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### Successful Delivery Reward Criteria

The SDRC matrix in Table 1 illustrates at a high level how the SDRC 9.6 criteria are met in this report and its appendices.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Evidence</th>
<th>Supporting Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDRC 9.6 - Full evaluation of the benefits realised by power electronics devices on the LV network.</td>
<td>Completion of Dissemination of learning for the operation of power electronics devices on LV network architectures and for network performance.</td>
<td>• Appendix A of this report describes the completion of the learning dissemination activities</td>
</tr>
</tbody>
</table>
| | Completion of Cost Benefit Analysis fully quantifying the benefits for various scenarios and types of customer (case studies). The case studies will be based on site specific examples and operational data available during the trials. The business as usual approach will be compared with the FUN-LV methods. | • Section 2 of this report describes the CBA approach  
• Section 5 of this report provides the results of the CBA analysis for a generalised case  
• Sections 6 and 7, respectively, describe the sensitivity analysis, and the results of the replication study assessing the net benefit of wider FUN-LV roll-out |
| | Report including cost of installation and operation of power electronics devices on the network. | • Section 3 summarises the reinforcement and method costs assumed in this report  
• Appendix D – Method costs provides the detailed costs associated with the FUN-LV trials |
| | Demonstration of the benefits realised (financial and non-financial) and the capacity released. Multiple benefits will be evaluated for each case study; a primary benefit (i.e. the driver for the method deployment) and secondary benefits. | • Technical effects for both primary and secondary benefits are noted in SDRC 9.5  
• Financial and non-financial benefits are described in Section 4 of this report |
| | Assessment of the Cost Benefit Analysis. | • Section 2 of this report describes the CBA approach  
• Section 5 of this report provides the results of the CBA analysis for a generalised case  
• Sections 6 and 7, respectively, describe the sensitivity analysis, and the results of the replication study assessing the net benefit of wider FUN-LV roll-out |
| | Analysis of Power electronics device performance and reliability data. | • Section 2.2.2 summarises the device performance  
• Appendices B and C provide more detail on the device performance |
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaU</td>
<td>Business as Usual</td>
</tr>
<tr>
<td>CBA</td>
<td>Cost Benefit Analysis</td>
</tr>
<tr>
<td>CFL</td>
<td>Compact Fluorescent Lightbulb</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>DNO</td>
<td>Distribution Network Operator</td>
</tr>
<tr>
<td>DNV</td>
<td>Distribution Network Visibility</td>
</tr>
<tr>
<td>DSR</td>
<td>Demand Side Response</td>
</tr>
<tr>
<td>EPN</td>
<td>Eastern Power Networks plc</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>FUN-LV</td>
<td>Flexible Urban Networks – Low Voltage</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage</td>
</tr>
<tr>
<td>LCT</td>
<td>Low Carbon Technology</td>
</tr>
<tr>
<td>LPN</td>
<td>London Power Networks plc</td>
</tr>
<tr>
<td>LV</td>
<td>Low Voltage</td>
</tr>
<tr>
<td>M1-3</td>
<td>FUN-LV Methods 1-3</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>PED</td>
<td>Power Electronics Device</td>
</tr>
<tr>
<td>RES</td>
<td>Radially Embedded Substation</td>
</tr>
<tr>
<td>SDRC</td>
<td>Successful Delivery Reward Criteria</td>
</tr>
<tr>
<td>SOP</td>
<td>Soft Open Point (Methods 2 and 3)</td>
</tr>
<tr>
<td>SPN</td>
<td>South Eastern Power Networks plc</td>
</tr>
<tr>
<td>TRL</td>
<td>Technology Readiness Level</td>
</tr>
</tbody>
</table>
Executive Summary

Background

The aim of the FUN-LV project is to explore the use of PEDs to enable deferral of reinforcement, and to improve network performance, and facilitate the connection of low carbon technologies and distributed generation in urban areas, by meshing existing networks which are not meshed, and by removing boundaries within existing meshed networks.

The FUN-LV trials demonstrate three different methods with increasing levels of capacity sharing functionality, which are described in more detail in SDRC 9.5 (Successful demonstration of enhanced modes of operation of power electronics devices)\(^1\). In this report assesses the costs of these methods and compares them with the financial benefits they can deliver in order to develop an overall CBA and to understand the sensitivities around the business case.

The key benefit of the FUN-LV methods is that they create headroom at constrained substations. Even supposing a simple world of gradual and predictable load growth, this affords the DNO a means to defer conventional reinforcement. However, the full value of FUN-LV is expected to emerge in a context where the levels of EVs, Heat Pumps and DG increase in a manner difficult to forecast with certainty. These technologies increase the complexity of planning and managing the distribution network. There is a societal drive to allow these new technologies to connect, but their tendency to cluster is a particular challenge for the LV networks. Consequently, the DNO will need tools to accommodate this new demand in an efficient and cost-effective way.

Quantifying the challenge of accommodating these new technologies is a challenge given the uncertainty surrounding their uptake and load profile characteristics. The majority of the economic analysis in this report, therefore, focuses on the more conservative case of organic traditional load growth in order to explore the cost and technical parameters that deliver a positive business case in that world. While this analysis shows FUN-LV methods will provide a valuable, but specialised tool on today’s networks, their widespread deployment will be a key part of a response to a fast changing low carbon uptake scenario.

Trial scheme summary

36 suitable sites were chosen for analysis under the selection criteria and the approach defined in the SDRC 9.1 document (Successful completion of design and planning for power electronics devices – Overview Report)\(^2\). These 36 sites comprised 12 selected for each of Methods 1, 2 and 3. Of each set of 12, eight sites are located in the LPN region and four sites in the SPN region. The LPN sites were chosen to give an equal number of interconnected and radial network sites under each method, with all SPN sites being in radial networks.

Whilst some of the trial sites have addressed networks already constrained, the sites were primarily chosen to explore and demonstrate the technical capabilities of the FUN-LV methods, rather than to resolve immediate real network constraints. The results have therefore been used to calculate the capability of FUN-LV methods. This is then used to infer their benefit in avoiding complex and costly

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\(^1\)http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Flexible-Urban-Networks-Low-Voltage/Project-Documents/SDRC+9.5_FUNLV_+v1.0.pdf

\(^2\)http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Flexible-Urban-Networks-Low-Voltage/Project-Documents/SDRC+9.1+Successful+completion+of+design+and+planning+for+PEDs.pdf
reinforcement, particularly in a future network with large volumes of DG and clustered EVs and Heat Pumps.

The FUN-LV trials have successfully demonstrated the ability of three methods to operate in a range of modes, and has done so at scale (12 of each) on a range of network types (radial, meshed and mixed). As a result, the FUN-LV project has achieved a significant advancement in the maturity of these technologies increasing the TRL of these technologies, through the trial phase, from 4 to 6.

**Benefits for the LV feeder of the future**

It is expected that on the “LV feeder of the future” there will be more DG and the clustering of LCTs, leading to increasing voltage issues, current issues and complex flows on the network. The trial has demonstrated that the FUN-LV methods will be able to deliver a range of benefits, to address these issues, including:

- Active power headroom creation;
- Phase unbalance correction;
- Power factor improvement;
- Voltage management;
- Fault level control;
- Harmonic reduction;
- Support during HV faults;
- Enabling DG connections;
- Loss reduction;
- Improved asset health;
- Reduced customer complaints; and
- Reduced site disruption.

The FUN-LV trials effectively demonstrate that these technologies are an appropriate and viable tool for planning and operating what is expected to become an increasingly complex LV network. It will be important, as these technologies develop, to ensure that this full suite of capabilities is retained and enhanced, and that multiple issues can be resolved by a single method deployment. The value of future FUN-LV deployments is likely to be realised from the need for resolving multiple technical challenges simultaneously.

**Benefits: addressing today’s challenges**

Whilst the trial has proven the capability of FUN-LV methods to address future network challenges, the immediate challenge is to release network capacity in order to avoid reinforcement and enable new connections. An estimate of the conventional reinforcement cost associated with the 36 FUN-LV schemes, which were not selected for being particularly complex or costly reinforcement schemes, came to a total of £2.2m. This estimate is calculated from proposed minimum reinforcement schemes required upon each site becoming capacity constrained. Based on analysis of the trials site load profiles, 6,284kVA of headroom could be released to the connected networks through the use of all three methods.

FUN-LV methods have the potential to create headroom by sharing load between substations, thereby reducing the immediate need for reinforcement and enabling more load to connect more quickly and at lower cost. This could occur either between a heavily- and a lightly-loaded substation, or between two heavily-loaded substations with non-coincident peaks.
The FUN-LV trials demonstrated that all three methods, if deployed in the appropriate locations and if calibrated appropriately, can create significant benefits by sharing load in this way. The trials demonstrated that even assuming today’s FUN-LV method costs (early-stage technologies and trial deployment techniques) and conventional reinforcement costs, there are schemes that demonstrate a positive business case on headroom-creation alone, as is described below. This is important, since it provides a justification for deploying and refining these methods in specific instances in the short-term, but it should again be noted that the need for the other FUN-LV functions will become increasingly prevalent.

**Costs**
The key factor determining the economic viability of FUN-LV methods is their cost relative to the conventional reinforcement and new connection options. There was a wide variability, particularly in the installation cost, which partly reflected the constraints of specific sites but also reflected the fact that installers were learning as the trial progressed. For the “trial average” CBA case, the mean equipment and installation costs were used:

**Table 2 – Method cost breakdown (current costs)**

<table>
<thead>
<tr>
<th>Method #</th>
<th>Equipment Cost</th>
<th>Comms and remote monitoring</th>
<th>Installation and Commissioning</th>
<th>Current Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>£12,500</td>
<td>£2,507</td>
<td>£7,000</td>
<td>£22,007</td>
</tr>
<tr>
<td>2</td>
<td>£42,904</td>
<td>£7,450</td>
<td>£12,000</td>
<td>£62,354</td>
</tr>
<tr>
<td>3</td>
<td>£77,751</td>
<td>£10,850</td>
<td>£20,000</td>
<td>£108,601</td>
</tr>
</tbody>
</table>
However, one of the key features of FUN-LV methods is that they can be redeployed with relative ease. It was assumed therefore, that the technology costs (above the installation and commissioning costs) could be shared amongst multiple deployments. This significantly reduced the effective method costs, particularly in cases in which the methods were only required for a short period of time.

The average conventional reinforcement cost estimated for the 36 schemes was £62,600 (£63,900 in LPN and £59,700 in SPN), amounting to a total of £2.2m. The cost of conventional reinforcement option can have a wide range depending on the amount of work required and complexity associated with particular sites. The CBA was carried out on the basis of the trial average cost, subdividing by method, as shown below.

Table 3 – Conventional reinforcement costs estimated during the trial

<table>
<thead>
<tr>
<th>Method #</th>
<th>Conventional reinforcement cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>£36,500</td>
</tr>
<tr>
<td>2</td>
<td>£51,400</td>
</tr>
<tr>
<td>3</td>
<td>£91,800</td>
</tr>
</tbody>
</table>

However, it is not envisaged that FUN-LV methods will typically be deployed as an alternative to “average” reinforcement (although it can in some cases be justifiable). It is more likely that it will be deployed where the cost of the conventional reinforcement option is above-average or does not provide the flexible dynamic capabilities or can be achieved in the reduced deployment timescales of the FUN-LV solutions. Even from the trial sites (which were not selected for their high reinforcement cost) a wide range of costs can be seen. The effect of targeting higher-cost sites is explored in the sensitivity analysis, and the distribution of costs is reflected in the replication study.

Figure 2 – Distribution of conventional reinforcement costs
The key findings of the trial average, sensitivity and replication studies are given below.

**Trial average case results**

The “trial average” case used the method costs seen during the trial and the average conventional reinforcement cost estimated for each method. The CBA considered a gradual and deterministic load growth rather than the more unpredictable organic load growth and new connections that may benefit more from a flexible method such as FUN-LV. Finally, the additional range of benefits such as voltage management, whilst proven during the trial, were not quantified financially, so were not included in this analysis. As such, the following results should be seen as conservative.

**Method 1 (link box switches and remote control circuit breakers)**

On this basis, only two trial M1 schemes have a positive NPV at a 3.5% discount rate. These two schemes are the only M1 examples of achieving concurrent deferral. M1 devices do not offer a great deal of control over the power flows, so the ability to achieve the load balancing assumed for this CBA is not guaranteed, and will require careful site selection. It is also worth noting that M1 devices do not allow the user to control other network characteristics such as voltage or phase balancing (although the act of meshing does tend have an effect on these).

