My Electric Avenue (I²EV)

Successful Delivery Reward Criteria 9.8

An assessment of how much headroom an Esprit type solution would yield

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Date: 30 November 2015
Version: 1.4

The ‘My Electric Avenue’ Project is the public identity for the Low Carbon Networks Fund Tier 2 Project “I²EV.” The formal title “I²EV” is used for contractual and Ofgem reporting purposes.
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Executive summary

My Electric Avenue has deployed over 200 electric vehicles (EVs) for a period of 18 months to examine their impact on GB low voltage networks. Participants have driven over 3 million kilometres, saving more than 104 tons of direct CO₂ equivalent emissions, and have had their car charging curtailed on more than 7000 occasions in support of the distribution network.

This report evaluates the performance of a system (Esprit) which monitors LV networks and curtails EV charging to mitigate their impact throughout the My Electric Avenue trials. It takes the learning provided by this large scale Project, extrapolates the observed performance and models this performance for a range of uptake scenarios, technology configurations and network topologies. The learning is based on the operation of the Esprit technology on 200 EVs for a period of 18 months. The report seeks to provide a response to the objective set out in the Project Direction:

9.8 An assessment of how much headroom this sort of technical solution would yield, considering different network topologies and load types

In addition a cost benefit analysis and carbon calculation are provided to demonstrate the Esprit technology’s benefits to Distribution Network Operators (DNOs), customers, and wider society.

Results

1. During the trial the Esprit technology has worked as intended and the participants have had their car charging curtailed on more than 7000 occasions, in support of the distribution network.

2. The peak demand for residential EV charging has been found to coincide with the traditional residential evening peak. As a result, after-diversity maximum demand for households with EV chargers is approximately 2 kW: double the conventional residential demand.

3. This increased penetration of EVs can cause both thermal and voltage problems on LV feeders. Thermal problems typically occur ahead of voltage problems.

4. The results of modelling representative LV feeders have shown that 22% of LV feeders in one DNO license area will require intervention at EV penetrations of between 40% and 70%. This will occur across GB in 32% of LV feeders (312,000 circuits). Susceptible networks are typically characterised by available capacity of less than 1.5 kW per customer.

5. Esprit has been shown to be capable of mitigating thermal constraints in all types of residential networks, by using dynamic thresholds. This delivers thermal headroom of up to 46% at the highest levels of EV uptake.

6. Esprit also demonstrated additional voltage headroom equivalent to an additional 10% of customers connecting EV chargers. Furthermore, the number of non-compliant customers was reduced significantly, by up to 70% at the highest EV uptake considered. Delivery of greater voltage headroom is feasible but would require a sophisticated control system responding to customer voltage measurements.

7. Esprit is also technically capable of supporting significant numbers of additional EV connections on commercial networks. The flatter load profile of these networks can result in a long period of curtailment during which minimal capacity is available to share across
customers. This was found to be unacceptable to the My Electric Avenue commercial participants.

8. The timing of the first requirement for Esprit is very difficult to determine at a local level. An approach is proposed which can be applied across LV networks by designers in assessing whether there is a requirement and, if so, whether Esprit is appropriate.

9. The DNO industry smart grid reinforcement model Transform has been used to assess the likely uptake of Esprit. We find that Esprit will start to be deployed around 2021, and could be controlling up to 2 million homes by the end of ED4 (end of 2047). This corresponds to an economic benefit, compared to use of conventional reinforcement, of £2.2 billion.

10. My Electric Avenue has been a resounding success with successful deployment of Esprit technology, high levels of customer engagement and delivery of the expected learning. Participants have driven over 3 million kilometres and this has saved more than 104 tons of direct CO₂ equivalent emissions compared to internal combustion engine journeys of that distance.

It is important to consider these results in the context of the My Electric Avenue scope which considered 3.5 kW charging for the Nissan Leaf Mark 2 with its 24 kWh battery. As the industry moves to fast and rapid charge vehicles, with varying battery capacities, customer behaviour will undoubtedly change. In addition, the behaviour of the My Electric Avenue participants may not represent the behaviour of all customer types.

My Electric Avenue has taken an important first step in categorising the behaviour of large numbers of domestic EV users but additional work will undoubtedly be needed as this nascent technology evolves.
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1 Introduction

1.1 Purpose

This report accompanies a suite of reports that comprise the My Electric Avenue (I²EV) Successful Delivery Reward Criteria (SDRC).

The report provides an assessment of the technical benefits and disadvantages of the technology which was installed and under trial. The focus provided by the Project Direction (the Project contract with Ofgem) is stated as:

9.8 An assessment of how much headroom this sort of technical solution would yield, considering different network topologies and load types.

For the purposes of this report, this SDRC will be broken down into distinct topics:

1. Impact of uncontrolled charging of electric vehicles (Section 4)
2. Results of the practical evaluation of the Esprit technology (Section 4.3.5)
3. Technical benefits and disadvantages of the Esprit technology including additional headroom available and other network benefits (Section 6)
4. Cost and carbon savings expected if the Esprit technology is widely deployed, including an updated solution template for use in GB Smart Grid Forum modelling (Sections 7 and 8)
5. Additional learning beyond that set out in the My Electric Avenue Project direction (Section 9)

Whilst addressing each of these questions, this report will also cover the related learning points captured in the Project Direction:

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<td>• Evaluate how often switch off routines are likely to be initiated from real life trials and extrapolation via modelling using the results.</td>
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<td>• From the results and extrapolation via modelling, estimate the typical and maximum thermal capacity gained.</td>
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<td>Likely carbon savings of using the Technology.</td>
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1.2 **Document Structure**

The report is structured as follows:

**Section 2** describes the context for the My Electric Avenue Project, including the potential problem EV charging may represent for future networks.

**Section 3** provides a summary of the Project, with an overview of the aims and objectives, including the potential problem EV charging may represent for future networks.

**Section 4** sets out the impact of uncontrolled EV charging on low voltage distribution networks using calculated EV load profiles and modelling to project the impact on the My Electric Avenue clusters and representative feeders.

**Section 5** provides the learning on Esprit’s capability based on the field trials, including communications and control logic. Customer response is discussed briefly, but is covered fully by My Electric Avenue’s SDRC 9.6 report.

**Section 6** provides the assessment of the technical benefits and disadvantages of the technology; the key result shows the thermal and voltage headroom delivered by Esprit and other network benefits associated with a change in losses. This section also answers a number of My Electric Avenue’s technical learning outcomes and aims regarding approach to deployment and the amount of curtailment which is likely.

**Section 7** provides a cost benefit assessment of the Esprit system using EA Technology’s Transform Model®. This demonstrates the potential cost savings associated with Esprit, for various low carbon uptake scenarios, through to RIIO-ED4 (ends 2047).

**Section 8** sets out the potential environmental impact of Esprit, using the outputs of the Project’s academic partners and published life cycle assessments of relevant technologies.

**Section 9** provides details of additional learning which My Electric Avenue has produced, relevant to this report. This learning is beyond that set out in the Project Bid and Project Direction and will support My Electric Avenue’s ‘exceptional learning’ submission.

**Section 10** summarises each of the questions, requirements, technical and commercial learning points and related learning aims from the Project Direction. Under each point, it provides summary responses, with references to where more detail is located in this document.

1.3 **Limitations**

The scope of My Electric Avenue included a number of limitations which are translated to the results presented. It is important to consider these limitations when using the results of My Electric Avenue:
1.3.1 Charging Power and Battery Capacity

Whilst this Project is the largest network related EV project in the UK, and one of the largest in the world, the pace at which original equipment manufacturers (OEMs) are moving means that new technologies are changing, as is customer acceptance of plug-in vehicles.

The Nissan Leaf Mark 2 used by the My Electric Avenue participants is charged using 3.5 kW as standard, with an optional upgrade to 7 kW charging. The My Electric Avenue participants only used 3.5 kW charging; therefore, this was the peak demand from each technical trial participant’s charger. Consultation with EV OEMs has led to a clear understanding that increasing power available to chargers is highly desirable, and this is reflected in the EVs launched to market recently. The EV load profiles set out in Section 4 are likely to change as the power delivered by EV chargers increases.

The 24 kWh battery in the Nissan Leaf Mark 2 can be fully charged from empty in six to seven hours, using a 3.5 kW charger. Whilst some charging is limited by the customer disconnecting the car, it is more common for the car to be fully charged (see Figure 8c). Therefore, an increase in charger power will reduce the duration of a large proportion of charge events; whilst an increase in battery capacity will have the opposite effect.

In addition, variation in both charger power and battery capacity will change the customer experience. My Electric Avenue has demonstrated curtailment of EV chargers, prioritising those EVs which were most recently connected, in order to support the distribution network. Future generations of the technology may prioritise based on the EVs’ available range or predicted requirement. In addition, power may be reduced rather than switched and feedback presented to the customer directly. Whilst the response from customers to curtailment of EV charging has been largely positive\(^1\), future upgrades to Esprit logic are expected to improve customer response further.

1.3.2 Focus on Low Voltage Feeders

The My Electric Avenue Project scope was limited to the mitigation of EV impact on low voltage (LV) feeders. Connection of EV chargers resulted in a significant increase in after-diversity maximum demand (ADMD), shown in Section 4, which may require reinforcement for both 11 kV/LV transformers and higher voltage assets. Indeed, the additional learning discussed in Section 9.2 shows that 11 kV/LV transformers may be more likely to require early intervention than LV feeders.

1.3.3 Customer Behaviour

My Electric Avenue successfully recruited over 200 participants to the social and technical trials. These customers were incentivised by a relatively low-cost vehicle lease. However, the geographic and time limitations imposed by the Project necessarily incurred some selection of participants. Customers with different vehicle types or household requirements to those within the technical trials are likely to exhibit different behaviour, particularly associated with the timing and requirements for EV charging.

1.4 Document Map

This report sits as at a high level in the My Electric Avenue Project outputs. Along with the other SDRC reports, this document demonstrates the key learning generated by My Electric Avenue, as set out in the Project Direction and summarised in the Project Document Map shown in Appendix A.

The SDRC 9.8 document relies on relevant supporting work, particularly the analysis delivered by the University of Manchester, My Electric Avenue’s academic partner. These reports provided independent academic analysis of the impact of EVs and the efficacy of the Esprit solution. Relevant references, both to reports and academic publications, are highlighted where the relevant results are presented. A significant proportion of the results set out in this report were delivered by the University of Manchester.

In addition to setting out the key learning for My Electric Avenue, this report also supports My Electric Avenue’s top level documents: The Esprit White Paper and the My Electric Avenue Closedown Report; which set out the next steps for the Esprit solution, and the key Project learning from all work streams.
2 Context – Electric Vehicle Uptake

As sales of electric vehicles (EVs) increase, there is a need to assess the potential impact that clusters of EV owners may have in a local area served by one electricity substation. In the event of all EVs being recharged at the same time, and without any preparation, the demand on the local electricity network may exceed the substation capacity – causing outage.

New registrations of EVs has risen dramatically in the last two years (Figure 1). In January 2013, the SMMT\(^2\) noted only 113 new plug-in vehicles registered. This includes pure EVs and ‘other electric’ vehicles. In September 2014 3,093 new plug-in vehicles were registered according to the SMMT. Figure 1 shows that approximately 20,000 more EVs have been registered in just 3 years.

![Electric vehicle registrations](image)

**Figure 1: SMMT vehicle registration statistics for 'pure electric' and 'other electric' vehicles**

The trend to date shows a steady increase in new registrations, which, when forecast over a number of years suggests a significant challenge to electricity networks (Figure 2). In addition to the total number of EVs, other low carbon technologies have shown that very high penetrations can occur at local levels, an effect known as clustering. Clustering may result in a requirement for reinforcement of local network assets, even while the national average uptake remains relatively low. This effect has been seen in residential solar photovoltaic (PV) uptake, as shown in Figure 3.

