N/a	N/a	9	9	2022	N/a
DSM - PV Curtailment	Commercial Model	N/a	N/a	9	9	2022	N/a
Meshing - Temporary	Technical Device	0.160 x 0.115 x 0.185	-20 to 45	9	9	2022	Secondary Substation
Meshing - Permanent (Sub-Urban)	Technical Device	0.160 x 0.115 x 0.185	-20 to 45	9	9	2022	Secondary Substation
Meshing - Permanent (Urban)	Technical Device	0.160 x 0.115 x 0.185	-20 to 45	9	9	2022	Secondary Substation
Transformer Cooling - Active	Technical Device	Various (depends on method)	-20 to +70	7	9	2025	Secondary Substation
Transformer Cooling - Passive	Technical Device	Various (depends on method)	-20 to +70	8	9	2022	Secondary Substation

6. Conclusions and Recommendations

The growth of LCT uptake will have a significant impact on feeder voltage levels and thermal conditions of cables and transformers. It is essential that DNOs plan ahead and investigate smart solutions to mitigate these problems, in order to ensure that the distribution network is able to cope with the new loads and sources of generation introduced in the upcoming years. This literature review provides information of a range of solutions that are currently being trialled or implemented by UK or international distribution networks. This report provides the technical and commercial information that is required to model the solutions as well as engagement with suppliers to provide additional insight into how their device(s) work.

6.1 Conclusions

The main conclusions from the literature review are the following:

C1. As part of the literature review a range of solutions have been considered that have potential to provide either additional voltage or thermal capacity to the network. These solutions range from retrofit devices, physical network interventions, market solutions (encouraging consumer engagement) and policy solutions.

C2. The literature review has collected information on a range of solutions based on published material or responses to the RfI. Therefore, some novel solutions with a lower TRL may not be captured within this report.

C3. The Request for Information received six replies from suppliers, and the relevant commercial and technical information provided have been used to update the technical and commercial parameters required for modelling.

C4. The Request for Information was limited in its range compared to the list of solutions under consideration, therefore as the project progresses further engagement with suppliers may be needed. Late responses to the RfI can still inform solutions to be deployed in the Transform and PowerFactory analysis.

C5. Where possible, the technical and commercial parameters required for modelling have been updated from relevant previous studies.

6.2 Recommendations

The main recommendations from the literature review are the following:

R5. Engagement with suppliers should be continued in the next stages of the project, either through leaving the RfI portal open or direct communication with suppliers, to provide further information on the listed solutions.

R6. Further consideration should be made as to how engagement from suppliers could be improved. This may include being more clear in communications on what the benefits of engaging in the project are for the suppliers.

R7. The RfI is tailored for established products and may be too technically detailed for lower TRL solutions. The focus of this project are high TRL solutions, however WPD may wish to continue engagement with low TRL solutions as they become more established.

R8. For future studies, other factors to capture could include second order benefits (i.e. environmental / social benefits) for the solutions.

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EA Technology Limited
Capenhurst Technology Park
Capenhurst, Chester CH1 6ES

t +44 (0) 151 339 4181
e sales@eatechnology.com
www.eatechnology.com