It is likely that the case for specific M1 schemes will rely on their ability to defer or avoid reinforcement and to enable customer connections to be made on existing LV circuits that would not have been possible with radial operation. More over this tool is the fastest to deploy and lowest cost solution to address reinforcement constraints. As discussed, our CBA approach is expected to be conservative in the sense that the full value of these devices may come from their ability to be deployed rapidly and in cases where conventional reinforcement is unfeasible or does not meet the customer requirements. As will be shown in Section 6, focusing M1 devices on such schemes can deliver substantial benefits.

**Method 2 (2-port Soft Open Point)**

M2 costs are significantly higher, but offer full control over power flows and can deliver a wider range of services, particularly enabling customer connections to be made on existing LV circuits that would not have been possible with radial operation and especially for circuits that cross key operational boundaries. Given the limited scope of the trials, no schemes were seen to be financially viable. However, M2 devices are able to manage load flows in a controlled way (unlike M1 devices), so it should be expected that for a given site a M2 device will be able to create as much, if not more, headroom and hence achieve the same or more reinforcement deferral and be central to the faster connection of customer loads and generation on existing circuits. The fact that large transfers were not seen in the trial suggests that the substation load profiles in the M2 trial sites were not sufficiently complementary and that the trials deliberately did not set out to demonstrate the connection of new customer loads or generation. The project expects that substations with more complementary profiles will be a common part of the future network.

It should be noted that M2 SOP devices have the ability to provide a much wider suite of benefits than the M1 devices such as the ability to manage constrained LV circuits with point loads which are larger or have rapidly shifting load profiles. Although the cost of M2 devices is higher, the opportunity for benefits is greater (if the site warrants those additional benefits), particularly if concurrent deferral of multiple substations can also be achieved.
Method 3 (3-port Soft Open Point)
Whilst M3 costs are higher than either M1 or M2 the potential benefits are higher for a number of reasons:

- The deferred cost is higher because the conventional reinforcement options are on average higher;
- The capacity of M3 devices is higher, allowing higher power flows and hence more headroom creation; and
- Being a 3-port device, they provide the opportunity for deferring reinforcement at multiple substations while M1 or M2 do not typically achieve this.

As a result, two schemes show a positive NPV, even on the limited scope of the trial. This is primarily because they can deliver concurrent deferral on two substations, doubling the effectiveness of the device, which more than outweighs the increased method cost.

As with M1 and M2, the benefit estimated in this CBA is expected to be conservative for a number of reasons:

- The trial average cost is expected to decrease once these methods are deployed under BaU;
- The gradual, deterministic load growth and deferral arising from headroom creation understates the benefits of these devices, particularly when rapid clustered load growth requires a quick intervention, or when load growth and the need for reinforcement is uncertain; and
- There is a range of other benefits that were demonstrated technically in the trial. These resolve network issues that are expected to become more pressing and more prevalent in the LV network of the future as a result of the increasing uptake of DG and LCTs.

Commercial Case
The analysis in Section 6 reveals that the business case for FUN-LV is very sensitive both to the method costs and the reinforcement alternatives. A 30% method cost reduction has been indicated by suppliers, as a result of economies of scale and improvements in installation that would be expected if FUN-LV methods were deployed more widely. Reinforcement costs are not, on average, expected to increase. However, the sensitivity analysis suggests that FUN-LV should be targeted at the more expensive instances of conventional reinforcement involving, for example, new substations or many cable works in dense urban environments or where there are time and space related customer demands.

To explore the range of sensitivities, and to reflect the expected improvement in the business case arising from lower method costs and more targeted method deployment, a sensitivity analysis has been conducted showing the effect of these and other factors.

In order to show the overall effect of the sensitivity progression on the 36 schemes, including those with negative NPVs, we can look at the improvement in average scheme NPV against the trial average baseline, shown in Figure 3. To contextualise the relative size of these improvements, the average conventional reinforcement costs from the trials are £36.5k, £51.4k and £91.8k for Methods 1, 2, 3 respectively, as previously listed in Table 3.
The absolute contribution of one sensitivity will depend on whether the others have been applied, so the order in which they are considered matters. Nevertheless, the key sensitivities are:

- **Method cost** reduction, expected to be 30% under BaU roll-out, will be a significant determinant of the viability of a number of scheme-specific business cases.
- **Asset lifetime**, which has a significant effect on the overall business case because by increasing the asset lifetime the device can be deployed elsewhere for longer, thereby reducing the effective cost of any particular scheme.
- **Reinforcement cost.** This is a key variable since deferring this expenditure is the one of the key benefits of FUN-LV methods. It is not anticipated that average reinforcement cost will increase substantially. Rather, this sensitivity reflects the fact that FUN-LV methods should be targeted at the more costly conventional reinforcement schemes as well as time-constrained customer related connections.

The cumulative effect of these sensitivities changes the overall case for FUN-LV methods substantially. By considering the proportion of the 36 trial schemes that would have been viable, the analysis reveals that if a 30% cost reduction can be achieved as expected, device lifespans can be extended by five years (e.g. through maintenance or part replacement), a large proportion of schemes would be viable if the conventional reinforcement option were more than 20% above the current average. Hence we can conclude most (above 80%) schemes are financially profitable with a commercial production scenario (high volume) of the existing generation technology in combination with a targeted approach to sites with high cost reinforcement options.
Figure 4 – Proportion of schemes with positive NPVs

Again, it should be noted that FUN-LV methods are more suited to rapid deployment, uncertain load growth projects and situations in which the network has a number of issues (e.g. voltage and phase unbalance). This analysis demonstrates the opportunity presented by the methods and justification that they can be viable on just one relatively conservative use case.

The option value associated with uncertain load growth is explored in the Option Value for Flexible Technologies report by Imperial College London. Based on selected case studies, their analysis showed that option value could be significant if the flexibility associated with FUN-LV methods were accounted for and factored into the planning process. The option value for the selected cases can be considered as an alternative assessment to the value associated with deferral under deterministic load growth (basis of this report’s CBA). The option value (NPV) for each case study method was estimated to be:

- Method 1 (Eastbourne Terrace): £18.5k (high flexibility)
- Method 2 (Boyce’s Street): £33k (moderate flexibility)
- Method 3 (Prudential North): £46.7k (moderate flexibility)

Replication
The purpose of the replication study is to estimate the net benefit of a UK Power Networks’ LPN network rollout and GB wide rollout of FUN-LV methods, based on the possible deferral benefit provided by the method.

The replication analysis estimated the NPV of sites based on 7,913 substations, comprised of the subset of LPN substations which have Remote Terminal Units (RTUs) installed. The results of this analysis can be extrapolated and provides the total NPV of a rollout of the methods across the LPN region and a GB wide rollout. The LPN area contains 17,789 substations, as stated in the V1 Asset Register as of 31 March 2016. The analysis carried out by Ricardo Energy & Environment (formerly PPA energy), in the
FUN-LV bid submission document estimated there are 87,000 substations in GB in dense urban areas, where the FUN-LV methods would be applicable for installation. Table 4 displays the number of unique sites identified in the replication study sample with a positive business case for reinforcement deferral, excluding those for which installing such methods was estimated to be unfeasible. Extrapolating these figures provides an estimate of the number of feasible, unique sites in both the LPN area and GB-wide.

Table 4 – Number of feasible unique sites

<table>
<thead>
<tr>
<th>Method #</th>
<th>Replication Study unique sites with positive NPV</th>
<th>LPN Rollout unique sites with positive NPV</th>
<th>GB Rollout unique sites with positive NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>454</td>
<td>764</td>
<td>5,031</td>
</tr>
<tr>
<td>2</td>
<td>29</td>
<td>48</td>
<td>315</td>
</tr>
<tr>
<td>3</td>
<td>82</td>
<td>204</td>
<td>1,344</td>
</tr>
</tbody>
</table>

Focusing on only those sites that show a positive business case for reinforcement deferral, the headroom that can be created by deploying these methods is summarised in Table 5. This illustrates that, where conventional reinforcement is too costly or unviable given space or time constraints, there is significant potential to use FUN-LV methods instead. This would free up capacity to install large volumes of EVs and heat pumps. Also, these estimates have been made on the basis of historic load profiles, but if increasing volumes of LCTs are seen on the network, the flexibility of FUN-LV methods is expected to deliver additional value as they provide a means to shift load between substations in real-time. To understand the relative size of headroom figures below, the typical urban secondary substation transformer capacities are 500kVA, 750/800kVA and1000kVA.

Table 5 – Headroom released by FUN-LV methods

<table>
<thead>
<tr>
<th>Method #</th>
<th>Average headroom released per site (kVA)</th>
<th>LPN Rollout Total headroom released for sites with positive NPV (kVA)</th>
<th>GB Rollout Total headroom released for sites with positive NPV (kVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>126</td>
<td>128,714</td>
<td>629,495</td>
</tr>
<tr>
<td>2</td>
<td>183</td>
<td>11,768</td>
<td>57,553</td>
</tr>
<tr>
<td>3</td>
<td>167</td>
<td>30,640</td>
<td>149,851</td>
</tr>
<tr>
<td>Total</td>
<td><strong>159 [average]</strong></td>
<td><strong>171,122</strong></td>
<td><strong>836,899</strong></td>
</tr>
</tbody>
</table>

Table 6 displays the total NPV of method installation for sites with a positive NPV, discounted by the infeasibility percentage, across the substations analysed in the replication study. These results have then been extrapolated to a LPN wide rollout and a GB wide rollout of the methods.

Table 6 – Total NPV of method installation for sites with a positive NPV

<table>
<thead>
<tr>
<th>Method #</th>
<th>LPN Rollout</th>
<th>GB Rollout</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>£3,877,779</td>
<td>£18,964,912</td>
</tr>
<tr>
<td>2</td>
<td>£128,304</td>
<td>£627,490</td>
</tr>
<tr>
<td>3</td>
<td>£5,199,460</td>
<td>£25,428,804</td>
</tr>
<tr>
<td>Total</td>
<td><strong>£9,205,543</strong></td>
<td><strong>£45,021,205</strong></td>
</tr>
</tbody>
</table>
The rollout of M1 and M3 components show a far greater potential NPV in comparison to a rollout of M2 components. The high NPV of M1 sites is due to the low ratio of method cost to reinforcement cost, meaning that even with the potential to only defer a reinforcement for a small proportion of the method equipment life-time the deferral benefit is still large enough to justify installation of the method. The high NPV of M3 sites is due to the load utilisation amongst three, as opposed to two, substations which increases the likelihood that a deferral will be for the lifetime of the asset. This results in a large deferral benefit which increases the likelihood of a positive site NPV. M2s have a high ratio of method cost to reinforcement cost and, due to the sharing of load between only two substations, the average length of deferral is likely to be less than the lifetime of the asset. This results in a low likelihood of a positive NPV for M2 installation.

**Conclusions**

FUN-LV methods offer a long list of potential benefits for a DNO looking to reduce reinforcement costs, connect new customers more efficiently and address various technical challenges, such as managing voltage and reducing phase unbalance. The extent to which each of these benefits can be realised will depend on the particulars of the scheme being considered. Nevertheless, focusing only on the benefit of headroom creation and reinforcement deferral it is estimated that there will be a considerable volume of cases in which a FUN-LV method is preferable to the conventional options. This should be seen as a conservative case that justifies developing the methods further, but the full value is not expected to emerge until the DNO needs to accommodate the large volumes of EVs and other LCTs that are expected to connect to the distribution network in the near future.
1. Introduction

1.1 Background

Efforts to decarbonise electricity generation, heat and transport will place increasing demands on electricity distribution networks, particularly so for the LV networks closest to our customers, where Distribution Network Operators (DNOs) have the obligation of supplying customers within tightly defined voltage limits, which their devices have been designed to expect, and at a sufficient quality (harmonics, sags, swells and flicker).

Interconnected networks, as suggested in the Transform model, offer one potential solution to this challenge. In interconnected networks, also termed as meshed networks, customers are supplied via two or more different routes through the LV network, with the result that their demand can be shared across substations. This can reduce loading on transformers, suppress voltage fluctuations, reduce losses, and customers benefit from in-built resilience to high voltage (HV) network faults. UK Power Networks has run some parts of its networks meshed for many years. In urban and central business districts, both in UK Power Networks and other DNOs, there is potential for further meshing.

The overarching aim of the FUN-LV project is to explore the use of Power Electronics Devices (PEDs) to enable deferral of reinforcement and facilitate the connection of low carbon technologies and distributed generation in urban areas, by meshing existing networks which are not meshed, and by removing boundaries within existing meshed networks. Power electronics allows the reversion of the meshed network to two radial networks in the event of a fault. The FUN-LV trials demonstrate three different methods with increasing levels of capacity sharing functionality. This report assesses the costs of these methods and compares them with the financial benefits they can deliver in order to develop an overall Cost Benefit Analysis (CBA) and to understand the sensitivities around the business case.