Figure 2: National Grid Future Energy Scenarios EV uptake predictions

Statistics at end of Q3 2014
- 35.9 million vehicles
- 125,270 hybrids
- 4,132 electric

Figure 3: Residential Photovoltaic installations, demonstrating potential for clustering of low carbon technologies

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3 My Electric Avenue Project

3.1 Overview

The My Electric Avenue Project was led by EA Technology, with Project Partners Southern Electric Power Distribution (SEPD) (the host Distribution Network Operator), Northern Powergrid (collaborating DNO), Nissan (EV supplier), Fleetdrive Electric (EV rental programme management) and Zero Carbon Futures (charging point network developer). In addition there were two academic institutions supporting the Project, the University of Manchester (providing network modelling and analysis), and De Montfort University (providing socio-economic data gathering and analysis). The Project was funded by Ofgem’s Low Carbon Networks (LCN) Fund.

As SEPD and Northern Powergrid were Project Partners, the Project was based within both distribution licence areas.

3.2 My Electric Avenue Aims and Objectives

My Electric Avenue aims to trial a solution to the potential impact that the EV may pose to low voltage networks in the future, whilst providing a commercial blueprint for other non-Distribution Network Operators (DNOs) to deliver LCN Fund projects.

Specifically, the Project aims to deliver two strands of innovation:

1. A new commercial arrangement whereby a non-DNO manages a LCN Fund Project on behalf of a DNO.
2. New technology which monitors and controls EV charging tested with real customers and EVs.

For the purposes of the Successful Delivery Reward Criteria (SDRC) presented within this report, only the second point will be discussed.

3.2.1 The Technical and Social Trials

The trials are separated into two distinct groups: ‘technical trials’ and ‘social trials’. The ‘technical trials’ aims to simulate scenarios anticipated in the future where penetration of EVs on low voltage network feeders is significantly higher than it is today. The uptake of other low carbon technologies such as solar PV in previous years suggests a similar pattern may develop in the uptake of EVs (see Figure 3). As such, this trial has created clusters of EVs across ten locations, including nine residential areas (charging at home) and one business location (charging at work), details of each cluster are set out in Table 1.

Within seven of the ten clusters, the Project has recruited ten or more customers to lease an EV for 18 months at a reduced price, in return for having trial technology installed in their home which

\text{http://tools.decc.gov.uk/en/content/cms/statistics/local_auth/interactive/domestic_solar/index.html}
\text{Accessed 22 October 2015} \]
monitors and controls their EV charging. Three other clusters have fewer than ten customers taking part, as per the recruitment criteria stipulated within the Project Direction.

The ‘Social Trials’ were conducted in parallel with the technical trials and were designed to provide a comparison with the participants who had their EV charging directly controlled. Social trial participants have been recruited to lease an EV for at least 18 months and do not have any constraints imposed by the Project on their EV charging behaviour.

The data from both Technical and Social trials is presented and discussed in this document.

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<td>South Shields</td>
<td>Northern</td>
<td>Urban</td>
<td>Home</td>
<td>✓</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>South Gosforth</td>
<td>Powergrid</td>
<td>Suburban</td>
<td>Home</td>
<td>✓</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Wylam</td>
<td></td>
<td>Rural</td>
<td>Home</td>
<td>✓</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Your Homes</td>
<td></td>
<td>Urban</td>
<td>Work</td>
<td>✓</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>South Shields 2</td>
<td></td>
<td>Urban</td>
<td>Home</td>
<td>✓</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>8</strong></td>
<td><strong>111</strong></td>
</tr>
</tbody>
</table>

### 3.3 The Esprit Technology

The Esprit technology is defined as the combination of an ‘Intelligent Control Box’ (ICB) and a ‘Monitor Controller’ (MC). Together these two units provide the current form of Esprit as it was trialled during My Electric Avenue.

Esprit implements Demand Side Response (DSR) by direct control, and curtails EV charging by switching off the power supply to charging points preventing them from consuming electricity at times when the demand on the network is high. During such times of curtailment, Esprit also cycles the power supplies of different chargers on and off to ensure that cars that are plugged in receive some charge periodically.

The Esprit control functionality deployed to trial the technology operates using on three modes:

---


6 Just prior to installation of the Esprit system at the Slough BC cluster, the Project team was made aware that Slough Borough Council was due to undergo a significant office renovation and that several members of the cluster were in the process of relocating to other offices. Therefore, the use of project funds on acquisition and installation of charging infrastructure, without guaranteed usage, could not be justified and participants were allocated to the social trials.
1. Normal Mode – when the monitored phase current is below the Phase Current Threshold.
2. Curtailment Mode – activated when the phase current rises above the Phase Current Threshold. The MC creates a priority list of ICBs, based on the currents recorded at the ICBs at the time the mode was activated. A curtail signal is sent to all ICBs on that phase (with the exception of one) instructing the ICB to switch off the power supply to the charging point. The exception is the ICB of the highest priority within the priority order created by the MC.
3. Reforming Mode – activated when the monitored phase falls below the Phase Current Threshold during Curtailment Mode. Cycles through each ICB, according to the same priority assigned during curtailment, to allow power supply back to each charging point.

The set-up is illustrated in Figure 4. During times of curtailment, Esprit cycles the power supplies of different charging points on and off to ensure that cars plugged in will receive some charge periodically. For more information on how Esprit operates, and how it is integrated within the trials, please see the My Electric Avenue SDRC 9.7.1 Report\(^7\)

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\(^7\) My Electric Avenue (2015) “My Electric Avenue Successful Delivery Reward Criteria 9.7.1: An Assessment of ‘Esprit’ Integration”
4 Impact of Charging of Electric Vehicles

4.1 Electric Vehicle Usage

SDRC 9.8.1b: The Project will deliver an updated Solution template(s) specific to the Technology, and any updated EV charging profiles for use in the GB Smart Grid Forum modelling.

Updated EV charging profiles are presented in Figure 11 - Figure 15. Diversified peak demand from EV charging coincides with typical peak residential demand leading to a doubling of ADMD, for 1000 customers, when each customer has an EV.

This section investigates the charging behaviour of the EV users involved in the My Electric Avenue Project. It illustrates the changes in the diversified demand for different numbers of EVs, using the creation of probability density functions (PDF) which describe the My Electric Avenue participants’ EV usage. More detail concerning this methodology is included in the My Electric Avenue outputs by the University of Manchester.8,9

4.1.1 Charging Behaviour (CARWINGS) of Domestic EVs

Data was collected from each of the My Electric Avenue participants using Nissan’s telematics system – CARWINGS – which was installed in each vehicle. Information was collected every time an EV was charged or driven. For each recorded EV charge, the following parameters were recorded: start charging time, end charging time, initial state of charge (SoC), and final SoC. The Nissan LEAF Mark 2 has a battery capacity of 24 kWh, which is represented in the data as 12 units (2 kWh per unit, 1 unit equals 8.3% of battery capacity). At the time of writing, over 62,000 CARWINGS samples had been analysed. CARWINGS data is collected for both technical and social trial participants.

In total, 217 vehicles were monitored during My Electric Avenue. From those, 99 are involved in the technical trial (86 are residential and 13 are commercial) and 118 are in the social trial. Residential EVs involved in the technical trial are referred to as ‘managed’, as their charging point may be disconnected by the Esprit technology. Commercial EVs are also managed, but given their nature they are referred to as ‘commercial’ to separate their results from participants with Esprit control at their homes. Social trial participants, without Esprit technology, are referred to as ‘non-managed’.

CARWINGS data have been statistically analysed to understand the behaviour of EV users, specifically:

- when they are more likely to charge their EV
- the initial SoC at each charge
- the final SoC for each charge
- the number of connections (charges) per day

---


PDFs of the charging behaviour were created, using the process set out in other Project outputs. Analyses, aggregated by My Electric Avenue cluster, have also been completed to understand charging variation across the regions. However, results showed that no significant difference exist between the residential clusters.

4.1.1.1 Analysis of CARWINGS Data – Technical Trial vs Social Trial

In order to understand the difference in behaviour between technical, social and commercial participants, their results were analysed and compared. Figure 5 shows the PDFs of different variables extracted from the CARWINGS data. The following conclusions are drawn:

- The residential EV charging pattern is very similar, irrespective of whether the EV user has their charging curtailed or not.
- The charging behaviour, particularly the start charging time, is different between residential and commercial EVs.
- A number of ‘non-managed EVs’ are connected at 23:30 – most likely due to a time of use tariff.
- Residential EVs can be connected at any time during the day and the charging behaviour follows the UK residential load curve, peaks occur around 8:00 and 18:00 each day.
- Most of the EV users charge their EV when the SoC is between 3 and 8 units (25% to 66% of the battery capacity). This could mean that many EV users perceive as ‘low SoC’ any value between 3 and 8.
- More than 60% of the EVs charges continue until they reach 100% SoC – perhaps because many EVs are connected at night after EV users return home (see Figure 5a).
- The vast majority (~70%) of EV users charge their EV only once a day, compared to a minority (5%) who charge three times per day.

---

10 It should be noted that My Electric Avenue participants were neither encouraged nor discouraged from using ToU tariffs.
Figure 5: PDF (a) Start charging time. (b) Initial SoC. (c) Final SoC. (d) Number of connections per day.
4.1.1.2 Analysis of CARWINGS Data – Learning Period

To understand if EV users adapt their behaviour after some ‘learning period’, several cases (one, two and three weeks) were analysed. Since the behaviour of residential participants in both social and technical trials is similar, this analysis considers all participants, except commercial. It was found that during the first week of use, the EV charging behaviour is significantly different from the remaining period. To illustrate this, Figure 6 compares the PDFs of different variables calculated from CARWINGS data during the first week of use and those from the remaining trial period. The following conclusions are drawn:

- During the first week, 10% of the EVs are connected when the initial SoC is 100%.
- During the first week, about 40% of the EVs are charged more than once a day.
- After one week, most EV users are likely to adopt a repetitive charging behaviour with fewer connections per day (70% of customers charge once per day after one week); perhaps due to an increased confidence on the car capabilities. Thus, one week can be considered as the ‘learning period’.
Figure 6: PDF (a) Start charging time. (b) Initial SoC. (c) Final SoC. (d) Number of connections per day.
4.1.1.3 Analysis of CARWINGS Data – Seasonality

Different seasons may also cause EV users to change their charging behaviour. Figure 7 shows the PDFs of different variables calculated for different seasons. This analysis also considers all the EVs. It is concluded that users do not significantly change their EV charging pattern during different seasons.

It should also be noted that winter time was coincident with the initial months of the trial. Hence, the charging behaviour has improved over summer and autumn. Additionally, when assessing the whole year, it was found that the number of EVs that end their charging process with full charge slightly decreases over time. This could mean that EV users have realised that it is not necessary to always charge their EV until it reaches full charge. It should be noted that the impact of battery ageing on these results is not clear.
Figure 7: PDF (a) Start charging time. (b) Initial SoC. (c) Final SoC. (d) Number of connections per day.
4.1.1.4 Analysis of CARWINGS Data – Weekday vs Weekend

It was expected that the charging behaviour would change from weekdays to weekends, in common with other domestic electricity demand. Figure 8 compares the PDFs of different variables calculated for weekdays and weekends. This analysis also considers all the EVs. It was found that EV users do change their charging behaviour from weekdays to weekends. During weekends:

- The average starting SoC starts is higher
- Disconnections are more frequent before EVs are fully charged
- The average number of connections per day is higher
Figure 8: PDF (a) Start charging time. (b) Initial SoC. (c) Final SoC. (d) Number of connections per day.
4.1.1.5 Summary of the Analysis of CARWINGS Data

The PDFs shown in Sections 4.1.1.1 - 4.1.1.4 can be used to create stochastic, realistic and detailed EV profiles (see Section 4.1.2). Since no significant differences between EVs involved in the trials have been found, except for commercial participants, all the residential EVs are considered as a single population. Moreover, as the ‘learning period’ was found to be one week, the charging data registered during this period was excluded from the sample; this represented less than 2% of the available data.