1.2 Report Scope and Objectives

This report details the necessary and sufficient evidence to complete SDRC 9.6 “Full evaluation of the benefits realised by power electronics devices on the LV network.”:

- Section 2: Outlines the CBA approach;
- Section 3: Details the costs associated with FUN-LV methods and the conventional reinforcement, and describes the assumptions used for developing the CBA;
- Section 4: Describes the technical benefits that can be derived from FUN-LV methods (as were evidenced in SDRC 9.5) and the way in which these translate into financial benefits;
- Section 5: Combines the costs and benefits into a central CBA case, which uses the observed behaviour of the trial schemes, but uses average method and reinforcement costs to derive a general view of the value of such methods to DNOs and end consumers;
- Section 6: Sensitivity analysis exploring the effect of operating the Methods in different ways, and the effect of changes to costs and other economic parameters;
- Section 7: Describes a replication study investigating how FUN-LV methods can be scaled up across GB and the overall benefit that can therefore be derived from such schemes
- Section 8: Draws out conclusions and identifies the next steps that need to be taken to further understand and potentially deploy FUN-LV more widely

The target audience for this report are Ofgem and DNOs seeking to understand the costs and benefits of using power electronics devices in the ways demonstrated in this project. It is therefore important to assess appropriately all benefits in context to a representative network of the future for this to be recognised as keystone research.
2. CBA approach

2.1 Introduction

On the basis of the evidence gathered during the FUN-LV trials, a CBA has been conducted. The purpose of this was to assess the trade-off between the costs associated with a particular method and the benefits that this method can bring. The trials demonstrated that the FUN-LV methods will be able to deliver a range of benefits, including:

- Active power headroom creation;
- Phase unbalance correction;
- Power factor improvement;
- Voltage management;
- Fault level control;
- Harmonic reduction;
- Support during HV faults;
- Enabling DG connections;
- Loss reduction;
- Improved asset health;
- Reduced customer complaints; and
- Reduced site disruption.

It is expected that all of these measures will be required for the “LV feeder of the future”, which is expected to see more DG and the clustering of LCTs, leading to increasing voltage issues, current issues and complex power flows on the network. The FUN-LV trials effectively demonstrate that these technologies are an appropriate and viable tool for planning and operating what is expected to become an increasingly complex LV network. It will be important, as these technologies develop, to ensure that this full suite of capabilities is retained and enhanced, and that multiple issues can be resolved by a single method deployment. The value of future FUN-LV deployments is likely to be realised from the need for resolving multiple technical challenges simultaneously.

Whilst the trial has proven the capability of FUN-LV methods to address future network challenges, the immediate challenge is to release network capacity in order to avoid reinforcement and enable new connections. As with DSR and other “opex” solutions, FUN-LV methods have the potential to create headroom, thereby reducing the immediate need for reinforcement and enabling more load to connect more quickly and at lower cost. In the case of FUN-LV, this is done by sharing load between substations. This could occur either between a heavily- and a lightly-loaded substation, or between two heavily-loaded substations with non-coincident peaks. It is this headroom creation, and the resulting benefit of deferring conventional reinforcement, that is the focus of this section of the report, but it should be recognised that the suite of capabilities that FUN-LV methods offer is significantly wider than this.

2.2 Scheme summary

2.2.1 Schemes

Using the selection criteria and approach defined in the SDRC 9.1 document, 36 suitable sites were chosen for analysis. These 36 sites, shown in Table 7, consisted of 12 sites meeting the selection criteria for the implementation of M1, 12 for M2, and 12 for M3, respectively. Of each set of 12, eight sites are located in the LPN region and four sites in the SPN region. The LPN sites were chosen to give an equal number of interconnected and radial network sites under each method, with all SPN sites being in radial networks and to demonstrate the technical operation of the methods under a wide range of operational conditions, they were not selected as examples of where conventional reinforcement would be need or would be difficult or expensive nor where the installations would be expected to be financial viable.
### Table 7 – FUN-LV Trial Sites

<table>
<thead>
<tr>
<th>Region</th>
<th>Network Configuration</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPN</td>
<td>Inter-connected</td>
<td>LPN 1.1i Pall Mall</td>
<td>LPN 2.1i Piccadilly, Piccadilly South Side W1J 9BR</td>
<td>LPN 3.1i Shaftesbury Ave 125 24410, WC2H 8HR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LPN 1.2i Portman Cl</td>
<td>LPN 2.3i Jermyn Street SW1 6DT</td>
<td>LPN 3.2i Bulstrode Clifton Frd Htl 34179 - 47 Welbeck St, London W1G 8DN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LPN 1.3i Edgware Rd 112-130</td>
<td>LPN 2.7i Ryder Street (Junction with St James Street) SW1A 1ES</td>
<td>LPN 3.3i Nutford Pl Holiday Inn (G) 30107 - W1H 5DN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LPN 1.4i Edgware Rd 168-172</td>
<td>LPN 2.8i Portman Square W1H 6LW o/s 20 Portman Square</td>
<td>LPN 3.4i 36 Pall Mall (LV Only) 36223 - SW1Y 5JN</td>
</tr>
<tr>
<td>LPN</td>
<td>Radial</td>
<td>LPN 1.1r ACRE LANE</td>
<td>LPN 2.2r Gladstone Place 1 Roman Rd, London E3 5ES</td>
<td>LPN 3.2r Ellwood Ct Shirland Rd 30123 (LV Only), Clearwell Drive W9 2JX</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LPN 1.2r ALBERT EMBANKMENT</td>
<td>LPN 2.3r Morden Road (Public) 115 Morden Rd, Mitcham, CR4 4DG</td>
<td>LPN 3.3r Bushey Rd West (LV Only) 08070 SW20 8LW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LPN 1.3r MILKWELL YARD</td>
<td>LPN 2.4r Loughborough Park 226 Loughborough Park, Brixton, SW9 8TD</td>
<td>LPN 3.4r Loughborough Rd Newark Hse (LV Only) 90260, SW9 7SH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LPN 1.7r EASTBOURNE TERRACE</td>
<td>LPN 2.5r Morden Road (Substation Compound) 115 Morden Rd, Mitcham, CR4 4DG</td>
<td>LPN 3.5r ALFRED RD OVERLEY HSE NTH 34819, W2 5EU</td>
</tr>
<tr>
<td>SPN</td>
<td></td>
<td>SPN 1a.2r M&amp;S Dyke Road</td>
<td>SPN 2.1r Boyces Street</td>
<td>SPN 3.1r Prudential North Street [ T1 ] 523637</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SPN 1a.4r Buckingham Street</td>
<td>SPN 2.2r Queens Road</td>
<td>SPN 3.2r Robert Street [ T1 ] 523280</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SPN 1a.5r North Street Quadrant</td>
<td>SPN 2.3r Buckingham Road</td>
<td>SPN 3.3r Church Street [ N2 ] 523036</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SPN 1a.6r Paradox Club</td>
<td>SPN 2.4r Cannon Place</td>
<td>SPN 3.4r Kings Road [T1+T2] 523025</td>
</tr>
</tbody>
</table>

#### 2.2.2 Device performance

As would be expected on a trial, the deployment of the FUN-LV methods required calibration and, in some cases, required modifications and repeat site visits to ensure the devices were performing properly. This process is described in detail in Appendices B and C. However, for the purpose of the CBA it is necessary to distinguish between performance issues that are inherent to the devices...
themselves, and would be expected to endure upon wider roll-out of these methods, and those performance issues that arise because of the exploratory nature of a trial of this sort.

In particular, there are a number of operating modes and settings that can be chosen for the PEDs. For the trial, these settings were being explored, and were not permanently set up to deliver the maximum economic benefit throughout the trial period. It is assumed for the analysis that the optimal theoretical load balancing settings would be used in practice.

Throughout this report, therefore, the analysis is based on the assumption that all the devices are continuing to deliver active power transfer as intended for their primary function, and have been configured appropriately given what has been learnt during the trial.

2.3 CBA process

This section describes the steps that were taken in order to carry out the CBA. Note that for ease of explanation the example of M2 has been used, and the assumption is made that load sharing occurs between two substations. As will be shown in Section 4, in practice more than two substations can see their loading affected, even by a 2-port PED.

The CBA process is summarised in Figure 5, with additional details given in the subsequent text:

Figure 5 – Cost Benefit Analysis Logic

- Calculate reinforcement requirements **under counterfactual**
  - Note the capacities of substations associated with a given scheme;
  - Import historic load profile data for each substation and extract peak load;
  - Extrapolate annual peak load into the future based on growth projections; and
  - Determine substation reinforcement timings

- Calculate reinforcement requirements **with FUN-LV method in place**
  - Assume FUN-LV method is installed in first year in which reinforcement would otherwise be required;
  - Assume that the installation cost is incurred in full, but only the relevant share of the asset costs are reflected, which depends on the duration of the deferral relative to the total asset lifetime;
  - For each substation peak load, extract the corresponding load for the other substation(s) in the scheme;
  - Apply the load balancing rule determined for each Method and Scheme; and
  - Recalculate substation reinforcement timings

- Compare Base and FUN-LV cases
  - Calculate NPV for:
    - Counterfactual case reinforcement profile;
    - Method reinforcement profile; and
    - FUN-LV method cost
2.3.1 Calculating reinforcement requirements and cost under base case

There are four pieces of information required to estimate the timing and amount of reinforcement expenditure required in the base case:

1. The effective capacity of the substation: This is the maximum level of loading that a given substation can accommodate. This is related to the nameplate capacity of the substation, but a network operator may use an effective capacity that is lower or higher than the nameplate capacity depending on network configuration and the shape of the load profile, as described in SDRC 9.1 Appendix A – Guidance Document on Traditional Planning Considerations for Power Electronic Devices3.

2. The observed peak load at that substation: In reality, loading time series and detailed information about circuit length may be relevant for accurately evaluating the ability of a method to create headroom. For the purposes of the CBA model, however, given that load-related reinforcement is driven by peak loading, only a single peak load value is required, which is extracted from the historic load profiles.

3. The expected annual increase in peak load: In order to estimate the load growth on the LV substations, UK Power Networks adapted pre-existing projections carried out at the Primary substations. These original projections were informed by a combination of historical trends, government projections and Element Energy models of the uptake of energy efficiency measures and low carbon technologies. They forecast the impact of differing assumptions regarding the financial incentive regimes, rate of technology cost and performance improvements and energy costs on the rate of uptake. For this more recent analysis, load growth projections for the LV substations were made on the basis of the mix of customer profile types. The original projections come with a high degree of uncertainty, and this uncertainty is exacerbated for the LV substations, where the changing behaviour of a small number of consumers can have a significant impact on the load profile. Sensitivities on these load growth assumptions are therefore included in Section 6.

4. The cost of reinforcement: For this analysis, we have used the reinforcement cost estimates made for each scheme and taken the mean average costs for M1, M2 and M3, respectively, for the trial average case. This provides a central view of typical reinforcement cost. It should be noted, however, that reinforcement costs can vary widely, with some works being very complex, expensive and time-consuming, particularly in dense urban areas with space and/or logistical constraints. It may be for these sites that FUN-LV is particularly well-suited.

2.3.2 Calculating reinforcement requirements and cost with FUN-LV method in place

2.3.2.1 FUN-LV installation assumptions

We have assumed, for the core CBA, that the FUN-LV method device would be installed only when reinforcement would otherwise be required, with any additional benefits (e.g. voltage support or fault level management) supplementing this primary Use Case. We have further assumed that the device would be installed only temporarily, and would be removed once it had served its purpose and reused on a different scheme, thereby reducing the effective cost per scheme. Some of the cost, such as labour and site preparation, will be non-recoverable, but the method equipment itself is expected to be movable once its purpose has been served. This possibility is explored in Section 7.

---

2.3.2.2 Load-sharing rules

By the nature of the trial design, the substations chosen for the FUN-LV trial schemes were not at the point of requiring immediate reinforcement. This was to minimise the risk of adverse impacts on customers during the trial. The key question for the purpose of carrying out the CBA is:

“How much headroom does this method create for a given substation, and by how many years can the reinforcement of that substation therefore be deferred?”

To this end, the effect of the FUN-LV method on the loading of each substation needed to be understood at the point in time at which reinforcement would otherwise be required, and for subsequent years during which the method would be in effect. In order to make this determination, a set of rules needed to be derived from the trials to describe how each of the FUN-LV methods would behave for a given network configuration, substation capacity and relative loading.