The PDFs for this dataset, calculated for weekdays and weekends, for different seasons, are shown in Figure 9 and Figure 10. In general, more EVs are connected at morning and evening weekday peak times. The latter is critical as this is coincident with the peak residential demand, which was expected to result in significant impacts on the LV network. During weekdays, EVs are charged mostly when their SoC is between 3 and 8 units, but a number of EVs may be connected when their SoC is higher than 10 units. Regardless of the day of the week, most EVs are charged until they reach full charge. Finally, it can be noted that most EVs (almost 70%) are connected only once a day, but about 20% of them may have a second connection during the day.
Figure 9: Seasonal variation in PDF for weekdays (a) Start charging time. (b) Initial SoC. (c) Final SoC. (d) Number of connections per day.
Figure 10: Seasonal variation in PDF for weekends (a) Start charging time. (b) Initial SoC. (c) Final SoC. (d) Number of connections per day.
4.1.2 Creation of Electric Vehicle Load Profiles

4.1.2.1 Methodology

The PDFs presented in Section 4.1.1, show the probability of when EVs are connected to the LV network, the initial SoC and the final SoC, and the number of connections per day. The initial and final SoC determine how long the EV needs to be connected to the LV network, taking into account the charging capacity (the Nissan LEAF has a battery rating of 3.5 kW/24 kWh). It is assumed that the EVs are connected at home, using a slow charging mode at 230 V. Thus, if the energy required was 24 kWh, the EV must have been connected for around 7 hours. Given that the Nissan LEAF represents the battery SoC in 12 units, 1 unit would be equal to around 35 minutes of charging.

Based on these considerations, it is possible to create a pool of EV profiles to be used in our studies. The following process was implemented by the University of Manchester for the creation of each EV profile, assuming only one connection per day:

1. Random selection of the connection time using the corresponding PDF.
2. Random selection of the initial SoC using the corresponding PDF.
3. Random selection of the final SoC using the corresponding PDF (larger than the initial SoC).
4. Calculation of the time needed from the initial SoC to the final SoC based on the required number of units to be charged (final SoC minus initial SoC).

The charging process occurs between the connection time (item 1) and finishing time (item 1 + item 4). Examples of this process are shown in Figure 11a and Figure 11b.
Figure 11: Example of individual EV profiles and diversified EV demand for weekdays and weekends
4.1.2.2 Results

With the procedure set out in Section 4.1.2.1, it was possible to create very large numbers of different EV profiles. To illustrate this, Figure 11a and Figure 11b show individual load profiles for weekdays and weekends during winter. These profiles show different charge durations given the different energy requirements of the cars and their different start charging times.

The creation of several individual profiles allows the creation of diversified profiles. These are useful to understand the peak coincidence demand of the EV in one particular feeder and/or secondary substation. Figure 11c and Figure 11d show the diversified profile for 1000 EVs for weekdays and weekends. The diversified maximum demand is 1.16 kW and 1.02 kW for weekdays and weekends, respectively.

Figure 12 and Figure 13 show the diversified EV demand for different numbers of EVs. It can be seen that the lower the number of EVs, the higher the diversified peak demand. To illustrate this point, the diversified peak EV demand for between 1 and 200 EVs is shown in Figure 14. Variation in peak demand with number of connected EVs, \( n \), can be represented by the function \( 2.585 \times n^{-0.149} \).
Figure 12: Example of diversified load demand (winter weekday) for various EV numbers
Figure 13: Example of diversified load demand (winter weekend) for various EV numbers.
Finally, Figure 15 shows the average diversified winter residential demand of 1000 households (created using the CREST tool\textsuperscript{11}, see Section 4.2.6), the average diversified demand of 1000 EVs, as well as the sum of average residential and EV demands. The combined average diversified peak demand doubles when all houses have one EV compared to the case without EVs.

Figure 14: Example of total diversified peak EV demand during winter for various EV numbers


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4.2 Models of Low Voltage Electricity Distribution Networks

**Deliverable 7.1: Network models of the impact of EV charging and the Technology.**

In order to assess the impact of increased EV penetration on LV distribution networks, the University of Manchester created models in OpenDSS. Two groups of models were used:

1. Models representing the My Electric Avenue feeders
2. Models representing a statistically significant selection of LV networks, originally created for Electricity Northwest's LVNS Project\(^\text{12}\).

4.2.1 Framework for representing distribution networks

OpenDSS is an open source software package to solve power flows, harmonics analysis and fault current calculations in electrical distribution systems\(^\text{13}\). This computational tool was developed by

the EPRI (USA) to help the analysis associated with distributed generation. This software is able to solve problems involving unbalanced networks and it can be driven from other modelling software.

One of the main characteristics of OpenDSS is the ability to represent the time sensitivity in networks with distributed generation. This is important to quantify the impacts of intermittent generators and loads, particularly low carbon technologies, on distribution networks.

The typical structure for OpenDSS models is one master file that controls the reading and the executing of the data files, which include data for:

- Transformers
- Conductors and their connections
- Time sensitivity
- Loads and load profiles

In order to model a network, all of this data is required. In order to carry out efficient analysis, this process needed to be automatic. Figure 16 shows a flow chart detailing this automatic process.

![Figure 16: Automatic translation into OpenDSS](image)

The information shown in Figure 16 was collected from different sources: EA Technology, Northern Powergrid and SEPD. The network topology information was taken from a database following pre-processing, where required. The load information was created using the CREST tool which was used to generate a realistic pool of profiles that were allocated at customer nodes to model their demand.

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14 My Electric Avenue (2015), "Work Activity 2 “Low Voltage Networks” – Report for Deliverables 2.1, 2.2 and 2.3“
These profiles were allocated to the different Meter Point Administration Numbers (MPANs), which are found on a given LV network. MPANs were supplied for each customer connected to the monitored feeders.

With the topology information, the technical data, the load and generation profiles and the relationship between the MPAN and the adopted load profiles, it was possible to create an automatic process to translate all the data into OpenDSS.

A more detailed review of this process, and the resulting network models is set out in My Electric Avenue’s academic partner reports. A model for each DNO involved in My Electric Avenue, in addition to the representative LVNS networks, is shown in Section 4.2.2 and 4.2.3 to illustrate the Deliverable 7.1 (Network models of the impact of EV charging and the Technology).

### 4.2.2 Northern Powergrid (South Gosforth)

The My Electric Avenue cluster at South Gosforth is connected to the 11 kV/LV substation described in Table 2 and has been mapped in the model to generate the topology shown in Figure 17.

<table>
<thead>
<tr>
<th>Transformer Capacity (kVA)</th>
<th>Feeder Number</th>
<th>No. of Customers</th>
<th>Main Cable Length (m)</th>
<th>Cable Type (first segment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>Feeder 1</td>
<td>136</td>
<td>706</td>
<td>0.30x4CCu</td>
</tr>
<tr>
<td></td>
<td>Feeder 2</td>
<td>57</td>
<td>670</td>
<td>0.30x4CAl</td>
</tr>
<tr>
<td></td>
<td>Feeder 3</td>
<td>81</td>
<td>987</td>
<td>0.30x4CAl</td>
</tr>
<tr>
<td></td>
<td>Feeder 4</td>
<td>62</td>
<td>966</td>
<td>30x4CCu</td>
</tr>
<tr>
<td></td>
<td>Feeder 5</td>
<td>92</td>
<td>476</td>
<td>30x4CAl</td>
</tr>
</tbody>
</table>

---

4.2.3 Scottish and Southern Energy Power Distribution

The My Electric Avenue cluster at Chiswick is connected to the 11 kV/LV substation described in Table 3 and has been mapped in the model to generate the topology shown in Figure 18.

Table 3: Details of Chiswick Network

<table>
<thead>
<tr>
<th>Transformer Capacity (kVA)</th>
<th>Feeder Number</th>
<th>No. of Customers</th>
<th>Main Cable Length (m)</th>
<th>Cable Type (first segment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>Feeder 2</td>
<td>55</td>
<td>392</td>
<td>185 Wavecon</td>
</tr>
<tr>
<td></td>
<td>Feeder 3</td>
<td>149</td>
<td>1152</td>
<td>185 Wavecon</td>
</tr>
<tr>
<td></td>
<td>Feeder 4</td>
<td>126</td>
<td>198</td>
<td>185 Wavecon</td>
</tr>
</tbody>
</table>

*A reconfiguration was made during My Electric Avenue, Feeder 1 is no longer connected to this substation.*
4.2.4 Representative LVNS Networks

The representative LVNS feeders were developed as part of a Tier 1 Low Carbon Networks Fund project\textsuperscript{12}. These characterise 141 LV networks (232 feeders) located in the North West of England and are constructed based on their network parameters as well as monitoring data. The main features of these LV feeders are summarised in Table 4, including two additional rural feeders, not used by the LVNS Project.

Table 4: Summary of Features of the Representative LVNS Feeders

<table>
<thead>
<tr>
<th>Feeder Name</th>
<th>Main Path Length (m)</th>
<th>Total Cable Length (m)</th>
<th>First Segment Cable Type</th>
<th>Rating (A)</th>
<th>Number of Customers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PC1     PC2 Other</td>
</tr>
<tr>
<td>Feeder 1</td>
<td>270</td>
<td>1207</td>
<td>Consac 185 mm\textsuperscript{2}</td>
<td>235</td>
<td>34 2 0</td>
</tr>
<tr>
<td>Feeder 2</td>
<td>374</td>
<td>1676</td>
<td>Cu 0.25 in\textsuperscript{2}</td>
<td>355</td>
<td>96 6 6</td>
</tr>
<tr>
<td>Feeder 3</td>
<td>370</td>
<td>1871</td>
<td>Cu 0.15 in\textsuperscript{2}</td>
<td>260</td>
<td>30 1 7</td>
</tr>
<tr>
<td>Feeder 4</td>
<td>517</td>
<td>2963</td>
<td>Cu 0.30 in\textsuperscript{2}</td>
<td>400</td>
<td>91 10 7</td>
</tr>
<tr>
<td>Feeder 5</td>
<td>253</td>
<td>962</td>
<td>Consac 240 mm\textsuperscript{2}</td>
<td>320</td>
<td>9 0 14</td>
</tr>
<tr>
<td>Feeder 6</td>
<td>360</td>
<td>1828</td>
<td>Cu 0.25 in\textsuperscript{2}</td>
<td>310</td>
<td>73 3 0</td>
</tr>
<tr>
<td>Feeder 7</td>
<td>522</td>
<td>3673</td>
<td>Cu 0.25 in\textsuperscript{2}</td>
<td>525</td>
<td>161 6 2</td>
</tr>
<tr>
<td>Feeder 8</td>
<td>264</td>
<td>797</td>
<td>Consac 360 mm\textsuperscript{2}</td>
<td>360</td>
<td>19 12 0</td>
</tr>
<tr>
<td>Rural 1</td>
<td>238</td>
<td>1154</td>
<td>AAC 0.05 in\textsuperscript{2}</td>
<td>214</td>
<td>16 0 0</td>
</tr>
<tr>
<td>Rural 2</td>
<td>609</td>
<td>1678</td>
<td>ABC 95 mm\textsuperscript{2}</td>
<td>242</td>
<td>22 0 0</td>
</tr>
</tbody>
</table>
4.2.5 Network Data and Assumptions

In order to overcome limitations in the geographic information system data available for the relevant LV networks, and to manage the very large amount of data, the following assumptions were used:

- **Phase connection**: When the phase connection of the service cable was available, this was allocated. Where no phase connection data was available, the phase connection of a service cable was allocated randomly.

- **Service cable type**: In multiple cases, information about the cable type was not given for service cables. The conductor information was assumed based on the most common service cable for single-phase customers: 25 mm² XLPE.

- **Three-phase cables**: For the three phase cables without conductor information, the cable was assumed to have the same construction as the conductor immediately upstream, or the previous conductor if required.

- **Impedance**: To allocate the impedance values for each conductor, the characteristics of each cable were obtained from manufacturer manuals. However, it was not always possible to identify which conductor in the files corresponds to which conductor in the manuals. To overcome this issue, the size of the cable was used, and the most common cable type for that size was used.

- **Monitor placement**: Measurements for the network models were assumed to be taken at the 11 kV/LV transformer, the head of each feeder, and the customer nodes.

4.2.6 Residential Load Profiles

To create residential load profiles, the CREST tool was used. This tool creates profiles for different classes’ residential loads, based on industry data from ELEXON, which is based on the domestic behaviour of British customers. Using this method, it was possible to create one minute resolution load profiles, indicating which appliances were used and how much power each required.

A pool of profiles, for typical weekdays and weekends of each month, was created using this tool. The proportion of profiles associated with customer types was based on UK statistics. In this case, the proportion of houses with one person, two people, three people and four or more is 29%, 35%, 16% and 20%, respectively. Figure 19 shows example individual residential load profiles and the diversified demand from 1,000 load profiles for typical weekdays and weekends during January.

To illustrate how the diversified demand changes for different customer numbers, Figure 20 and Figure 21 show the variation with number of customers connected to the LV feeders. It can be seen that the lower the number of customers the higher the diversified peak demand due to the lower diversity.

---


Figure 19: Example of individual load profiles and diversified load demand (for 1,000 customers) during winter.
Figure 20: Example of diversified load demand (winter weekday) for various customer numbers.
Figure 21: Example of diversified load demand (winter weekend) for various customer numbers.
4.2.7 Validation of LV Feeders

4.2.7.1 Feeder Validation Overview

This section describes the methodology used to validate the models of the LV feeders involved in the My Electric Avenue Project. The feeder validation used the monitored current at the head of each feeder, which was compared to the results of the equivalent models.

Due to the assumptions made when modelling the LV feeders, it was inevitable that differences would be found but this validation ensured that the models were representative. Information such as the phase connection, service cable type, three phase cable and the impedance of the cables was not available during the creation of the computer-based models.

Therefore, the main aim of the feeder validation (detailed in [3, 4]) was to determine to what extent these assumptions were valid. If significant differences were found, assumptions were revised; in particular, phase connections of customers were modified to minimise mismatches.

LV models were created for 31 feeders. However, only the nine My Electric Avenue feeders were monitored to allow validation. Therefore, the results in this section focus on those feeders.

4.2.7.2 Feeder Validation Results

When the power flow analysis was undertaken, the validation methodology compared the total energy consumed of the simulated feeder and that derived from the corresponding monitoring data quantified as single-phase errors, $E_{\phi,a,b,c\ (all\ day)}$, and three-phase errors, $E_{3\phi\ (all\ day)}$, for the day, and during peak demand, $E_{\phi,a,b,c\ (5-8pm)}$ and $E_{3\phi\ (5-8pm)}$.

The peak kVA demand was also compared to highlight differences between the models and the real LV feeder in terms of maximum demand, particularly during evening peak times. These errors were calculated based on a single random simulation of a day, and then multiple days. Success thresholds were defined as 30% per phase and 20% three-phase errors. In all cases, network models were validated successfully. The following section illustrates this process for the Chiswick cluster.

4.2.7.2.1 Single-Day Analysis

For each LV feeder involved in the My Electric Avenue Project, the validation methodology used the domestic demand (i.e. monitored phase current minus EV demand) for comparison against the simulation results. It was assumed that the voltage at the head of the feeder was 424 V line-to-line.

Considering an arbitrary day (16/03/2015), the domestic demand measured for the Chiswick LV feeder was compared to synthetic load profiles used in the simulations. However, this LV feeder supplies customers whose homes are occupied mostly by one or two persons, so the modelled load profiles created for this feeder were constrained to those for one or two residents.

The initial mismatches were found between measured and simulated data, particularly for energy values per phase, which led to the re-distribution of some customers to other phases. To illustrate the performance of the LV feeder model for Chiswick, the corresponding 10 minute average power flow results are shown per phase in Figure 22. It can be observed that the patterns show a good match.

The final values of the validation metrics for the Chiswick LV feeder are given in Table 5. According to the energy criteria and the peak kVA demand; all energy metrics per phase are smaller than 30% and the variation in the three-phase energy metrics are smaller than 20%. In addition, it can be seen that the peak kVA error is small (less than 15%). Therefore, it can be concluded that the updated model of the Chiswick LV feeder was valid for this particular day.
Table 5: Network validation metrics for Chiswick LV feeder

<table>
<thead>
<tr>
<th></th>
<th>( E_{\phi,a} ) (mean)</th>
<th>( E_{\phi,b} ) (mean)</th>
<th>( E_{\phi,c} ) (mean)</th>
<th>( E_{3\phi} ) (mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Error (all day)</td>
<td>11.8</td>
<td>3.6</td>
<td>3.4</td>
<td>0.04</td>
</tr>
<tr>
<td>% Error (5-8pm)</td>
<td>13.0</td>
<td>10.3</td>
<td>2.8</td>
<td>8.8</td>
</tr>
<tr>
<td>% Error Peak kVA</td>
<td>5.9</td>
<td>5.4</td>
<td>13.1</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 22: Comparison of measured and simulated data for the Chiswick LV feeder.
4.2.7.2.2 Multiple-Day Analysis

To validate the new LV feeder model for Chiswick, the analysis presented in Section 4.2.7.2.1 was carried out for up to 10 random days. Table 6 shows that the model for Chiswick LV feeder is valid, when different days are considered. If the standard deviation is considered, a maximum of 20.0% of error may be obtained in ‘phase c’ throughout the day. During peak times (from 5pm-8pm), all the phases show error smaller than 30%. For the peak kVA demand, it can be seen in Table 6 that the difference in the peak demand between the monitored data and the simulated data is smaller than 25% in all the cases (considering one standard deviation).

Therefore, it can be concluded that the model for the Chiswick LV feeder is valid, when multiple days are taken into account.

| % Error (all day) | 12.5±6.7 | 6.8±5.3 | 10.9±9.1 | 7.3±3.3 |
| % Error (5-8pm)  | 10.2±8.9 | 14.9±7.3 | 15.0±12.7 | 8.2±5.1 |
| % Error Peak kVA  | 12.8±12.1 | 14.9±9.5 | 12.7±9.1 | - |

Table 6: Network validation metrics for Chiswick LV feeder for 10 days.

4.3 Impact of Uncontrolled EV Charging on Electricity Distribution Networks

Deliverable 7.1: Network models of the impact of EV charging and the Technology

This section assesses the impact of different EV penetration levels on residential LV feeders.

4.3.1 Deterministic Impact Study Methodology

The objective of the methodology presented in this section was to assess, using a deterministic approach, the impacts of different EV penetration levels on the LV feeders introduced in Section 4.2.

For a given LV feeder, the methodology can be summarised as follows:

- Different load profiles were allocated to each customer node on the feeder. The load profiles were randomly selected from a pool, as set out in Section 4.2.6, to represent the diversity among the residential customers.
- For a given penetration level (from 0% to 150% in steps of 10%), the properties with an EV were randomly selected. In this report, the penetration level is defined as the percentage of houses with an EV. Where EV penetration is greater than 100% some customers were allocated two EVs.
- Once the residential and EV profiles were allocated to the feeder, a time-series three-phase four-wire power flow, with 1 minute resolution data, was executed using OpenDSS. A line-to-line voltage of 424 V was considered at the secondary of the distribution transformer (which is aligned with Northern Powergrid and SEPD practices).

4.3.2 Assessment Metrics

To assess the deterministic EV impacts, three metrics are considered in this report: voltage problems, thermal problems and energy losses. To illustrate the methodology, the EV impacts on the My Electric Avenue Chiswick cluster and the representative LVNS Feeder 7 are shown throughout Section 4.3.2.
4.3.2.1 Voltage Problems

To understand the EV impacts in terms of voltages on the LV feeders, the percentage of customers who would experience voltages outside of the statutory ranges was determined. This metric tests if the voltage profile at each customer node satisfied the British Standard BS EN 50160\textsuperscript{18}. If the voltage at the customer node is outside of the statutory range then the customer is considered to have a voltage problem.

Considering a winter weekday, Figure 23 shows the minimum voltage per phase for all customers on the My Electric Avenue Chiswick cluster, for a 24 hour period at 0\% and 100\% penetration levels. It can be observed that the voltages are all above the minimum threshold even when all customers have an EV. This analysis was conducted for each of the My Electric Avenue clusters and the representative LVNS feeders.

\[\text{18 British Standards Institution (2000), "BS EN 50160: Voltage characteristics of electricity supplied by public distribution systems"}\]
A similar analysis has been carried out for a typical weekday among the other seasons (i.e., spring, summer and autumn). Given that the residential load composition during spring and autumn are similar and the EV charging behaviour does not significantly change across seasons, ‘shoulder’ refers to both spring and autumn. Figure 24 shows the number of customers outside the statutory voltage ranges for LVNS Feeder 7 for different seasons and penetration levels. The variation at higher penetrations is most likely due to the random allocation of EVs across the feeder.
In addition to the number of non-compliant customers, throughout this analysis it was observed that voltages during weekdays of summer are slightly higher than during other seasons. This is mainly due to the effect of seasonality on residential demand; residential demand during summer is lower than any other season.

In general, it was found that voltage problems occur at higher penetration levels than thermal problems, for equivalent feeders. However, it should be noted that feeders may experience low voltages under some particular circumstances, due to uncertainties in the residential and EV demand and location. This cannot be catered for using a deterministic approach, but a stochastic one which is beyond the scope of My Electric Avenue and discussed in Section 9.6.  

---

4.3.2.2 Thermal Problems

To understand the impacts of EVs on the thermal capacity of LV feeders, the utilization factor at the head of the feeder was calculated in each simulation. This metric assesses the proportion of the feeder capacity required to deliver the customer demand. The utilization factor was calculated as the maximum current (from 10 minute averages) divided by the ampacity (cable rating) of the main segment of the feeder.

To demonstrate this, the My Electric Avenue cluster most sensitive to an increase in thermal capacity is considered for a winter weekday (time period of highest electricity demand). Figure 25 shows the feeder current modelled on the Chiswick cluster, for a 24 hour period at 0% and 100% penetration levels. It can be seen that the feeder is expected to exceed its thermal capacity at 100% penetration, particularly phase B which exceeds the capacity by 35% at peak time. The thermal limit shown in Figure 25 is the winter static rating, the impact of cyclic ratings is discussed in Section 6.4.

Figure 25: Example of feeder utilization analysis for winter weekdays for the Chiswick Cluster.
Figure 25 focused on two cases (i.e. without EVs, and one EV per household), during winter weekdays. However, it is important to investigate the penetration level at which feeder overloads are first experienced, for different seasons. This is critical to define the hosting capacity of the LV feeder.

Therefore, the analysis for each season has been extended for every penetration level (from 0\% to 150\% in steps of 10\%). To illustrate an example of these results, LVNS Feeder 7 is considered for weekdays and weekends across different seasons.

Figure 26 shows that the utilisation level (proportion of thermal capacity required) for this feeder increases linearly with the penetration level. In addition, it shows that the feeder utilisation level in winter is higher compared to the other two seasons and, crucially, that feeders represented by LVNS Feeder 7 require intervention when the EV penetration level exceeds approximately 60\% (approximately 100 houses with an EV). It should be noted that the rate of increase in feeder utilisation, with increased EV penetration, is most likely due to the reduction in after-diversity maximum demand (ADMD) shown in Section 4.1.2.
4.3.2.3 Energy Losses

It was expected that the energy losses would increase with the EV penetration. To understand this effect, the daily energy losses are calculated. Daily energy losses are defined as the total daily energy losses as a percentage of the total energy consumption in the feeder for each EV penetration. The difference between the power supplied at the head of the feeder and the sum of power consumed in each load was calculated in each time period. This value was then divided by the total energy consumption in the feeder to give the energy losses as a percentage of the total energy demanded\textsuperscript{8}.

For each penetration and season, Figure 27 shows that the energy losses increase as the EV penetration increases. In general, the losses are higher in winter and lower in summer. For each season, Figure 27 shows that the highest EV penetration level results in a doubling of energy losses compared to the scenario without EVs.