The rules themselves have been described in detail in the SDRC 9.5 (Successful demonstration of enhanced modes of operation of power electronics devices) report. These rules are, by necessity, a simplification of the actual behaviour of the FUN-LV methods in the real world, but have been developed in order to be applicable to a range of substation combinations, and to allow extrapolation into the future.

It should also be noted that the rules describe the behaviour of the FUN-LV methods in what has been determined to be the optimal running modes. As part of the FUN-LV trials, a number of these method devices were adjusted in order to find these optimal settings. For example, the deadband was initially set at 10%, but this was subsequently reduced to 5% in order to improve the amount of transfer that could be achieved between the sites since this was determined to give a more appropriate balance between load sharing between substations and losses across the device, and there is potential for further improvement if the dead band is eliminated.

2.3.2.3 Applying the load-sharing rules to load profiles

Having devised the rules describing the way in which load is shared between two or more substations, these rules need to be applied to the load profiles. The rules vary depending on the method in question and the characteristics of the substations (e.g. capacity, network topology, and device deadbands) but for the illustrative purpose of this section, a two-substation case is taken with identical capacities and perfect load-balancing behaviour exhibited by the FUN-LV device.

In the case illustrated in Figure 6, at each point in time the rule can be applied, resulting in the load being shared equally between the two substations in proportion to their ratings. This results in the peak of the most constrained substation (Substation 1) falling considerably, with a corresponding rise in the loading of Substation 2. In this case it would be expected that the FUN-LV method would defer the reinforcement of Substation 1. On reinforcing Substation 1, the method device could be deactivated or uninstalled, thereby unwinding the load-increasing effect on Substation 2.

Although for any scheme there will be one substation that is closer to requiring reinforcement, there are situations in which a FUN-LV method could reduce the peak loading at more than one substation. This presents the opportunity to defer the reinforcement of two or more substations with the installation of a single FUN-LV method. An illustrative example of this is given in Figure 7. In this case, the two substations see their peak loading at different times (e.g. morning vs evening, or summer vs winter).
For a clean spine circuit, the LV circuit through which power transfer occurs, an initial estimate of substation loadings, transfers and headroom under meshed operation can reasonably be estimated by a simple tool, using knowledge of:

- Transformer sizes (kVA);
- The equivalent length of spine circuit (to estimate the % equalisation);
- Time series data to identify the time of the group peak from the co-incident radial transformer demands; and
- The co-incident radial transformer demands at the time of group peak.

Figure 8 – Extracting key data points from load profiles

In addition, the point of maximum group load was taken, which can be different from the timing of either substation peak, but can result in a new maximum when a FUN-LV method is deployed.

Having derived the new peak loads for each substation, the same load growth assumptions are applied as in the base case in order to determine the new pattern of reinforcement required with the FUN-LV device in place.

2.3.3 Comparing base case and FUN-LV case

The underlying premise for the CBA is that there is a benefit from deferring substation reinforcement, which is reflected by the discount rate, taken to be 3.5%\(^5\), applied to those reinforcement costs. By pushing reinforcement expenditure into the future, the discounted cost is reduced. Provided the deferral is sufficiently large, the cost associated with deploying a FUN-LV method can be justified because of the reinforcement savings.

In order to make this determination, the base case and FUN-LV reinforcement profiles are calculated over the modelled period. If the discounted reinforcement cost reduction is greater than the cost of deploying the FUN-LV method itself, this translates into a positive NPV. A positive NPV indicates that the deployment of the FUN-LV scheme makes financial sense for the scheme in question.

\(^5\)This is consistent with Ofgem’s guidance for assessing innovation projects for their customer impact. A private enterprise considering the use of such technologies may choose a higher discount rate for its assessment, which would improve the apparent business case of such methods.
2.4 Additional benefits

It was expected that, in addition to load balancing, FUN-LV methods could deliver a number of additional benefits such as voltage management and phase unbalance reduction. In order to explore this, 10 trial sites were selected for further study. The results of this work are described in SDRC 9.5 (Successful demonstration of enhanced modes of operation of power electronics devices)\(^6\), but they are also explored in Section 4.

\(^6\)http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Flexible-Urban-Networks-Low-Voltage/Project-Documents/SDRC+9.5_FUNLV_+v1.0.pdf
3. Cost of FUN-LV methods and traditional reinforcement

3.1 Introduction

Whether FUN-LV methods are used to defer general reinforcement or to enable and reduce the cost of new connections, the economic viability of such methods is in large part determined by the cost of those methods relative to conventional reinforcement options.

The trials themselves revealed the cost of installing FUN-LV methods, including the cost of the devices themselves, the cost of associated communications and control systems and the cost of installation. These costs, as observed, are reflected in the trial average case. It is, however, expected that these costs will come down for two reasons: first, equipment cost should decline as a result of economies of scale and learning associated with increasing the number of devices and, second, as the DNO becomes more experienced at deploying these devices the efficiency of installation should improve. The sensitivity analysis in Section 6 includes an upside (positive) case that considers the impact of these cost reductions.

For the conventional reinforcement costs, these were estimated for each scheme as part of the trial. For the trial average case we have taken the average of these costs, broken down by Method. There is, however, a wide range of reinforcement costs around that average. As already discussed, it is not expected that FUN-LV methods are appropriate for typical reinforcement or connection schemes. Rather, these methods are more likely to be targeted at particularly costly or complex schemes, which may become more prevalent as the network becomes distressed with a high uptake of EVs and LCTs. In a sense, therefore, assessing FUN-LV against the mean average reinforcement cost seen today is of limited insight. We therefore explore not only the average, but the distribution of reinforcement costs and assess in later sections the tipping points at which FUN-LV methods become viable.

3.2 FUN-LV method costs

A full breakdown of the costs incurred whilst trialling the FUN-LV methods is detailed in Appendix D – Method costs. As discussed in the introduction, both the equipment costs and the installation costs are expected to decline from the levels seen in the trial, as installation techniques improve and economies of scale are achieved.

Furthermore, one of the potential advantages of using FUN-LV methods is that they can be redeployed elsewhere on the network once they have served their purpose. A distinction should therefore be made between:

- **Installation costs** associated with deploying a FUN-LV method, such as labour costs and materials required to prepare the site; these are incurred each time the method is deployed
- **Asset lifetime costs**, which refers to the cost of the device itself, which can be recovered over the lifetime of the asset, potentially over multiple installations. Note also that given that the technology is still relatively new, its lifetime is only an estimate. Also, it may be that some components age more rapidly than others, and that some components can be replaced or refurbished without necessarily needing to incur the full cost of the original installation.

For the purpose of the trial average CBA case, it is assumed that the full installation cost is incurred, but only a share of the asset lifetime costs are considered to reflect the residual value of the device once it has been removed. For example, if a device with a 20-year lifetime is deployed for 10 years, 50% of the asset lifetime costs are taken. For each method, the mean of the observed costs are taken from the trial, resulting in the costs shown in Table 8.
### Table 8 – Method cost breakdown (current costs)

<table>
<thead>
<tr>
<th>Method #</th>
<th>Equipment Cost</th>
<th>Comms and remote monitoring</th>
<th>Installation and Commissioning</th>
<th>Current Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>£12,500</td>
<td>£2,507</td>
<td>£7,000</td>
<td>£22,007</td>
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<td>2</td>
<td>£42,904</td>
<td>£7,450</td>
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<td>3</td>
<td>£77,751</td>
<td>£10,850</td>
<td>£20,000</td>
<td>£108,601</td>
</tr>
</tbody>
</table>

### 3.3 Conventional reinforcement costs

As part of the trial, estimates were made for reinforcing the most heavily-loaded substation in each scheme. This, combined with the scheme-specific method cost, provides the basis for the site-by-site CBA. Because the sites selected for the trials were deliberately not heavily loaded, these costs are based on an estimate of the future reinforcement works required to create headroom equivalent to each FUN-LV method (see SDRC 9.1 Appendix A – Guidance Document).

In order to provide a more generalised view of costs that would typically be incurred to reinforce secondary substations, we have based the trial average case on the mean average reinforcement cost for the M1, M2 and M3 schemes, respectively. These averages are shown in Table 9.

### Table 9 – Conventional reinforcement costs estimated during trial

<table>
<thead>
<tr>
<th>Method #</th>
<th>Conventional reinforcement cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>£36,500</td>
</tr>
<tr>
<td>2</td>
<td>£51,400</td>
</tr>
<tr>
<td>3</td>
<td>£91,800</td>
</tr>
</tbody>
</table>

Note that, whilst sites were chosen to have appropriate geographical positions and complementary load profiles for FUN-LV to be effective, they were not targeted at schemes that were expected to have high reinforcement costs (e.g. needing new substations, sites with high land costs, or schemes requiring long lengths of HV cable). So whilst these averages describe typical reinforcement costs, it may be that in practice FUN-LV is targeted at schemes where the conventional reinforcement option is considerably more expensive than the average.

Figure 9 shows the distribution of reinforcement costs. Even for the trial sites, which were not explicitly selected for the complexity of the conventional reinforcement option, there is a wide range of costs. The most expensive M1 site is 23% higher than the mean. This spread increases to 52% for M2. The figure shows that 30% of M3 scheme costs are above the M3 mean, indicating a skewed distribution including a small number of expensive reinforcements. The most expensive M3 site is 95% higher than the mean, reflecting the fact that larger reinforcements can result in disproportionately large and complex works compared to smaller reinforcements that can often be accommodated within existing substations.

7http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Flexible-Urban-Networks-Low-Voltage/Project-Documents/SDRC+9.1+Successful+completion+of+design+and+planning+for+PEDs.pdf
said, even small transformers can be challenging and costly where substations are inaccessible. The effect of assessing FUN-LV methods against these larger reinforcement costs is explored in Section 6.

Figure 9 – Distribution of reinforcement costs estimated for trial sites
4. Benefits associated with FUN-LV methods

4.1 Introduction

As part of the FUN-LV trials, a number of potential benefits were explored for each scheme. Depending on the particular scheme it was hypothesised that a number of beneficial effects could be delivered, whether as a deliberate “mode of operation” or as a spontaneous side-effect resulting from the new network configuration (i.e. meshing).

This section of the report describes the set of potential benefits that were hypothesised at the start of the project, how these were tested during the trial, and what results were seen, drawing on the evidence described in SDRC 9.5.

The latter part of this section then focuses on those benefits that were considered as part of the CBA. This includes those that have a clearly identifiable and quantifiable benefit to one or more network stakeholders, but also takes a broader view to consider qualitative benefits that could improve the FUN-LV business case if they could be realised for a particular scheme.

4.2 Benefit shortlisting

During the initial scoping of the project, a range of possible benefits were identified that could be derived from using FUN-LV methods. These potential benefits are summarised in Table 10. Note that a number of these benefits are interrelated (e.g. losses are affected by load balancing and phase unbalance correction).

Table 10 – List of hypothesised FUN-LV benefits

<table>
<thead>
<tr>
<th>Effect</th>
<th>Primary benefit</th>
<th>Other benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load balancing</td>
<td>Create headroom at constrained substation, deferring the need for reinforcement or enabling new connections and LCTs such as EVs and heat pumps more quickly or cheaply than conventional reinforcement would allow.</td>
<td>• Loss reduction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Asset health improvement</td>
</tr>
<tr>
<td>Phase unbalance correction</td>
<td>Most constrained phase will be the trigger for requiring reinforcement, so balancing the loads across the phases creates additional headroom.</td>
<td>• Loss reduction on the phase and neutral conductors</td>
</tr>
<tr>
<td>Power factor improvement</td>
<td>Would increase the ratio of active to reactive power, and hence create additional headroom.</td>
<td>• Loss reduction from reduced apparent power</td>
</tr>
<tr>
<td>Voltage management</td>
<td>By managing voltage within network limits, more load or DG can be connected. Reduced voltage sag along the feeder can allow the voltage to be reduced through the use of tap changers.</td>
<td>• Loss reduction where lower average voltage can be achieved</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Less risk of voltage deviations and customer complaints</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Effect</th>
<th>Primary benefit</th>
<th>Other benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault level control</td>
<td>M2 and M3 allow circuits to be meshed without increasing the fault level, or to connect DG or motors without adversely impacting the fault level.</td>
<td>• More DG on import-constrained feeders creates additional headroom, which is a key focus of the project</td>
</tr>
<tr>
<td>Harmonic reduction</td>
<td>The take-up of CFLs and other non-linear loads increases losses in transformers, thus reducing their capacity whilst deteriorating their operational efficiency. This can be reduced through the reduction in harmonics that M2 and M3 devices can achieve</td>
<td></td>
</tr>
<tr>
<td>Support during HV faults</td>
<td>Control of power flows post-fault allow the network to be restored more rapidly, reducing customer minutes lost</td>
<td></td>
</tr>
<tr>
<td>Enabling DG connections</td>
<td>The creation of active power headroom, voltage control and fault level control can enable additional DG to connect</td>
<td>• Creates additional headroom on import-constrained feeders, which is a key focus of the project</td>
</tr>
<tr>
<td>Loss reduction</td>
<td>Load balancing, power factor improvement, phase unbalance correction, DC offset reduction all can reduce losses</td>
<td></td>
</tr>
<tr>
<td>Improve asset health</td>
<td>Overloading assets and/or power quality issues can reduce asset life</td>
<td></td>
</tr>
<tr>
<td>Reduce customer complaints</td>
<td>Power quality issues, including harmonics and voltage deviations, can result in reduced customer satisfaction</td>
<td></td>
</tr>
<tr>
<td>Less site disruption</td>
<td>FUN-LV methods can in some cases require less space and site disruption than conventional reinforcement options</td>
<td></td>
</tr>
</tbody>
</table>

### 4.3 Studied benefits and observed results

#### 4.3.1 Introduction

It is anticipated that the decision to deploy a FUN-LV method will be made on the basis of more than one of the potential benefits listed in Table 10. The FUN-LV trials were not designed to test each one of these posited benefits, however. Those that were actively studied are explored in more detail below.