![Figure 27: Daily energy losses per penetration and season for LVNS Feeder 7](image)

\textsuperscript{8}
4.3.3 License Area Summary Results

The EV impact assessment previously presented is useful for understanding the behaviour of one particular feeder under different penetration levels. Nonetheless, the lessons learnt from one feeder cannot be necessarily extrapolated to another. Two feeders can present different technical problems at different EV penetration levels. The feeders involved in the My Electric Avenue Project are analysed in this section to assess the impacts from EVs. This analysis is carried out for each season and for typical weekdays and weekends.

When considering the My Electric Avenue feeders, it was found that two feeders experienced thermal problems at some EV penetration level (Chiswick at 50% penetration and Chineham at 70% penetration); none of the My Electric Avenue feeders are found to present voltage problems. Both of these networks would require intervention at these penetration levels.

It should be noted that My Electric Avenue was field-testing a new technology. Therefore, care was taken to ensure trial networks had a high safety margin considering the number of EVs deployed and the risk that the new technology may not always work as intended. Consequently, the trial networks were considered to be robust with significant available capacity.

The representative LVNS networks were selected for usage because, at the outset of My Electric Avenue, they were the best available models for statistically significant representative LV networks. The LVNS networks are representative of one of GB’s DNO license areas (Electricity North West), and the proportion of that license area’s feeders represented is taken from the results of the LVNS Project12. The Transform Model, set out in Section 7, includes representative networks for GB as a whole. However, the Transform feeders are parametric, rather than nodal, models so were not suitable for load flow analysis20.

Of the representative LVNS feeders, four were found to require intervention at some penetration level, including LVNS Feeder 7 whose results are shown in Section 4.3.2. These four feeder types represent 22% of the LV feeders in one license area. The proportion of one license area’s LV networks represented by the eight urban LVNS feeders is taken from the results of the LVNS project12, whilst the rural networks representation is defined as part of EA Technology’s Transform Model®20. The EV penetration found to cause the first problem for each LVNS feeder is shown in Table 7.

22% of the LV feeders in one distribution license area will require intervention at EV penetrations levels up to 100%, and in some cases as low as 40%. It should be noted that these results are based on usage of the 3.5 kW/24kWh Nissan Leaf and consider only the LV feeder, not the transformer or higher voltage systems, and are constrained by the My Electric Avenue participants’ demographics.

Table 7: EV penetration level showing first technical problem for the representative LVNS networks, with the proportion of the ENWL LV networks represented by each LVNS feeder.

<table>
<thead>
<tr>
<th>LV Feeder</th>
<th>Proportion of ENWL License Area LV Feeders Represented</th>
<th>Winter</th>
<th>Spring/Autumn</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Weekday</td>
<td>Weekend</td>
<td>Weekday</td>
</tr>
<tr>
<td>Feeder 1</td>
<td>61.0%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Feeder 2</td>
<td>1.0%</td>
<td>70</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Feeder 3</td>
<td>4.0%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Feeder 4</td>
<td>1.0%</td>
<td>40</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Feeder 5</td>
<td>3.0%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Feeder 6</td>
<td>17.0%</td>
<td>50</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>Feeder 7</td>
<td>3.0%</td>
<td>70</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>Feeder 8</td>
<td>4.0%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rural 1</td>
<td>2.5%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rural 2</td>
<td>0.5%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4.3.4 GB Summary Results

The results summarised in Table 7, set out the EV penetration level at which different types of networks require intervention, to accommodate the increased demand. However, one license area is not representative of GB as a whole. In particular, the LVNS networks do not include meshed networks and do not represent the mix of urban, suburban and rural populations across GB.

The results presented in Section 4.1 have been used with the DNO industry Transform Model®. This model considers the impact of low carbon technologies (LCTs) on DNO networks at voltages of 33 kV and below. Using the EV load profiles, with randomised clustering, the outputs of Transform illustrate the network types susceptible to increased EV penetration. More detailed results from Transform, to quantify the cost saving associated with the Esprit solution are presented in Section 7.

By examining the Transform results, the susceptibility of different network types is shown. The properties of these networks are examined further in Section 6.2. It should be noted that Transform allocates different proportions of EVs to particular network types, dependent on the likely uptake of the technology and geographic limitations. The allocation of low carbon technologies to network types was completed by Smart Grid Forum Work Stream 3 and included projections for technologies enabling EV uptake, particularly on terraced streets20. The My Electric Avenue Project has not altered the projections for network specific EV uptake made by the Smart Grid Forum.

Table 8 shows the number of Esprit interventions for each Transform network type20, from this the impact of uncontrolled EV charging on GB LV networks is inferred. It can be seen that town centre and terraced street network types are particularly affected. However, rural and meshed networks are relatively unaffected. This supports the results set out in Section 4.3.3.

In summary, 32% of LV feeders (312,000 circuits) across GB are expected to require intervention due to EV uptake through to the end of ED4.

However, it is important to also consider which networks are likely to require intervention in the short term; and so merit immediate consideration. As shown in Table 10, very few interventions are required in ED1. However, each intervention carries a reputational risk for the DNO due to public interest in continuing uptake of LCTs. Therefore, short term action is needed to mitigate this risk and manage EV uptake, particularly on meshed new build residential networks.
### Table 8: Proportion of GB LV Network Types Requiring Intervention through to ED4 for the DECC High Abatement in Heat and Transport Scenario

<table>
<thead>
<tr>
<th>Network Type</th>
<th>Number of Networks in GB</th>
<th>Proportion of GB Feeders Represented</th>
<th>Number of Esprit Deployments for Network Type</th>
<th>Proportion of the network type with requiring intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV1 Central Business District</td>
<td>16,246</td>
<td>2%</td>
<td>2,762</td>
<td>17%</td>
</tr>
<tr>
<td>LV2 Dense urban (apartments etc)</td>
<td>50,099</td>
<td>5%</td>
<td>4,509</td>
<td>9%</td>
</tr>
<tr>
<td>LV3 Town centre</td>
<td>32,154</td>
<td>3%</td>
<td>28,778</td>
<td>90%</td>
</tr>
<tr>
<td>LV4 Business park</td>
<td>70,119</td>
<td>7%</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>LV5 Retail park</td>
<td>13,502</td>
<td>1%</td>
<td>270</td>
<td>2%</td>
</tr>
<tr>
<td>LV6 Suburban street (3-4 bed semi detached or detached houses)</td>
<td>122,765</td>
<td>13%</td>
<td>42,968</td>
<td>35%</td>
</tr>
<tr>
<td>LV7 New build housing estate</td>
<td>149,493</td>
<td>15%</td>
<td>8,970</td>
<td>6%</td>
</tr>
<tr>
<td>LV8 Terraced street</td>
<td>336,922</td>
<td>35%</td>
<td>213,945</td>
<td>63%</td>
</tr>
<tr>
<td>LV9 Rural village (overhead construction)</td>
<td>24,122</td>
<td>2%</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>LV10 Rural village (underground construction)</td>
<td>24,802</td>
<td>3%</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>LV11 Rural farmsteads small holdings</td>
<td>4,993</td>
<td>1%</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>LV12 Meshed Central Business District</td>
<td>6,179</td>
<td>1%</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>LV13 Meshed Dense urban (apartments etc)</td>
<td>13,284</td>
<td>1%</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>LV14 Meshed Town centre</td>
<td>11,677</td>
<td>1%</td>
<td>1,985</td>
<td>17%</td>
</tr>
<tr>
<td>LV15 Meshed Business park</td>
<td>12,096</td>
<td>1%</td>
<td>60</td>
<td>0%</td>
</tr>
<tr>
<td>LV16 Meshed Retail park</td>
<td>2,520</td>
<td>0%</td>
<td>13</td>
<td>1%</td>
</tr>
<tr>
<td>LV17 Meshed Suburban street (3-4 bed semi detached or detached houses)</td>
<td>26,208</td>
<td>3%</td>
<td>3,276</td>
<td>13%</td>
</tr>
<tr>
<td>LV18 Meshed New build housing estate</td>
<td>5,040</td>
<td>1%</td>
<td>25</td>
<td>0%</td>
</tr>
<tr>
<td>LV19 Meshed Terraced street</td>
<td>44,482</td>
<td>5%</td>
<td>-</td>
<td>0%</td>
</tr>
</tbody>
</table>

### Table 9: Proportion of GB LV Networks Requiring Intervention by through to ED4 for the DECC High Abatement in Heat and Transport Scenario

<table>
<thead>
<tr>
<th></th>
<th>Number of LV Feeders in GB</th>
<th>Proportion of GB Feeders Represented</th>
<th>Number of Esprit Deployments</th>
<th>Proportion of all networks requiring intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>All GB LV Networks</td>
<td>966,702</td>
<td>100%</td>
<td>307,561</td>
<td>32%</td>
</tr>
</tbody>
</table>
## Table 10: Proportion of GB Network Types Requiring Intervention in ED1 for the DECC High Abatement in Heat and Transport Scenario

<table>
<thead>
<tr>
<th>Network Type</th>
<th>Number of Networks</th>
<th>Proportion of GB Feeders Represented</th>
<th>Number of Esprit Deployments for Network Type</th>
<th>% of network type with intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV1 Central Business District</td>
<td>16,246</td>
<td>2%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV2 Dense urban (apartments etc)</td>
<td>50,099</td>
<td>5%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV3 Town centre</td>
<td>32,154</td>
<td>3%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV4 Business park</td>
<td>70,119</td>
<td>7%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV5 Retail park</td>
<td>13,502</td>
<td>1%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV6 Suburban street (3-4 bed semi detached or detached houses)</td>
<td>122,765</td>
<td>13%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV7 New build housing estate</td>
<td>149,493</td>
<td>15%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV8 Terraced street</td>
<td>336,922</td>
<td>35%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV9 Rural village (overhead construction)</td>
<td>24,122</td>
<td>2%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV10 Rural village (underground construction)</td>
<td>24,802</td>
<td>3%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV11 Rural farmsteads small holdings</td>
<td>4,993</td>
<td>1%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV12 Meshed Central Business District</td>
<td>6,179</td>
<td>1%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV13 Meshed Dense urban (apartments etc)</td>
<td>13,284</td>
<td>1%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV14 Meshed Town centre</td>
<td>11,677</td>
<td>1%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV15 Meshed Business park</td>
<td>12,096</td>
<td>1%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV16 Meshed Retail park</td>
<td>2,520</td>
<td>0%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV17 Meshed Suburban street (3-4 bed semi detached or detached houses)</td>
<td>26,208</td>
<td>3%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>LV18 Meshed New build housing estate</td>
<td>5,040</td>
<td>1%</td>
<td>25</td>
<td>0%</td>
</tr>
<tr>
<td>LV19 Meshed Terraced street</td>
<td>44,482</td>
<td>5%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Totals</td>
<td>966,702</td>
<td>100%</td>
<td>25</td>
<td>0%</td>
</tr>
</tbody>
</table>
4.3.5 Sensitivity to Clustering

The impact of unconstrained EVs on GB distribution networks can be further understood by considering the impact of clustering. This analysis indicates further networks with sensitivity to increased EV penetration, during RIIO-ED1.

The Transform model includes an assumed level of clustering: LCTs are distributed unevenly and so the impact of technologies not uniform. Each LCT has an assumed level of clustering, principally based on the data from Feed-In Tariff (FiT) register. The level of clustering considering is shown in Figure 28, which illustrates how clustering is applied to the relative distribution of LCTs. In the scenario without clustering, EVs are allocated uniformly across GB networks; whereas, in the high clustering scenario a large proportion of EVs are connected to a small proportion of GB networks. The FiT scenario refers to the default assumption used by Transform, which is that LCTs cluster at the level shown by the FiT register.

Transform models were run with varying levels of clustering applied to EVs. For the baseline level (no clustering) the total cost network interventions was calculated for the RIIO-ED1 period. For each of the other clustering levels the variation in total cost of intervention during ED1 was calculated, for each LV network type, see Figure 29. The variation in total cost of intervention is solely attributable variation in EV clustering. This result indicates the likely impact of significant clustering of EVs, and highlights those network types which are most sensitive.

The results in Figure 29 show that three network types will require different interventions during the ED1 period, if significant clustering of EVs occurs; these are rural village networks (both underground and overhead construction) and meshed new build housing estates. It is important to note that the cost of intervention will both increase and decrease, as increased clustering will require intervention on fewer networks and EVs may enhance or mitigate the impact of other LCTs.

![Modelled Variation in Clustering](image-url)
Both types of rural networks show a reduced cost of intervention with increased EV clustering, indicating a positive interaction with other LCTs. This further supports the results shown in Section 4.3.3 which show that rural networks are relatively unsusceptible to increased EV penetration. Indeed, these results indicates the impact of EVs on rural networks may be to reduce the requirement for reinforcement during ED1. However, the limitations of this result to 3.5 kW charging should be noted.

The meshed new build housing estate network type (LV18) should be regarded as the focus for EV interventions during ED1 as increased clustering is shown to increase the total cost of intervention during ED1. This reinforces the result shown in Table 10, which shows Esprit is likely to be cost effective for this network type in the next five years.

![Impact of Clustering Interventions Cost during RIIO-ED1](image)

**Figure 29:** Variation in total cost of intervention during RIIO-ED1 for different LV network types, as a result of variation in clustering level.
5 Evaluation of the Technology through Trial Results

This section sets out the summary of practical learning from operation of Esprit throughout My Electric Avenue. Section 6 contains the detailed analysis, based on work by the Project’s academic partners, including calculation of headroom, approaches for deployment, and network limitations. The points in Section 4.3.5 relate to the practical performance of the Esprit hardware at the time of My Electric Avenue and supplement the detailed learning from installation set out in the SDRC 9.7.1 report.

5.1 Esprit Performance

One of the aims of the My Electric Avenue Project was to determine if the technology utilised within the trials, Esprit, was capable of providing benefits to the network to alleviate the need for traditional reinforcement.

The Esprit technology was manufactured under licence by a third party that specialised in Power Line Carrier (PLC) communication equipment. The control algorithm and functional requirements were provided to the PLC specialists who adapted pre-existing proprietary hardware to deliver the required functionality. The precise logic embedded within the control algorithm was described but was withheld due to intellectual property restrictions.

The control logic implemented was simplistic, but sufficient to test the concept of Esprit on the wider LV network, utilising three control cycles responding to the status of the low voltage (LV) network being monitored.

1. When in a monitoring state, the control system monitored the phases of the connected LV feeder for the load to exceed a pre-determined threshold.
2. If this threshold were breached, the system would move into a curtailment mode, seeking to reduce load on the network whilst continuing to monitor it.
3. Once network load has dropped below a lower, pre-determined threshold, the system would begin re-enabling charging for connected EVs.

A test system was established at EA Technology offices in Capenhurst to verify readings reported by the equipment installed in the trial clusters. This enabled the system to be operated under controlled conditions enabling verification of the software capability and effectiveness.

The Esprit system was found to be capable of delivering the core requirements, specifically:

- Monitor load on the LV network.
- Determine if action is required to alleviate network stresses.
- Implement that action and reduce network load.

However, effective operation of the system was found to be erratic due to a combination of both the unreliability of PLC for communication of control signals, and the need for further refinement of the control software.

PLC communications were found to work well in situations where the transmission distance was relatively short or where penetration levels were high providing multiple communication paths. If communications failed, either for triggering curtailment or re-engaging charging, the control system was unable to adapt to the unanticipated behaviour. Software issues were experienced as well however as other unanticipated behaviours were experienced under the controlled test conditions where PLC failure was not a factor.
Overall, prior to wide scale deployment the control algorithm implemented by the manufacturer would require refinement or replacement to be capable of responding appropriately to changing situations. With respect to communications, PLC can be an effective method where high penetration of communication equipment can be achieved but this is unlikely to occur before network load requires mitigating. A report setting out the My Electric Avenue Project learning on usage of PLC is available in support of SDRC 9.8

Therefore we conclude that Esprit as a system concept holds great potential to manage future network loads. But it requires integration to an effective means of communication and further development of the control logic.

5.2 Customer Acceptance of Commercial Operation

This document sets out the technical impact of Esprit and does not consider the customer acceptance in detail; this is set out in the SDRC 9.6.1 report. However, in the case of the commercial customers there were sufficient objections to the Esprit control to alter the planned Esprit thresholds. Therefore, this learning is presented with the results of the technical trials, in addition to the more detailed market research set out in SDRC 9.6.1.

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Figure 30: Average load profile for the Your Homes commercial feeder.

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The commercial load profile seen on the Your Homes feeder was the primary reason for this customer response. The load profile, which is typical of commercial demand, is shown in Figure 30. The morning and evening peaks, typical of domestic demand, do not occur and the daytime load is relatively consistent. As a result, the thresholds applied to Your Homes for the purpose of ensuring operation of Esprit mostly resulted in curtailment operating throughout the working day; or not at all. This was exacerbated by the use of a hysteresis value which was applied to avoid ongoing oscillation between curtailment and non-curtailment modes.

However, the resulting operation was such that once the threshold was exceeded, the majority of the working day passed before current fell below the threshold required (original threshold minus 17 A) to end curtailment. The result of this mode of operation was that there was minimal capacity to be shared between small numbers of customers. It is expected that where a greater capacity is shared between the EVs, operation on commercial networks will be more acceptable to customers.

Therefore, we conclude that the control logic, deployed in the current version of Esprit, is not sufficient to maintain customer satisfaction on commercial feeders, with flat load profiles and low capacity for EVs.

5.3 Practical Learning to Apply Beyond My Electric Avenue

A number of learning outcomes were delivered through the operation of Esprit which relate to the practical implementation of Esprit, or similar demand side response (DSR) technologies; these are briefly set out:

5.3.1 Communications

Throughout the My Electric Avenue Project, difficulties were encountered with the communications between substation and customer. Whilst the communication was sufficient for the operation of the trial, it would prove a significant limitation to a wider roll-out of Esprit. EA Technology undertook analysis in an attempt to establish the cause of the communications difficulties, and mitigate them where possible. The outcome of this analysis is documented in the review of power-line carrier (PLC) communications published in support of this SDRC. Average communication reliability, defined as the proportion of operational time for which a valid measurement was available, across My Electric Avenue was 68%. It is not expected that this would be sufficient for business-as-usual operation of Esprit and we recommend that future implementations of the technology utilise an alternative communication system, or operate with much higher penetration of PLC devices on the network.

5.3.2 Control Logic

My Electric Avenue deployed a version of Esprit which switched all EV chargers off when the defined load threshold was exceeded on the feeder. After all chargers were switched off, they were cycled one-by-one to enable charging to continue. This system was robust and simple which allowed for reliable monitoring of the system, understanding of customer response and demonstration of the core functionality. However, customer feedback – particularly from the commercial customers – has proved that customers will not tolerate EV charging restrictions indefinitely.

Therefore, as expected at the outset of the trial, we recommend that future implementations of Esprit employ a more dynamic approach which would allow the maximum number of EVs to charge, within the limitations of the LV network’s capacity. This approach is reflected in the University of Manchester’s modelling of Esprit’s capabilities (Section 6).
5.3.3 Direct Feedback to Customers

Anecdotally, My Electric Avenue participants have reported occasional frustration at not having a mechanism to determine easily whether the EV is being curtailed, has completed charging, or is not correctly connected. We recommend that future implementations of Esprit include a simple user interface to allow customers to view the operation of Esprit. This recommendation is reinforced by the positive customer response to similar user interfaces in other LCN Fund Projects, such as Western Power Distribution’s SoLa BRISTOL.  

23 http://www.westernpowerinnovation.co.uk/Projects/SoLa-Bristol.aspx
6 Technical Benefits and Disadvantages of the Technology

**T1.2: What are technical benefits and disadvantages of the technology?**

My Electric Avenue’s technical aim T1.2 is sub-divided into the aims discussed in each of the following sections and is met by the combination of Section 6 and SDRC 9.7, which considered Technical Aim 1.2.4.

6.1 How Much Headroom Is Released?

**SDRC 9.8.1: Modelling to understand additional headroom available / other network benefits from using the Technology**

**SDRC 9.8.1a: The models will assess the % of thermal and voltage headroom estimates produced.**

**T1.2.1: How much headroom is released?**

Based on the LV network models, EV and domestic load profiles set out in Sections 4.2 and 4.3, My Electric Avenue’s academic partners modelled the impact of Esprit in mitigating the technical problems caused by increased uptake of EVs on the LV networks, set out in Section 4.3. This section presents the Esprit algorithm considered, followed by the benefits in terms of overcoming thermal and voltage problems and in terms of the associated network benefit of reducing losses.

6.1.1 The Modelled Esprit Algorithm

This section details the Esprit control algorithm that is modelled for the management of EV charging points to mitigate thermal problems on LV feeders. The mitigation of voltage problems and thermal problems at the transformer are not considered in this report. However, this was thoroughly investigated by My Electric Avenue’s academic partners and is summarised in Section 9 as additional learning.

The control algorithm considered in this section checks for thermal problems at the head of the feeder, for each phase, for every control cycle; this is similar to both the control algorithm deployed in the trials, and some more sophisticated theoretical options. At each control cycle, the algorithm measures the average phase current at the head of the feeder and notes whether each EV is charging. The latter is used to establish the time between the start of a charging event and its uncontrolled end, at which point the counter is reset. This internal counter is used to define the most suitable EVs to curtail.

6.1.1.1 Disconnection

When the control algorithm detects a need to mitigate thermal problems, the controller calculates the number of EV charging points needed to reduce the phase current to below a corresponding threshold. If the phase current on phase $i$ ($I_{\phi,i}$) at the head of the feeder exceeds a threshold $\alpha$ (expressed as a percentage of the cable capacity $I_{\phi,i}^{\text{max}}$) the control algorithm determines the number

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of EV charging points, \( X_i \), that must be disconnected on phase \( i \) to mitigate the thermal problem. This is defined in (1):

\[
X_i = \left\lceil I_{\phi,i} - I_{EV} \alpha I_{\phi,i}^{max} \right\rceil
\]

where the bracket \( \lceil \cdot \rceil \) represents the ceiling function (i.e. rounding up), and \( I_{EV} \) is the phase current of an EV (16A in the case of a Nissan LEAF, assuming 3.5 kW and 230 V). This process is repeated for each of the phases of the feeder.

Once the number of EV charging points to be switched off is calculated, the next step is to decide which EV charging points to curtail. The control algorithm selects those at the top of a ranking list based on the corresponding charging times, adopting a first-in first-out approach. Once the EV charging points to be disconnected are known, the corresponding EV charging points are disconnected one minute later. In practice, the one minute delay would correspond to communications and switching actions.

### 6.1.1.2 Reconnection

If no thermal problems are detected at the start of a control cycle, some EV charging points are reconnected, with consideration given to a security margin. To achieve this, the controller calculates the number of EVs that can be connected with a resultant total phase current below the defined threshold, including security margin.

If the phase current, \( I_{\phi,i} \), in the feeder is below a security margin, \( \beta \), a number of EV charging points, \( Y_i \), that can be reconnected is defined by (2):

\[
Y_i = \left\lceil \frac{(1 - \beta) I_{\phi,i}^{max} - I_{\phi,i}}{I_{EV}} \right\rceil
\]

The security margin, \( \beta \), allows for the accommodation of the connection of other loads, including EVs, to that phase of the feeder. For simplicity, \( \beta \) is always set 10% below \( \alpha \) in this report. Once the number of EV charging points to be reconnected is defined, the control algorithm determines the most suitable ones using an inverse ranking to that used for disconnection (i.e. those EVs with the lowest charging durations are those to be reconnected first). Once the EV charging points to reconnect are calculated, the corresponding EV charging points are reconnected after one minute.

### 6.1.2 Example Result – Chiswick Cluster

Example results are shown for Phase C of the My Electric Avenue Chiswick cluster, with detailed results for other clusters shown in the relevant My Electric Avenue outputs\(^8\),\(^9\). In the model, the phase current at the head of the feeder, voltage at customer connection points, and energy losses are quantified. These metrics are used to assess the technical benefits of the Esprit control algorithm in managing EV charging points; this follows the approach set out in Section 4.2.