#### 4.3.2 Headroom creation

Headroom creation is the one of the key benefits of using FUN-LV methods as it allows the deferral or avoidance of reinforcement that might otherwise be required to accommodate organic load growth, LCT uptake or new connections. For all three methods, if deployed appropriately, they are able to reduce the loading at one or more heavily-loaded substation by increasing the loading at one or more lightly-loaded substation. Assuming that the loading on those substations is expected to increase over the subsequent years, this load sharing delays the time at which substation reinforcement has to occur. Alternatively, in the case of a new connection this can reduce the cost or time to connect. Where substations have complementary profiles (e.g. one summer peaking and one winter peaking, or one with a daytime peak
and one with an evening peak), it is possible for a single FUN-LV method to defer the reinforcement of multiple substations.

Because transformer reinforcement size options are discrete, small amounts of headroom can have disproportionate benefits. Some connections may not be possible because the required capacity is greater than the available spare capacity on the network (e.g. if a Network has 150kVA available and a connection of 200kVA is required). In some of these instances the use of a SOP could be used to provide the additional small amount of capacity from an adjacent network. For example, although the SOP is only providing 50kVA of headroom it is enabling a 200kVA connection that otherwise would not have been possible. A smaller rated SOP could be employed to do this. It could also be installed where the adjacent network has only a small amount of headroom available (e.g. in situations outside from the typical “heavily loaded network adjacent to a lightly loaded network” scenario).

As anticipated, the trials demonstrated that in the majority of cases the FUN-LV methods were indeed able to defer reinforcement. It was observed that M2 and M3 devices were fully able to balance the load between two or three substations, respectively, up to the rating of the devices and provided the differential was larger than the device deadband. These higher rated devices can also provide for circuits that are constrained by cable ratings by providing new pathways for power through other circuits e.g. with larger cores/ratings. In the event of short LV outages and HV circuit faults the devices can also respond by providing emergency rating transfers.

The behaviour of the M1 devices was more complex, since it depends on the loading on the circuit(s) between the scheme substations. The key point to note is that for M1 power flows according to Ohm’s law (rather than the controlled power flows with the SOPs). Understanding the circuit layout, lengths, position, size of loads and circuit load is therefore critical at the design stage. Meshing can work to increase capacity headroom for distributed loaded circuits, but may reduce capacity headroom for weak meshed networks with large point loads and heavily loaded tees. Understanding the effects of network architecture is key to predicting transfers. Furthermore, it should be noted that it is not sufficient to understand the distribution of loads at the point in time where the M1 device is deployed. What is important to the subsequent need to reinforce is the future distribution of loading along the circuit as demand profiles change and new customers connect.

A final point to note about the benefit of load balancing is that the analysis detailed in the CBA assumes a deterministic load growth projection. This is likely to present a conservative view of the potential benefits. In reality, the future demand on the network is uncertain, resulting in two possible outcomes:

1. **Load growth stalls or reverses**, meaning that any reinforcement that has occurred on the basis of assumed load growth risk becoming a "stranded asset". This risk is minimised because the reinforcement of secondary substations or circuits does not tend to occur until the thermal rating or voltage constraints are already being reached, but if loading does indeed reverse then stranding remains a possibility, meaning that capital was expended unnecessarily. The use of flexible solutions such as FUN-LV allows this risk to be reduced since, if load does decline the device can be removed and deployed elsewhere, incurring only the cost of installation and removal.

2. **Load growth increases rapidly**, meaning that assumptions about the acceptable time between detecting that a transformer or circuit has reached its thermal limit or voltage limits and having to reinforce it are challenged. As more DG, EVs and heat pumps come onto the system, potentially clustered in small areas, it is expected that demand growth and emergence of large daily swings in power flow with resultant swings in voltages could occur very rapidly. In this case, the benefit of methods such as FUN-LV may come more from the relative speed with which they can be deployed rather than their ability to defer reinforcement per se.
This uncertainty means that a flexible solution such as FUN-LV provides option value, allowing the DNO to commit relatively small expenditure whilst the need for more costly reinforcement remains uncertain. This is explored in more detail in the Option Value of Flexible Technologies Report by Imperial College.

4.3.3 Fault current

M2 and M3 devices do not pass fault current. This allows multiple feeders to be connected without resulting in an increase in fault level, which in a fault current-constrained network enables meshing, and the connection of motors and generators, that could not otherwise have occurred. This effect was observed on the RES sites within the interconnected networks during the trial. Furthermore, the same effect could be used to connect more DG without increasing fault current, which was not included as part of the trial, but should be seen as a key benefit of SOPs that should be considered when evaluating a scheme.

Note, however, that the inability of the present generation of SOP devices to pass fault currents can be a limitation, since this can restrict the operation of conventional protection. The use of a M2 or M3 converter ensures that fault level capability is retained since at present they can only be used where fault current is available on both sides of the SOP (although this has not been a constraint on the trial site selection). This should be considered when looking to deploy such devices on the network.

4.3.4 Phase unbalance correction

For all M1 schemes trialled, an improvement in phase unbalance was seen (although it should be noted that this was not a controlled effect, and it is not known what behaviour would be seen with a higher installed capacity of DG). M2 and M3 had the option to run in a phase unbalance support mode. This operated as designed, although whilst the effect was seen at the device terminals, the improvement did not cascade to the remote substation feeder end. In summary, all the FUN-LV devices have the potential to improve phase unbalance, although more work in this area is required to validate the initial learning.

4.3.5 Voltage management

With the exception of the RES sites themselves, the deployment of M1 devices increased the voltage seen on the network, as illustrated in Figure 10. This relates to the increased total apparent power demand discussed above. In high voltage-constrained networks this could be a detriment, particularly if there is a desire to connect additional DG.

Figure 10 – Illustration of voltage sag under meshing

However, if used in BaU the voltage profile could be lowered slightly by adjusting transformer tap position, as shown in Figure 11. A SOP, such as M2 or M3, can then be used to manage the voltage
along the connected feeders. This is useful because some feeders may suffer capacity restrictions due to voltage constraints.

Figure 11 – Illustration of lowering voltage on meshed network through tapping

Furthermore, many connections are single phase, so phase balancing performed by the SOP can also be used to release headroom on voltage constrained feeders, where the constraint does not appear on all phases.

As an extension to the above argument, it is possible to envisage future scenarios by which a single substation has different voltage conditions present on its feeders. For example, in Figure 12 there may be high loading on some feeders, and DG on others, resulting in risk of breaching statutory voltages. Due to high loading on some and distributed generation on others, particularly where the mix of loads, storage and generation is such that at different times of the day or year very different or rapidly varying voltage profiles are produced. The voltage profile (decrease across a feeder length and increase with a generator can be balanced with the introduction of a SOP device, as shown in Figure 12. Hence transformer tapping is of limited use in solving the issue if a voltage limit is breached.

Tools deployed along feeders or at feeder ends are therefore required to influence voltage away from the substation (where no problem is apparent). A SOP is such a tool that can be used to manage the feeder voltage by providing voltage support between feeders.

This type of approach can be used to “buy time” for conventional reinforcement works. It may also be useful in affording the DNO a “connect and manage” approach to connections, by offering tools that can be used to actively manage constraints, effective a high percentage of the time (minimising curtailment). More work is required in this area outside of the FUN-LV project to analyse the financial benefits of such options.
The SOP has been successfully shown to change the voltage at the terminals of the SOP by exporting or importing real power. However, the trialled algorithm looked for a large difference between the voltages, whereas these voltage differential conditions were not typically seen at the FUN-LV trial schemes, where the voltage is typically high at all ports. Despite voltage effects being seen at the SOP terminals, the associated substation voltages were not impacted, since the substation voltages are more influenced by the 11kV network. Also, it should be noted that using these devices for voltage management incurs losses across the device, so it may not be appropriate to use them for equalising small voltage differentials.

4.3.6 Power factor improvement

Under all M1 schemes (with the exception of the RES site) the power factor improved. M2 and M3 devices also demonstrated capacity to provide power factor support (PFS). For the trial sites, reactive power flows on the LV network were relatively low, which limited the potential benefit of this operating mode, but it may have value in other parts of the network, particularly with the increased uptake of non-linear loads expected in the future.

So whilst these devices can improve power factor, it may be that this is only of material benefit in cases where reactive power flows are particularly high, rather than being a general secondary benefit of deploying these schemes.

4.3.7 Losses

The impact of FUN-LV methods on system losses depends to a large extent on how the devices are used in practice. As discussed above, the majority of the benefits that FUN-LV methods can deliver (headroom creation, voltage management, phase unbalance, power factor improvement) have a knock-on effect on losses.

As discussed in SDRC 9.5, the trials themselves observed three effects of the FUN-LV methods:

1. When in operation, losses are incurred across the SOP device itself.
2. There is a small decrease in the losses in 11kV/LV transformers when the SOP is utilised, due to better load sharing.
3. There is a small increase in losses in LV lines when the SOP is utilised, which can be either from higher transfer currents on clean and point loaded circuits, or from increased voltages on distributed loaded circuits.

The net effect reported in SDRC 9.5 was a small increase in losses, primarily across the SOP devices. However, it should be noted that in practice this effect can almost certainly mitigated and probably reversed for a number of reasons:

1. Headroom creation is only required for short periods during the year, so once operational the SOP parameters will be set to ensure that device losses are not incurred unnecessarily.
2. To the extent that headroom creation defers or avoid the need for a new or uprated transformer, the additional iron and copper losses associated with that increased capacity can be avoided.
3. The secondary benefits such as phase unbalance and power factor improvement were not assessed in detail for their effect on losses, and the sites chosen for the trial were not selected on that basis.

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10Ibid.
4. In some cases the overall voltage on the local network can be reduced where the implementation of the FUN-LV method flattens the voltage profile. This was not tested as part of the trial, but could result in significant benefits in terms of reducing network losses. This will be dependent upon the voltage load characteristics of the mix of loads over time, which is at present largely unknown and needs to be the subject of separate research.
5. Cost Benefit Analysis results

5.1 Introduction

This chapter carries out a CBA of the method installation based on the trial average view of substation reinforcement and method costs as introduced previously, and the historic load profiles of the 36 trial sites. The CBA calculates the NPV of installing a method at a specific site.

As discussed in the CBA approach chapter, whilst there are a range of benefits associated with FUN-LV methods, the key quantifiable benefit at present is the creation of headroom at a constrained substation. Based on an analysis of the load profiles seen at the FUN-LV trial sites, the potential for headroom creation is summarised in Table 11. Average headroom released figures below range from 14% to 47%, if taken as a proportion of the typical urban secondary substation transformer capacities of 500kVA, 750/800kVA and 1000kVA.

Table 11 – Headroom released by FUN-LV methods

<table>
<thead>
<tr>
<th>Method #</th>
<th>Total headroom released (kVA)</th>
<th>Average headroom released (kVA/scheme)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,739</td>
<td>145</td>
</tr>
<tr>
<td>2</td>
<td>1,732</td>
<td>144</td>
</tr>
<tr>
<td>3</td>
<td>2,813</td>
<td>234</td>
</tr>
</tbody>
</table>

This headroom allows the connection of additional load without the need for reinforcement. This could be particularly beneficial in the future as EVs and other complex loads become more prevalent, and where conventional reinforcement options are particularly costly, time-consuming or otherwise complex to deliver.

In the short-term, however, the benefit of headroom is expected to manifest as deferred reinforcement. The benefit of this, as assessed in this section, comes from delaying the point at which that reinforcement is required.

The calculation of the NPV is a function of 4 main variables: reinforcement cost, method cost, discount rate, and the number of years a reinforcement is deferred for:

\[ NPV = B - M \]

\[ B = R \times \sum_{i=1}^{n} \frac{1}{(1 + d)^{s_i}} \left( 1 - \frac{1}{(1 + d)^{y_i}} \right) \]

Where

- **B** = Deferral Benefit
- **M** = Method cost attributed to the scheme
- **R** = Reinforcement cost
- **n** = Number of reinforcements deferred
- **d** = Discount Rate
- **s** = Years duration between method installation and start of deferral
- **y** = number of years reinforcement deferred.
This deferral benefit arises due to the discounted cost of paying for a reinforcement at a later date. A single FUN-LV deployment can result in more than one deferral for one of two reasons:

1. The substations in the scheme may have complementary loading patterns. The loading pattern is said to be complementary if at the peak loading of one substation, the other substation is under-utilised and vice versa (see Figure 7, for example). At times of peak loading the method can balance the load with the underutilised substation and therefore defer the reinforcement of both substations, or

2. After a deferral occurs at one substation in the scheme the method reaches capacity and the reinforcement must occur. At this point in time the remaining substations in the scheme may be approaching overloading, or would be if new load were to connect, and therefore by leaving the method in place a further deferral may occur.

Deferring two instances of reinforcement simultaneously doubles the benefit of a single FUN-LV deployment. This is most likely in the case of M3 deployments, where two heavily-loaded substations can be matched with a lightly-loaded one, but it is also possible for M2 schemes if complementary profiles can be found. Triple deferrals are technically possible for M3s by the same logic, but the instances in which there are three heavily-loaded substations with complementary profiles are expected to be rare today, although this could change as more LCTs are deployed, particularly if they cluster as expected.

### 5.2 Analysis of Results

#### 5.2.1 Method 1

M1 is the cheapest FUN-LV method at £22,000 per deployment, with £7,000 of that being fully sunk as installation costs and hence not recoverable at the end of the scheme.

Based only on the headroom creation and reinforcement deferral, LPN 1.3i and LPN 1.4i are the only schemes to have a positive NPV at a 3.5% discount rate. These two schemes are the only M1 examples of achieving concurrent deferral. In the case of LPN 1.3i, two reinforcements would have been required in the same year, but each can simultaneously be deferred by 13 years through the use of a M1 device. LPN 1.4i achieves a 10-year deferral on one substation. However, in the final three years of its use it concurrently reduces the loading at two nearby substations, deferring their reinforcement by 2 and 3 years, respectively.

M1 devices do not offer a great deal of control over the power flows, so the ability to achieve the load balancing assumed for this CBA is not a given, and will require careful site selection. Nor do these M1 devices allow the user to control other network characteristics such as voltage or phase (although the act of meshing does tend have an effect on these).

As a result, it is likely that the case for specific M1 schemes will rely on their ability to defer or avoid reinforcement. As discussed, our CBA approach is expected to be conservative in the sense that the full value of these devices may come from their ability to be deployed rapidly and in cases where conventional reinforcement is unfeasible. As will be shown in Section 6, focusing M1 devices on such schemes can deliver substantial benefits.
5.2.1 Method 2

At £62,000, M2 average costs are significantly higher than M1, with £12,000 being sunk in the installation. Only LPN 2.1i achieves concurrent deferral of more than one substation, but this is only for two of the 8 years total deferral. The combination of these two factors means that none of the M2 schemes demonstrated a positive NPV at 3.5% discount rate.

M2 devices are able to manage load flows in a controlled way (unlike M1 devices), so we should expect that for a given site a M2 device will be able to create as much, if not more, headroom and hence achieve the same or more reinforcement deferral. The fact that this was not seen in the trial suggests that the substation load profiles in the M2 trial sites were not sufficiently complementary.

It should be noted that M2 SOP devices have the ability to provide a wider suite of benefits than the M1 devices. So although the cost of M2 devices is higher, the opportunity for benefits is greater (if the site warrants those additional benefits), particularly if concurrent deferral of multiple substations can also be achieved.

5.2.1 Method 3

Whilst M3 costs are higher than either M1 or M2 (£109,000 average, of which £20,000 is installation cost) the potential benefits are higher for a number of reasons:

- The deferred cost is higher because the conventional reinforcement options are on average higher.
- The capacity of M3 devices is higher, allowing higher power flows and hence more headroom creation.
- Being a 3-port device, the opportunity for deferring multiple substations simultaneously is significantly higher than for M1 or M2.

As a result, two schemes show a positive NPV. LPN 3.3i delivers 23 years of deferral on one substation reinforcement, and concurrently defers a second reinforcement by 22 years. SPN 3.4r achieves a double deferral for 12 years, and given that the equipment retains some of its value after it is removed (since it can be deployed elsewhere), the effective cost of the device is only half (£55,000) of the headline device cost.

As with M1 and M2, the benefit estimated in this CBA is expected to be conservative for a number of reasons:

- The trial average cost is expected to decrease once these methods are deployed under BaU (as discussed in Section 6).
- The gradual, deterministic load growth and deferral arising from headroom creation understates the benefits of these devices, particularly when rapid load growth requires a quick intervention, or when load growth and the need for reinforcement is uncertain.
- There is a range of other benefits that were demonstrated technically in the trial. These resolve network issues that are expected to become more pressing and more prevalent in the LV network of the future, as a result of the increasing uptake of DG and LCTs.
5.3 Comparison with bid submission business case

The original bid\(^{11}\) estimated that benefits of £2.36m could be achieved across the 36 trial sites, whilst providing greater flexibility, faster connections and reducing the risk of long interruptions due to HV faults.

The trials have provided substantial evidence to support the ability of FUN-LV methods to deliver on the range of benefits cited in the bid. The £2.36m reflected the total anticipated reinforcement cost for the 36 sites. A more detailed assessment of the reinforcement requirements of those sites showed that the project released capacity that would otherwise have cost £2.2m to achieve through traditional reinforcement. In reality, most of those sites do not require reinforcement in ED1 (since they were selected to test the technical capability of the device, not to defer actual reinforcement). Also, it should be noted that the sites were not chosen to represent the challenging reinforcement cases for which FUN-LV might be most suited.

The key learning from the trial, though, is that FUN-LV should only be deployed when viable as determined on a whole-life basis, taking account of any eventual reinforcement that is required. As mentioned earlier, the trials were primarily chosen to demonstrate technical functionality and not necessarily schemes with immediate constraints, however, of those sites with a positive NPV, we have created savings of £26,000 through deferral benefits. As stated before, however, the use of the trial average cost for both the methods and the conventional reinforcement option is expected to understate the benefit significantly, and the range of other benefits has the potential to be increasingly valuable as the LV network becomes more complex to manage.

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6. Sensitivity analysis

6.1 Introduction

The purpose of this section is to explore the sensitivities of the CBA, focusing on the key drivers that are capable of making or breaking the business case of a FUN-LV method. In the trial average case, only a small number of schemes are viable: two M1s and two M3s. For this reason, we focus only on the upside scenario, noting that without specific secondary benefits it is unlikely that the majority of schemes will be viable if either Method costs or achievable benefits move against FUN-LV.

That being said, it is also expected that the cost elements will move in a favourable direction when compared against the trial average case, hence the upside is more likely to transpire. This is because the trial method costs will benefit from economies of scale and learning, and under BaU these methods will tend to be deployed to defer or avoid reinforcement that has above-average cost.

6.2 Sensitivity analysis results

Figure 13 shows the impact of each sensitivity factor, applied in turn, to the total NPV of the 36 schemes. This assumes that any schemes with negative NPVs do not proceed, so contribute zero to the total. It is for this reason that many of the sensitivity variables do not appear to have an effect (since unless they tip a scheme from a negative to a positive NPV they will show no improvement).\(^\text{12}\)

![Cumulative effect of sensitivities: Sum of Positive Net Present Values](image)

**Figure 13 – Sensitivity of total NPV from schemes with positive business cases**

\(^{12}\) Note that the relative impact of each change depends on the order in which they are applied.
The sensitivities are presented in a cumulative fashion. The variables included in this sensitivity are:

1. Baseline for the sensitivity, reflecting the trial average case;
2. Reducing the method costs by 30%, reflecting the expected reduction quoted by the technology provider on the basis of larger-scale deployment than was seen in the trial. Higher cost reductions of up to 50% have also been quoted by suppliers in Appendix C – Analysis of SOP performance and reliability data, although this may be at the expense of functionality around the additional benefits (e.g. voltage management), but since those secondary benefits are not being quantified here the 30% reduction seems conservative;
3. Reducing the load growth by 0.25 percentage points in order to increase the achievable deferral;
4. Reducing the M2 and M3 device deadbands from 5% to 0%;
5. Increasing the Method device lifespan by 5 years, reflecting either the uncertainty in the lifespan of the devices, or the ability to extend their lifespans cheaply through maintenance and component replacement;
6. Increasing the cost of reinforcement by 20%, reflecting either an increase in the average reinforcement cost or, more likely, demonstrating the effect of targeting at the more complex and costly reinforcement schemes; and
7. Increasing the cost of reinforcement by a further 30% above the trial average figure.

The same sensitivity analysis can be presented in a number of ways. Two perspectives that provide useful insights are the proportion of schemes that are viable and the average IRR of the schemes. These are shown in Figure 14 and Figure 17, respectively.

As Figure 14 shows, the cumulative application of each sensitivity tends to increase the proportion of schemes that are viable. Again, because a number of schemes show a negative NPV, this representation of the sensitivity analysis does not reveal a benefit unless a scheme is pushed from a negative to a positive NPV.

Figure 14 – Proportion of schemes with positive NPVs
In order to show the overall effect of the sensitivity progression on the 36 schemes, including those with negative NPVs, we can look at the improvement in average scheme NPV against the trial average baseline, as shown in Figure 15 and Figure 16.

Figure 15 – Average scheme improvement from sensitivity progression
One other way to consider the negative NPV schemes as part of the sensitivity analysis is to consider the average IRR. The IRR indicates the discount rate at which a scheme would be viable. The target discount rate of 3.5% is represented in Figure 17 as a green dotted line. When the solid line drops below the dotted green line, this indicates that the scheme is, on average, viable at the social discount rate of 3.5%. If a higher discount rate were applied (as might be the case for a private enterprise) a larger number of schemes could be deemed viable.
The absolute contribution of one sensitivity will depend on whether the others have been applied, so the order in which they are considered matters. Nevertheless, it is clear that the most significant factors are the method cost and the cost of conventional reinforcement.

**Method cost:** Although the absolute increase in NPV resulting from reducing the method cost by 30% appears relatively small, for M3 this results in a 168% NPV increase, and a 63% NPV increase for M1. This can be seen more clearly in Figure 14 in the number of viable M1 schemes increasing from 17% to 58%, and a substantial reduction average IRR for all three methods.

**Load growth** could reasonably be assumed to be a key variable. However, because FUN-LV methods can be redeployed, under deterministic load growth assumptions the absolute duration of a single reinforcement deferral is less important than the cost being deferred. This is predicated, however, on the flexibility of the assets being achieved in practice, which requires that the devices are designed with this in mind, and that there are subsequent schemes that would benefit from the same FUN-LV method. It should also be noted that load growth may, in reality, be an important indicator once load growth uncertainty is taken into account. For example:

- Rapid load growth, combined with a complex reinforcement scheme, may necessitate the use of methods that can be deployed more quickly in order to avoid asset degradation and the risk of customer outage; FUN-LV methods are suited to this purpose.
- Load growth may only endure for a short period of time if, for example, it is known that a DG subsequently intends to connect; in this case it may make sense to use a FUN-LV method as a temporary solution, avoiding the need for reinforcement altogether.
• Load growth may be uncertain, meaning that whilst it is not known that it will subsequently decline there is option value associated with being able to deploy a flexible solution such as a FUN-LV method.