It was assumed that the line-to-line voltage equals 424 V (1.06 p.u.). The control cycle was defined to be 10 minutes as this was determined as the most appropriate timing when considering the multiple factors affected by the control system, namely:

- Thermal constraints of the distribution network
  - Overhead lines heat up and cool down very quickly (in the order of minutes), so long cycle times risk extended thermal overload of these assets.
  - Buried cables heat up and cool down slowly (in the order of at least 30 minutes), so short cycle times require excessive control signals and monitoring for little benefit.
• Nissan recommended that the cycling of EV charging is not implemented more frequently than every six minutes to prevent, or minimise damage to the batteries.

The limitations on the control cycle are discussed in detail in SDRC 9.7. The disconnection threshold, \( \alpha \), is set to 1 (i.e. the asset’s thermal limit) and the security margin for reconnections, \( \beta \), is defined as 0.1 (i.e. 10% below the asset limit).

### 6.1.2.1 Thermal Results

The modelled winter demand for phase C of the Chiswick cluster, assuming 100% EV penetration, is shown in Figure 31. It can be seen that the exceedance is reduced from 120 A above cable thermal limit to 20 A above the limit. This represents a significant shift in load from the evening peak to the overnight period. However, this is not sufficient to mitigate the exceedance of the LV cable thermal limit and a lower threshold is required for the analysis shown in the remainder of this section.

![Winter Weekday Modelled Impact of Esprit on Thermal Capacity (Phase C)](image)

*Figure 31: Esprit impact on cable thermal overload for winter weekday for Phase C on the My Electric Avenue Chiswick cluster, where EV penetration = 100% (threshold defined as equal to cable thermal limit).*

### 6.1.2.2 Voltage Results

The modelled minimum customer voltage, assuming 100% EV penetration, is shown in Figure 32 both with and without Esprit. It should be noted that the Chiswick feeder does not show any customer with voltage problems for any of the penetrations and seasons analysed (see Section 4.3). Therefore, it was not expected that Esprit would significantly shift the customer voltages. However, the effect of managing some EV charging points can be seen in the voltage profile in this feeder. In general, the voltages are increased during peak time by use of Esprit, given that the demand is managed.
6.1.2.3 Loss Results

The objective of the Esprit system is to avoid thermal problems. To achieve this, it manages the demand. Although the control algorithm is designed to shift demand, it is important to understand the extent of other network benefits which are generated (i.e. energy losses).

The modelled results for energy losses, assuming 100% EV penetration, are shown in Figure 33. The results for increasing penetration, for a winter weekday are shown. It can be concluded that the energy losses are reduced slightly by the use of Esprit: on average, the energy losses are reduced by 9% at high EV penetration levels.
6.1.3 Thermal Headroom Created

The results shown in Figure 31 demonstrated that an Esprit threshold equal to the thermal limit of the circuit is not sufficient to mitigate thermal overload. Therefore, Esprit requires dynamic settings to completely mitigate thermal overload on LV networks. The following analysis assumes that each feeder has a threshold defined by equation (3).

\[
\alpha = \frac{1 - \alpha_{150\%}}{EV_{no\ problems} - 150} \left( EV_{penetration} - EV_{no\ problems} \right) + 1
\]  

(3)

This approach defined the penetration at which no thermal problems are experienced, \( EV_{no\ problems} \). The disconnection threshold which completely mitigates thermal problems for the highest EV penetration, \( \alpha_{150\%} \), was calculated on a trial and error basis. Then, the disconnection threshold \( \alpha \) was defined using the linear relationship between EV penetration and required threshold. In general the utilisation factor of the feeder increases linearly with the penetration level.

Assuming dynamic Esprit thresholds, results showing the calculated threshold and resulting thermal headroom gained, for each of the four affected LVNS networks, are shown in Appendix B.
### Table 11: Thermal Headroom delivered for LVNS feeders by Esprit.

<table>
<thead>
<tr>
<th>Feeder</th>
<th>EV Penetration of First Thermal Problem</th>
<th>Winter Esprit Threshold</th>
<th>Maximum Thermal Headroom Gained (i.e. exceedance at 150% Penetration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNVS 2</td>
<td>70%</td>
<td>$\frac{1 - 0.7(\text{EV penetration} - 60)}{60 - 150} + 1$</td>
<td>17%</td>
</tr>
<tr>
<td>LVNS 4</td>
<td>40%</td>
<td>$\frac{1 - 0.7(\text{EV penetration} - 30)}{30 - 150} + 1$</td>
<td>46%</td>
</tr>
<tr>
<td>LVNS 6</td>
<td>50%</td>
<td>$\frac{1 - 0.7(\text{EV penetration} - 40)}{40 - 150} + 1$</td>
<td>40%</td>
</tr>
<tr>
<td>LVNS 7</td>
<td>70%</td>
<td>$\frac{1 - 0.7(\text{EV penetration} - 60)}{60 - 150} + 1$</td>
<td>12%</td>
</tr>
</tbody>
</table>

Given dynamically calculated thresholds, it has been shown that thermal problems can be completely mitigated on the representative LVNS networks, delivering thermal headroom of up to 46%.

### 6.1.4 Voltage Headroom Created

As shown in Section 4.3, the Esprit algorithm targeted thermal exceedances and did not actively attempt to mitigate voltage problems. This approach was supported by thermal problems occurring at lower EV penetration levels than voltage problems, and the increase in voltage expected when Esprit acted to mitigate thermal problems. This approach was able to mitigate a number of voltage problems, but did not remove them entirely.

Figure 34 and Figure 35 show the number of LVNS feeders affected by thermal and voltage problems, with and without Esprit. These results are expanded in Table 12, for the three LVNS feeders that present voltage problems (LVNS feeders 4, 6 and 7). With Esprit prioritising thermal constraint, an additional headroom of 10% EV penetration is delivered, this corresponds to between 7 and 16 additional EV connections, depending on the feeder type. On average, the number of affected customers is reduced by 56%, for the worst case penetration level considered.

Esprit has the capability to mitigate voltage problems delivering an additional voltage headroom of 10%, despite an algorithm targeting thermal limits. However, a more sophisticated algorithm, which responds to customer voltage readings would be necessary to completely mitigate voltage problems due to EV uptake.
Figure 34: Count of representative LVNS feeders with thermal and voltage problems for increasing EV penetrations, weekdays.
Figure 35: Count of representative LVNS feeders with thermal and voltage problems for increasing EV penetrations, weekends.
Table 12: Voltage support provided by Esprit for the representative LVNS feeders.

<table>
<thead>
<tr>
<th>Feeder</th>
<th>Number of Residential Customers</th>
<th>EV Penetration at First Voltage Problem</th>
<th>Non-compliant Customers at 150% EV Penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without Esprit</td>
<td>With Esprit</td>
</tr>
<tr>
<td>LVNS 4</td>
<td>101</td>
<td>40%</td>
<td>50%</td>
</tr>
<tr>
<td>LVNS 6</td>
<td>76</td>
<td>40%</td>
<td>50%</td>
</tr>
<tr>
<td>LVNS 7</td>
<td>167</td>
<td>90%</td>
<td>100%</td>
</tr>
</tbody>
</table>

6.1.5 Network Losses

The other network benefit associated with the use of Esprit is a reduction in network losses, as shown in Section 4.3.2.3.

The results shown in Appendix B show a reduction in losses for the LVNS feeders of 9% on average, at high EV penetrations.

6.1.6 Commercial LV Networks

Despite the difficulties in operating Esprit on the My Electric Avenue commercial feeder (see Section 5.2), Esprit has been found to have the technical capability to allow a significant increase in the number of connected EVs.

However, work is required in order to improve customer acceptability prior to deployment. An extract of the results shown in My Electric Avenue’s academic outputs is shown in Figure 36 to illustrate the performance of Esprit for the Your Homes cluster.

The demand (per phase) and the EV charging behaviour was produced using the EV usage data for this cluster. Only weekdays were considered for this LV feeder given its commercial use. Two scenarios were investigated, considering different Esprit thresholds. Firstly, disconnection threshold and security margin were defined as $\alpha = 1$ and $\beta = 0.1$ (similar to the control settings demonstrated in Section 6.1.2). Secondly, the threshold $\alpha$ and security margin $\beta$ are set to be 0.9 and 0.2, respectively. The latter is done to demonstrate the effectiveness of the Esprit-based control algorithm in completely mitigating thermal problems in commercial LV feeders. Both cases consider a control cycle of 10 min. Figure 36 demonstrates that the Esprit-based control algorithm presented here can be adopted to effectively manage EV charging points in commercial LV feeders.
Esprit has been shown to be capable of mitigating thermal constraints on commercial networks and would allow connection of at least 30 additional EV chargers at the My Electric Avenue Your Homes cluster. However, development is needed before such control is acceptable to customers.

6.2 On What Type of Networks Can the Technology be used?

This section seeks to answer the question ‘On what types of network can Esprit be used?’ It reports on the analysis of networks where Esprit can provide mitigation against the effect of increasing concentrations of EV charging on LV feeder loading, and identifies those networks where it will not cause problems.

There are two perspectives that require consideration:
1. The first relates to the algorithm: Esprit defines an algorithm, based on local substation feeder load measurements and information from intelligent control boxes (ICBs) attached to car charging points on that same feeder, which reduces car charging load at times of network stress (see Section 6.1.1).

2. The second relates to the communication medium: The implementation of Esprit in this Project uses power line carrier as the two-way communication mechanism between the monitor controller in the substation and the ICBs at the charging points. As this uses the network itself, the physical attributes of that network become relevant for consideration.

6.2.1 The Esprit algorithm

| The Esprit algorithm has been found to be effective in managing thermal constraints and partially effective in managing voltage constraints, resulting from the growth of electrical vehicle charging load on all the types of networks studied apart from one. |

Unsurprisingly, as the algorithm essentially seeks to smooth the increased demand over a longer period and away from peak periods, it is successful in networks with feeder loads that exceed the nominal thermal limit (cable rating) for a period that is shorter than the total period over which sufficient car charge is expected to be delivered. Happily, this is the case for all the domestic networks studied, in both technical trial measurements and representative modelling, see Figure 37.

Using validated network models and a 10 minute Esprit algorithm cycle time, the academic work by the University of Manchester extrapolated the Project results out to a representative selection of GB LV network construction types – overhead, underground, rural, urban and suburban.

| The Esprit algorithm was found to be suitable for constraint mitigation on all physical types of networks. |

A particular output of the analysis was that there was significant benefit in reducing the set-point at which control actions were initiated by the monitor controller to a value less than the thermal limit (α<1). Whilst this initiated more control actions on more days, it significantly increased the number of chargers that could be accommodated on the affected networks.

In managing the thermal constraints, the Esprit algorithm is also managing voltage constraints as load-related voltage drops across the feeder are also reduced at peak times. Studies performed on validated network models by the University of Manchester team found that, for the representative sample of UK LV feeders, thermal issues preceded voltage problems as the limiting factor for the population of EVs that could be supported. Whilst it is possible for the Esprit algorithm to be modified to respond to low voltages reported from (ICBs) as well as feeder load, the benefits of this additional complication appear not to be warranted for the vast majority of networks.

| As discussed in Section 5.2, the Esprit algorithm was found to be not successful in providing customer-acceptable mitigation on the industrial/commercial feeder with a flat load profile and low available capacity to allocate to EVs. |
The modelling work performed during the Project and results recorded from the trial site show that constraint management on feeders supplying commercial customers was technically effective, using the Esprit algorithm. However, the My Electric Avenue trial also considers the social (customer) acceptability of this demand response intervention. Here, on the workplace feeder included in My
Electric Avenue, the extended curtailment over the period when charging was required, due to the flat profile of the feeder load, was found to be unacceptable.

Although not part of this Project scope, an associated piece of academic work\textsuperscript{25} showed that the Esprit algorithm, when applied to measurements of transformer load, would also be successful in mitigating transformer overloads likely to be reached in advance of feeder overloads on a higher proportion of UK LV networks as EV penetration increases (this is summarised in Section 9.2).