The option value associated with uncertain load growth is explored in the Imperial College London report\textsuperscript{13}. Based on selected case studies, their analysis showed that option value could be significant if the flexibility associated with FUN-LV methods were accounted for and factored into the planning process. The option value for the selected cases can be considered as an alternative assessment to the value associated with deferral under deterministic load growth that formed the basis of this report’s CBA. The option value (NPV) for each case study method was estimated to be:

- Method 1 (Eastbourne Terrace): £18.5k (high flexibility)
- Method 2 (Boyce’s Street): £33k (moderate flexibility)
- Method 3 (Prudential North): £46.7k (moderate flexibility)

When compared with the impact of each sensitivity shown in Figure 15 it is apparent that exploiting the option value of FUN-LV methods could be a significant factor in achieving a positive business case for these methods.

**Device deadband:** The device deadband has a comparatively small effect on the overall NPV. This is because, when increasing the deadband, only substations with very similar loading patterns and maximum utilisation experience a reduction in reinforcement deferral. This includes a small number of the trial sites and therefore the effect of the change in deadband is minimal. When load growth is increased the length of time a reinforcement can be delayed is decreased. When load growth is decreased, lightly loaded substations are not projected to become over-loaded for very long periods of time. Device lifetime sets the limit on the maximum possible reinforcement deferral possible. Increases in the lifetime therefore increases the deferral benefit seen in the trial sites.

**Asset lifetime** has a significant effect on the overall business case. The variable has two effects: first, it allows a single installation to defer reinforcement for longer, although this only has an impact in the rare cases in which deferral can endure for multiple decades. The second and more important effect arises because by increasing the asset lifetime the device can be deployed elsewhere for longer, thereby reducing the effective cost of any particular scheme.

**Reinforcement cost** is a key variable since deferring this expenditure is the one of the key benefits of FUN-LV methods. This sensitivity reflects the fact that FUN-LV methods should be targeted at the more costly conventional reinforcement schemes. For example, as streetworks in LPN become more of an issue, as they are expected to do, this may increase the case for using FUN-LV methods instead of the conventional reinforcement option. Assuming the preceding sensitivity variables were achieved, if FUN-LV were targeted at schemes with costs 50% above the average it could be expected that the majority would reveal a positive business case, even before accounting for the wider set of benefits that might be associated with a particular FUN-LV scheme.

\textsuperscript{13} ‘Option Value for Flexible Technologies’ report, Imperial College London
7. Replication: opportunity for wider FUN-LV deployment

7.1 Introduction

The purpose of the replication study is to estimate the net benefit of a UK Power Networks LPN rollout and GB wide rollout of FUN-LV methods, based on the possible deferral benefit provided by the method. This study uses the results of the site selection process, which identified the initial 36 trial locations, to determine a set of rules for identifying a suitable site. These rules are based on both the LPN and SPN site trials in order to give a more accurate reflection of feasible site installation across Great Britain. The cost of deploying the methods in suitable sites, the business as usual reinforcement cost, and the effectiveness of the methods have been quantified using the results of the trial and the subsequent project CBA.

In order to accurately estimate the number and proportions of suitable sites across Great Britain the UK Power Networks’ LPN network is used as a representative sample. The subset of LPN substations analysed in this study are distributed throughout the LPN region, including the high population density and high substation density central London areas as well as the less dense sub-urban areas such as Redbridge, Dartford and Merton. The number of feasible installation sites as a percentage of the number of substations in an area was not seen to be markedly different between the central London and outer London areas. Therefore, UK Power Networks LPN is considered to represent the potential for FUN-LV method deployment across GB dense urban area distribution networks, and has been analysed using available load and geographical data to provide an estimate of the number of suitable sites for deployment GB-wide.

This replication study builds upon the initial replication study carried out as part of the submission bid. That study used benefit estimates based on an initial CBA of specific trial sites. It scaled these benefits to a GB wide rollout by estimating the number of sites based on GB population density data and estimating the proportion of suitable sites from the number of heavily loaded substations in the UK Power Networks network. The results of the trial have provided the information required to refine this approach.

7.2 Rules for determining site selection

Geographical proximity
Qualifying sites must have substations that are geographically close and easy to connect, defined by a number of technical requirements including type of spine circuit, the load and the equivalent length. For a site to be eligible for any method, the substations must be within a 500m distance of each other.

Substation Loading and Complimentary Profiles
One of the substations in a potential site should be operating above 70% (heavily loaded) of their nameplate capacity and/or the substations should exhibit different times of peak and minimum loading (different load profile types e.g. residential, commercial or industrial).

Load growth projections
The average of the projected substation load growth for both LPN and SPN substations provided as part of the CBA. Both networks show an expected increase in year on year growth up to 2031. The average load growth across the 15-year period, 1.30%, is used to estimate substation load growth within the replication study.
Boundaries
M1 substations can only cross HV feeder boundaries, cannot cross primary substation, group or busbar boundaries and may be subject to fault level constraints where networks are already meshed. Methods 2 and 3 are best utilised when secondary substations cross feeder and primary substation boundaries and where M1 transfers can produce dis-benefits though uncontrolled transfers e.g. LPN 1,7.

Installation feasibility
A suitable site has a number of technical and practical requirements. These include space, weight and ventilation requirements, all of which may be accommodated in subsequent generations of the FUN-LV technologies (see Appendix B and C). Based on the site selection process undertaken to identify the 36 suitable test sites, the following proportions of sites satisfy the technical requirements:

- **M1 sites:** all sites investigated for trial sites in the LPN area were feasible for installation. In the SPN region around 14% of visited sites were found to be infeasible with the present M1 kit due to non-standard LV boards. It is therefore estimated that, in general, 7% of M1 sites are infeasible for installation.

- **M2 sites:** all sites visited in the SPN region were feasible. 25% of sites visited in the LPN area were infeasible for installation due to lack of pavement space, lack of depth or existing utility congestion. It is therefore estimated that in general, 12.5% of M2 sites are infeasible for installation, although this may improve with next generation equipment.

- **M3 sites:** the LPN interconnected M3 site visits revealed 5 of the 13 substations visited were infeasible for installation. This was due to a lack of substation space, ventilation or site access feasibility. The likelihood that, for any given triplet of substations, all of the substations are infeasible for installation is therefore approximately 6% \((5/13)^3 \approx 6\%\). The LPN radial M3 site visits revealed 5 of the 10 substations visited were infeasible for installation. The likelihood that, for any given triplet of substations, installation is infeasible in all substations is therefore 13% \((5/10)^3 \approx 13\%\). The SPN radial M3 site visits revealed 5 of the 10 substations visited were infeasible for installation. The likelihood that, for any given triplet of substations, installation is infeasible in all substations is therefore also 13%. Therefore, in general 11% of M3 sites are assumed infeasible for installation.

Cost of reinforcement
The benefit of the method is measured against the distribution of method specific reinforcement costs faced across the 36 trial sites. Table 12 displays the average reinforcement cost for a given percentile range i.e. the average of the lowest 15% of M1 site reinforcement costs are £28k and the average of the highest 5% of M1 site reinforcement costs is £44k. This distribution is illustrated in Table 12. In the study, the benefit of deferral is calculated based on the distribution of reinforcement costs in 5% intervals. This gives an accurate representation of the reinforcement cost that would be encountered in a rollout of the methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Percentile range of reinforcement cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0% - 15%</td>
</tr>
<tr>
<td>1</td>
<td>£28k</td>
</tr>
<tr>
<td>2</td>
<td>£34k</td>
</tr>
<tr>
<td>3</td>
<td>£68k</td>
</tr>
</tbody>
</table>

Table 12 – Distribution of reinforcement costs by Method type
Cost of method installation
The cost of the 36 methods installed during the trial period are assumed to be greater than the costs for a network-wide roll-out. A portion of the method costs are due to the fact that this is the first time the method has been trialled. If the method components are produced in larger volumes then economies of scale can be exploited to reduce the per-unit cost. In addition, the labour and commissioning costs will reduce as the DNO develops a trained and experienced workforce. Therefore, under a UK Power Networks LPN or GB wide network rollout, the average method cost is assumed to decrease by around 30%. Table 13 shows the specific replication method costs assumed in the study, the equipment learning curve represents the reduction in equipment cost due to economies of scale.

<table>
<thead>
<tr>
<th>Method #</th>
<th>Equipment Learning Curve</th>
<th>Replication Equipment cost</th>
<th>Replication Installation &amp; Commissioning costs</th>
<th>Replication total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25%</td>
<td>£9,379</td>
<td>£3,000</td>
<td>£14,886</td>
</tr>
<tr>
<td>2</td>
<td>31%</td>
<td>£29,561</td>
<td>£8,000</td>
<td>£45,011</td>
</tr>
<tr>
<td>3</td>
<td>31%</td>
<td>£53,529</td>
<td>£12,000</td>
<td>£76,379</td>
</tr>
</tbody>
</table>

Device rules
Methods 2 and 3 allow the designer to have full control of the device behaviour and therefore the rules assumed under the CBA hold for any suitable site. The effectiveness of M1 is highly site specific, as shown through the trial sites. The best-case scenario is complete substation utilisation which provides the same load equalisation function as a M2 or M3. This scenario is assumed in the replication study because the data required with which to make an informed site feasibility decision on this scale is unavailable.

7.3 Sample Study of UK Power Networks LPN wide roll-out
The UK Power Networks LPN area contains 187 primary substations and 17,789 secondary substations, as stated in the V1 Asset Register as of 31 March 2016. The area was chosen as the basis for the replication study due to the fact that around 50% of the secondary substations have remote monitoring units (RTUs) installed and therefore easy access to historical loading profiles. In addition, as justified in the initial project submission business case, the three methods are more likely to be useful in urban networks due to the relative high density of secondary substations, and the high cost and long timescales associated with conventional reinforcement. The LPN area comprises of dense urban and dense-suburban areas which reflects the mix of urban areas found in cities and large towns across GB. The analysis of the LPN substations with RTUs installed for suitability for a roll-out of the three methods can then be extrapolated to give an approximation for the whole UK Power Networks LPN network and further for a GB wide roll-out.

UK Power Networks LPN contains 17,789 secondary substations from which the DNV tool collated 46,932 possible combinations of secondary substation pairs. The process for identifying viable sites from this initial list was as follows:
- Data Clean Up
  - Loading data for 19,124 of the substation pairs is unavailable (no RTU installed), leaving 27,808 pairs.
Removing duplicate pairs and removing the double counting of substations with two transformers excludes 3,110 of these pairs, leaving 24,698 pairs.

369 of remaining pairs do not have sufficient transfer capacity data, leaving 24,329 pairs and 7,913 unique substations.

- **Geographical Proximity**
  - 4,139 of these pairs are within 500 metres of one another.

- **Loading Profile**
  - 3,153 of these pairs contain a substation with a high peak utilisation (over 70%) and/or complementary load profiles (i.e. residential, commercial and night). These pairs contain 3,128 unique substations.

### 7.3.1 M1 Analysis

- **Boundaries** – M1 devices are not suitable for installation across network boundaries. The number of the 3,153 substation pairs on the same feeder is 1,293.

- **NPV Calculation** – the headroom shared through the component is calculated based solely on the peak utilisation of the substations, in reality there may be more viable sites than suggested by this analysis.

- **Unique Sites** – after estimating the deferral benefits for each pair, of the pairs which had substations appearing in more than one pair, the pair with the highest deferral benefit was chosen. This left 674 unique substation pairs.

- **Site NPV** – Table 14 displays the distribution of NPV of M1 installation across the distribution of M1 reinforcement costs. For the lowest 15% of reinforcement costs, none of the sites considered have a positive NPV. Above this, the percentage of sites with a positive NPV increase from 73%, with an average NPV of £220, to a percentage of 91%, and a £3,040 average NPV, for sites with reinforcement costs in the top 5th percentile.

<table>
<thead>
<tr>
<th>Percentile of reinforcement cost</th>
<th>&lt;15%</th>
<th>15%</th>
<th>20%</th>
<th>25%</th>
<th>30%</th>
<th>35%</th>
<th>40%</th>
<th>70%</th>
<th>90%</th>
<th>95%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of sites with positive NPV</td>
<td>0%</td>
<td>73%</td>
<td>79%</td>
<td>82%</td>
<td>84%</td>
<td>85%</td>
<td>86%</td>
<td>87%</td>
<td>89%</td>
<td>91%</td>
<td></td>
</tr>
<tr>
<td>Average positive NPV (£000s)</td>
<td>0</td>
<td>0.22</td>
<td>0.81</td>
<td>1.32</td>
<td>1.62</td>
<td>1.79</td>
<td>1.95</td>
<td>2.10</td>
<td>2.67</td>
<td>3.04</td>
<td></td>
</tr>
</tbody>
</table>

### 7.3.2 M2 Analysis

- **Boundaries** – sites which cross feeder and primary substations boundaries can be connected via M2 devices, whereas this not be feasible for M1 devices. The number of substation pairs crossing these boundaries is 1,860 out of the 3,153 possible substation pairs.

- **NPV Calculation** – conservatively, the headroom shared through the component was calculated based solely on the peak utilisation of the substations.

- **Unique Sites** – after estimating the deferral benefits for each substation pair, of the pairs which had substations appearing in more than one pair, the pair with the highest deferral benefit was chosen. This left 788 unique substation pairs.
7.3.3 M3 Analysis

- **Geographical Proximity** – M3 components connect three substations together. Based on the 4,139 pairs of substations within 500 metres of each other there are a possible 7,387 combinations of three substations within sufficient distance of each other.
- **Loading Profile** – of these sites, 6,718 contain a substation with a high peak utilisation (over 70%) and/or complementary load profiles (i.e. residential, commercial and overnight). These triplets contain 3,073 unique substations.
- **Boundaries** – triplets of substations where at least one of the substations cross feeder and primary substations boundaries are considered more suitable for the installation of M3 devices. The number of substation triplets crossing these boundaries is 5,599 out of the possible 6,718 sites.
- **NPV Calculation** – conservatively, the headroom shared through the component was calculated based solely on the peak utilisation of the substations.
- **Unique Sites** – after estimating the deferral benefits for each site, of the sites which had substations appearing in more than one site, the site with the highest deferral benefit was chosen. This left **460 sites of unique substation triplets**.
- **Site NPV** – Table 16 displays the distribution of the NPV of M3 installation across the distribution of M3 reinforcement costs. For the lowest 80% of reinforcement costs, none of the sites considered have a positive NPV. Above this, the percentage of sites with a positive NPV increase from 1%, with an average site NPV of £420, to a percentage of 100%, and a £17,010 average site NPV, for sites with reinforcement costs in the top 5th percentile.

Table 16 – NPV of M3 installation across distribution of M3 reinforcement costs

<table>
<thead>
<tr>
<th>Percentile of reinforcement cost</th>
<th>&lt;70%</th>
<th>75% - 80%</th>
<th>80% - 85%</th>
<th>85% - 90%</th>
<th>90% - 95%</th>
<th>95% - 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of sites with positive NPV</td>
<td>0%</td>
<td>1%</td>
<td>99%</td>
<td>99%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Average positive NPV (£000s)</td>
<td>0.42</td>
<td>3.65</td>
<td>6.38</td>
<td>10.79</td>
<td>17.01</td>
<td></td>
</tr>
</tbody>
</table>

7.4 LPN and GB rollout

The replication analysis estimated the NPV of sites based on 7,913 substations, comprised of the subset of LPN substations with RTUs installed. The results of this analysis can be extrapolated and, using the
site infeasibility estimates from Section 7.2, provide the total NPV of a rollout of the methods across the LPN region and a GB wide rollout. The LPN area contains, according to the V1 Asset Register as of 31 March 2016, 17,789 substations. The analysis carried out by Ricardo Energy & Environment (formerly PPA energy) in the FUN-LV bid submission document estimated there are 87,000 substations in GB in dense urban areas, where the FUN-LV methods would be applicable for installation. Table 17 displays the number of unique sites identified in the replication study sample with a positive business case for reinforcement deferral, discounted by the infeasible installation percentage. These figures are based on rollouts of individual methods (not in conjunction) and extrapolated to provide an estimate of the number of feasible, unique sites in both the LPN area and GB-wide.

**Table 17 – Number of feasible unique sites**

<table>
<thead>
<tr>
<th>Method #</th>
<th>Replication Study unique sites with positive NPV</th>
<th>LPN Rollout unique sites with positive NPV</th>
<th>GB Rollout unique sites with positive NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>454</td>
<td>1,029</td>
<td>5,031</td>
</tr>
<tr>
<td>2</td>
<td>29</td>
<td>64</td>
<td>315</td>
</tr>
<tr>
<td>3</td>
<td>82</td>
<td>275</td>
<td>1,344</td>
</tr>
</tbody>
</table>

Focusing on only those sites that show a positive business case for reinforcement deferral, the headroom that can be created by deploying these methods is summarised in Table 18. This illustrates that, where conventional reinforcement is too costly or unviable given space or time constraints, there is significant potential to use FUN-LV methods instead. This would free up capacity to install large volumes of EVs and heat pumps. Also, these estimates have been made on the basis of historic load profiles, but if increasing volumes of LCTs are seen on the network, the flexibility of FUN-LV methods is expected to deliver additional value as they provide a means to shift load between substations in real-time.

**Table 18 – Headroom released by FUN-LV methods**

<table>
<thead>
<tr>
<th>Method #</th>
<th>Average headroom released per site (kVA)</th>
<th>Replication Study Total headroom released for sites with positive NPV (kVA)</th>
<th>LPN Rollout Total headroom released for sites with positive NPV (kVA)</th>
<th>GB Rollout Total headroom released for sites with positive NPV (kVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>126</td>
<td>57,255</td>
<td>128,714</td>
<td>629,495</td>
</tr>
<tr>
<td>2</td>
<td>183</td>
<td>5,235</td>
<td>11,768</td>
<td>57,553</td>
</tr>
<tr>
<td>3</td>
<td>167</td>
<td>13,630</td>
<td>30,640</td>
<td>149,851</td>
</tr>
<tr>
<td>Total</td>
<td>475</td>
<td>76,119</td>
<td>171,122</td>
<td>836,899</td>
</tr>
</tbody>
</table>

Table 19 displays the total benefit of method installation for sites with a positive NPV, discounted by the infeasibility percentage, across the substations analysed in the replication study. These results have then been extrapolated to a LPN wide rollout and a GB wide rollout of the methods. The rollout of M1 across LPN has an estimated NPV of £3.88m and a £18.96m NPV for a GB rollout. The rollout of M3 shows a similar NPV with a LPN NPV of £5.20m and a GB-wide NPV of £25.43m. There is a significantly smaller estimated NPV for M2 with a £0.13m NPV for LPN and a £0.63m NPV for GB.
The rollout of M1 and M3 components show a far greater potential NPV in comparison to a rollout of M2 components. The high NPV of M1 sites is due to the low ratio of method cost to reinforcement cost, meaning that even with the potential to only defer a reinforcement for a small portion of the method lifetime the deferral benefit is still large enough to justify installation of the method. The high NPV of M3 sites is due to the load utilisation amongst three, as opposed to two, substations which increases the likelihood that a deferral will be for the lifetime of the asset. This results in a large deferral benefit which increases the likelihood of a positive site NPV. M2s have a high ratio of method cost to reinforcement cost and, due to the sharing of load between only two substations, the average length of deferral is likely to be less than the lifetime of the asset. This results in a low likelihood of a positive NPV for M2 installation.

Table 19 – Total benefit of method installation for sites with a positive NPV

<table>
<thead>
<tr>
<th>Method #</th>
<th>Replication Study Substations</th>
<th>LPN Rollout</th>
<th>GB Rollout</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>£1,724,935</td>
<td>£3,877,779</td>
<td>£18,964,912</td>
</tr>
<tr>
<td>2</td>
<td>£57,073</td>
<td>£128,304</td>
<td>£627,490</td>
</tr>
<tr>
<td>3</td>
<td>£2,312,852</td>
<td>£5,199,460</td>
<td>£25,428,804</td>
</tr>
<tr>
<td>Total</td>
<td>£4,094,860</td>
<td>£9,205,543</td>
<td>£45,021,205</td>
</tr>
</tbody>
</table>

Note that these have sites have not necessarily required deferral immediately, but any future deferral benefit has been discounted to its present value.
8. Conclusions and Next Steps

8.1 Viable Use Cases for FUN-LV

FUN-LV methods offer a long list of potential benefits for a DNO looking to reduce reinforcement costs, connect new customers more efficiently and manage the network. The extent to which each of these benefits can be realised will depend on the particulars of the scheme being considered. Nevertheless, even focusing only on the benefit of headroom creation and reinforcement deferral it is estimated that there will be a considerable volume of cases in which a FUN-LV method is preferable to the conventional options.

As the sensitivity analysis shows, the key parameters to track when assessing the viability of a FUN-LV scheme are:

- **The cost of the FUN-LV method**: cost reduction needs to be seen for FUN-LV to become viable for a wide range of applications. Significant reductions are achievable, but given the projected learning curves of this generation it appears that this alone will not be sufficient to make FUN-LV viable alternative to the “average” conventional reinforcement case. However, a next generation of the technology is being specified that may provide even further improvement through reduced cost and more targeted functional capability. Regardless of this advance, this should not mean that current FUN-LV methods cannot be a valuable tool for a DNO – simply that it needs to be directed towards conventional options that are more complex and costly than average.

- **The cost of the conventional reinforcement being deferred**: although particularly dense urban environments that are already space-constrained have the potential to rise in price, it is unlikely that the average conventional reinforcement costs will increase. More likely, however, is that individual reinforcement schemes are found that will require above-average costs and timescales. It is these cases where FUN-LV is already a viable option. The average reinforcement, therefore, does not need to increase in order to find specific schemes with costs reaching or exceeding those identified in the “high” sensitivity case.

- **The total reinforcement deferral that can be achieved**: As important as the cost of the conventional reinforcement option is the degree to which it can be deferred. Long deferral can be achieved in one or more ways:
  - Creating large headroom by achieving significant load balancing from, for example, matching heavily- and a lightly-loaded substation.
  - Seeing low load growth on the heavily-loaded substation, making the created headroom endure for a long period of time.
  - Creating headroom on multiple substations simultaneously. This is possible for M1 and M2 sites where complementary load profiles can be found, particularly if future load profiles become more differentiated, as they are expected to do with the uptake of DG and new forms of load such as EVs. However, the benefit of deferring multiple substations simultaneously is most likely to be seen for the M3 sites, where a single lightly-loaded substation can alleviate two heavily-loaded substations.

- **Redeployment flexibility**: The extent to which the device can be redeployed usefully is the key factor in reducing the effective cost of any individual deployment. If FUN-LV method installation costs can be managed, warehousing costs are low, devices do not degrade whilst not in operation, and device lifetime can be extended through maintenance and component replacement, the effective cost of these devices can be considerably lower than the “sunk” cost of conventional reinforcement.
8.2 Next steps

Given the above, there are some conditions or some specific use cases where Network Planners should consider FUN-LV methods:

- **Conventional reinforcement costs are very high**, perhaps because a new substation site cannot be found close to where it is needed, or the land is particularly expensive or inaccessible.
- **Conventional reinforcement will be too slow** to alleviate the constraint. Today the load growth is typically slow enough to allow the identification of a maximally-loaded transformer to be addressed over the following 1-2 years. With the increased demand uncertainty that comes with DG, EVs and heat pumps there may be instances in which time is more pressing. A cluster of EVs, for example, may emerge over the course of just a few months. Alternatively, the uptake of roof-top solar alongside new EV installations may mask the impact of the additional load, but this masking effect could fall away at an inopportune time of year, revealing an unidentified need for rapid reinforcement.
- **Two or three complementary profiles are identified in heavily-loaded substations** in close proximity to each other, meaning that reinforcement can be deferred for multiple substations simultaneously, and for sufficient duration.
- **Device redeployment can be achieved** (i.e. the device is not too close to its end of life, and installation costs are not too high).
- **The need for reinforcement is uncertain**, meaning that conventional reinforcement risks resulting in stranded assets. This is predicated on the notion that FUN-LV methods can be deployed and removed flexibility, and that the costs of doing so are not prohibitive. Given the uncertainty over DG and EV uptake, it may be that this risk of stranded assets increases over time, in which case the flexibility of methods such as FUN-LV becomes more valuable.
- **Benefits that traditional reinforcement cannot provide are released**, such as the voltage management scenarios explored in Section 4.3.5.
- **Multiple benefits can be achieved simultaneously** such as headroom creation, voltage management and phase unbalance improvement.
- **Connecting customers** request a rapid connection option since they place a high value on the speed of connection rather than just the cost of conventional reinforcement.
Appendix A – Dissemination of learning

Please see the separate document for this appendix, this is also available on the innovation website.

Appendix B – Analysis of Method 1 performance and reliability data

Please see the separate document for this appendix, this is also available on the innovation website. 
EA Technology (2016) FUN-LV M1 - Performance Operability and Reliability Analysis

Appendix C – Analysis of SOP performance and reliability data

Please see the separate document for this appendix, this is also available on the innovation website. 
Methods 2 & 3: TPS (2016) Analysis Of Power Electronics Device Performance, Reliability and Operating Data

Appendix D – Method costs

Please see the separate report for this appendix*.

* This document is relevant for internal purposes and therefore not made available on the innovation website, although it has been made available to Ofgem.