\subsection*{6.2.2 Implementing Esprit with power line carrier communications}

The implementation of Esprit using power line carrier presented a number of problems during the Project. However, the type of network (physical construction) was only found to directly impede communications in one isolated instance: A mains branch joint in the South Shields 1 network appeared to block PLC signals\textsuperscript{21}, with even short range communications being ineffective. No other joint or feeder component acted in this way. The power line carrier worked to some degree over all the feeder topologies in the 10 trial networks apart from this one. Negative correlations were found between communication reliability and distance between the ICB and substation and the feeder loading. These correlations indicate against using the present implementation of this communication mechanism with the level of ICB penetration trialled. The ICBs act as power line carrier repeaters and it is possible that higher concentrations would bring the communication reliability up to a level acceptable for a network demand management system such as Esprit. PLC has been found to be effective with very high penetrations. For example, the Iberdrola Smart Meter roll-out in Spain is using PLC as the communication technology successfully\textsuperscript{26}.

\subsection*{6.2.3 Networks where EV load mitigation will be required}

In considering where Esprit could be beneficially applied, it is worth pointing out that many of the feeders studied, both in the trial and the representative GB networks used for extrapolation, could accommodate the full complement of 150\% penetration of EV chargers studied without Esprit or other mitigation. Two of the nine technical trial feeders and four of the nine UK representative feeders (representing 22\% of GB LV feeders) were predicted to have cable rating exceedances.

A good first indicator of the networks where load growth (expected to result from increasing numbers of EVs) would be an issue, was found by estimating the remaining headroom per customer for the network feeders in areas where home charging was viable (typically considered to be areas with off-street parking). Using the residential After Diversity Maximum Demand (ADMD) formula generated in the Customer Led Network Revolution Project\textsuperscript{27}, the number of customers per feeder (n) and the rating of the first section of cable from the substation (R), the estimated remaining headroom per customer is:

\begin{equation}
\text{Remaining headroom per customer} = \frac{R - n \times \text{ADMD}}{n - 1}
\end{equation}


Remaining Headroom per Customer (kVA) = \frac{R}{n} - ADM_{\text{residential}} \tag{4}

where

\[ ADM_{\text{residential}} = 4.6(n^{-0.22}) \tag{5} \]

A remaining headroom per customer of less than 1.5kVA is observed to be associated with the feeders that cannot accommodate full penetration of EVs using the studies performed in the My Electric Avenue Project.

A similar analysis would be relevant also for predicting future network stress from transformer loading.

6.3 How close to the Thermal Rating should Load be Before Deployment?

T1.2.2: How close to the thermal rating should load be before deployment?

6.3.1 “Just in Time” Deployment of Esprit

In order for an Esprit type technology to be effective, it must be available to mitigate the impact of load growth ahead of the time of the first network problems.

Esprit should be installed so as to mitigate increased numbers of EVs on a feeder specific basis, by anticipating uptake and acting “just in time”, noting the technology’s lead time. The social and technical trials have shown no reason to install Esprit ahead of this requirement.

My Electric Avenue’s technical assessment (see Section 6.1) showed that thermal problems are the first network problems to occur as a result of increased EV penetration. Esprit’s manufacturer, for the current iteration of the system, has indicated a lead time of up to 12 weeks. Therefore, an ideal scenario would be to install Esprit 12 weeks prior to the date of the first exceedance of the LV feeder’s thermal ratings, or for DNOs to carry sufficient inventory of Esprit systems to initiate immediate action.

The following, feeder specific, information would be required to deliver this scenario:

- Number of EVs on the feeder
- Number of EVs at which the feeder’s thermal capacity would be exceeded
- Rate of uptake of EVs for other customers on the feeder

With sufficient modelling and customer engagement it is possible for a DNO to make this judgement for each feeder susceptible to increased EV penetration. The following example, for My Electric Avenue’s Chiswick cluster, illustrates one possible approach:

- At the time of writing, 8 of the Chiswick feeder’s 149 customers have an EV (i.e. 5% penetration).
- University of Manchester’s modelling indicates that the thermal rating will first be exceeded when EV penetration reaches 40%.
- If the customers on the Chiswick feeder follow the national EV uptake projections, set out in the National Grid Future Energy Scenarios³, the Chiswick feeder will reach 40% penetration by 2019 (note that customer engagement would be required to verify this assumption).

Therefore, in order to mitigate the additional demand due to EVs at Chiswick, Esprit would need to be installed in September 2018 to allow for a (worst case) 12 week lead time prior to successful
implementation which would be complete before December 2018 (i.e. the beginning of winter 2019).

In principle, this approach could be adopted for planning purposes on any LV feeder, where a DNO is aware of the number of installed EVs, the current load and feeder rating, and the customer uptake rate of EVs. However, the average growth at a national level is likely to be very different from the uptake at a local level. In addition, it is not currently possible for a DNO to access detailed information on local EV penetration.

Therefore, whilst this analysis answers Technical Learning Outcome T1.2.2 and is informative, it does not support DNO engineers in determining which LV feeders require intervention or when the intervention is required.

The analysis set out in Section 7 shows the likely number of interventions where Esprit will be the most cost effective solution for LV networks across GB. This is the industry standard approach for planning investment at a strategic level. However, at a planning level, a more detailed approach is required to determine whether to reinforce a particular LV network and with what tools.

6.3.2 Information Available to Network Planners

Following consultation with LV designers, the following information sources were identified as those presently available to assess if an LV feeder requires reinforcement:

- annual variation in the reading of the Maximum Demand Indicator (MDIs) for each 11 kV/LV substation
- customer input on power quality or voltage problems
- operation of LV fuses
- winter and summer static and cyclic rating for the LV feeder and rating of the associated protective fuse

In addition to these items, a number of initiatives are underway which have the potential to deliver new data relating to the operation of the LV network or customer EV uptake:

- Enhanced monitoring of LV feeders and substations\textsuperscript{28,29,30}
- Processes obliging installers of EV chargers to inform DNOs, similar to the process by which installers of distributed generation are required to inform DNOs under Engineering Recommendation G83\textsuperscript{31}. The Project has recommended a new process for DNOs to follow\textsuperscript{32}, making use of this information to determine when to deploy Esprit.

\textsuperscript{28} SSEPD (2013) "Demonstrating the Benefits of Monitoring Low Voltage Network with Embedded PV Panels and EV Charging Point” \[\text{http://www.smarternetworks.org/Files/Benefits_of_Monitoring_LV_Networks_130327132144.pdf}\]
\textsuperscript{29} ENWL “Customer Load Active System Services (CLASS)” \[\text{http://www.enwl.co.uk/class}\]
Other LCN Fund projects showed that data on the operational performance of LV networks is sparse under present working practices. DNOs typically allow LV networks to operate passively, ensuring their safe operation by design. This approach has historically represented the most cost-effective method for operating LV distribution networks. However, in situations with rapid change in network usage, the lack of data poses challenges.

It is neither desirable to reinforce all LV networks which may be affected by an EV cluster, nor to wait to act until there is a possibility of damage to the network. Due to the limited data, and associated uncertainty regarding particular LV feeders, we propose the following approach to deploying Esprit, or other solutions, to mitigate EV demand.

6.3.3 Proposed Approach

We propose an approach, summarised in Figure 39, which involves a phased deployment of Esprit. Rather than intervening on an LV network based on available headroom, intervention is planned at the first opportunity, given the sparse available information. This leads to a three stage approach:

1. "Business as Usual": routine information gathering and processing
2. "Monitoring": requires installation of equipment to assess the extent of any problem
3. "Intervention": selection of the most cost effective intervention, and if Esprit is selected, monitoring performance to ensure value for money

This approach does not directly align with that set out in the My Electric Avenue Project Direction at the outset of the Project (i.e. at what headroom should Esprit be deployed?). Rather, it captures the uncertainty in the available information to propose deployment of Esprit aligned with current practice, available data and likely future developments.

The text below details the results of My Electric Avenue which enable this workflow, and considers the various decision points which are implied.

6.3.3.1 Data Available to Assess Network Requirements

During the "Business as Usual" phase of operation, the conventional data sources are customer input, operation of LV fuses and variation in Maximum Demand Indicators (MDIs). As these data become available, it is likely that a need for further investigation or immediate intervention will be recognised and initiated. In effect, the presence of data – using current data sources – indicates a potential need to intervene on the LV network.

Likely future scenarios, based on LCN Fund projects and work by the ENA, include increased availability of data regarding both LV network operation and changing customer behaviour. However, there is a gap between collection of data and obtaining the knowledge necessary to direct intervention. My Electric Avenue results showed the following thresholds for intervention:

- Some networks require intervention at 40% EV penetration (Section 4.3)
- Networks with capacity per customer below 1.5 kW are likely to be affected (Section 6.2)

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32 My Electric Avenue (2015) "An assessment of third party delivery of a low carbon innovation project (SDRC 9.2 & 9.3)"
• Particular network types which are most susceptible (Section 6.2)

However, these results cannot be readily compared with the operational data, held by DNOs, on LV networks.

It is recommended that a suitable tool for mapping network sensitivities is developed in conjunction with improvements to data regarding customer behaviour and network operation. Such a tool would need to process the available data and generate the knowledge to notify a DNO of a potential problem. It is not in the scope of My Electric Avenue to specify this network sensitivity tool. However, a number of My Electric Avenue results support development of such a tool and the workflow proposed here.

The following results of My Electric Avenue increase the information available to network planners in assessing the reinforcement of LV networks.
Figure 39: Proposed Approach to Deployment of Esprit. Information currently available is shown blue; information likely to become available is shown in grey.
6.3.3.1.1 Change in Cable Rating

LV cables are typically rated using seasonal cyclic ratings; this methodology recognises that the operating temperature of a cable is a function of the demand over a period of hours and is influenced by the ground conditions. Equivalent analysis is conducted for LV overhead lines because the thermal time constant of overhead lines is significantly lower than underground cables, negating the use of cyclic ratings.

For underground cables, it was expected that the variation in load profiles shown in Section 4.1.2 would result in a change to the cyclic ratings of LV cables. The load profiles, calculated by the University of Manchester were converted into hourly averages for processing by EA Technology’s cable rating tool CRATER.

Four load profiles were considered, and are shown in Figure 40:

1. ELEXON Residential Load Profile (LLF = 0.3360)
2. ELEXON Residential Load plus one EV per household (LLF = 0.3459)
3. ELEXON Residential Load plus one EV per household with Esprit like control (LLF = 0.4664)
4. "Load Curve G" the industry standard load profile for cable rating calculations (LLF = 0.5061)

The Loss Load Factor (LLF) indicates the variation from a sustained rating to cyclic rating for the load profile shown. It can be seen that increased EV usage flattens the load profile, increasing the area under the curve (even when normalised to 1), and increasing the LLF. Therefore, it was expected that the cyclic rating would be reduced from the typical residential load profile to that including EV usage.

The change in rating is shown as the difference between the static and cyclic ratings for the four cable types used in the My Electric Avenue clusters (Figure 41). The change in load profile results in a reduction in cable cyclic ratings of 4.3% from residential load to that including one EV per household. If this load is managed by Esprit then a feeder specific reduction in cyclic ratings is
expected. For example, if a threshold applied to the load profile shown in Figure 15 to reduce peak load by 10%, resulting in an evening curtailment of 2.5 hours duration, a reduction in cyclic rating of 8.3% should be applied.

The change in rating is a function of the load profile, not its peak value and applies regardless of the associated increase in load. This is one factor to be considered when assessing whether an LV network requires intervention. Depending on the level of accuracy required, specific cable ratings may be calculated when reviewing an LV network.

It should be noted that all cases show ratings greater than those calculated using Load Curve G. Load Curve G was created in 1976 from 11 kV load so it is unsurprising that the result is different for 2014/15 residential demand. However, these results suggest that some tolerance is included in any LV residential cable rating calculated using Load Curve G.

6.3.3.1.2 Increase in ADMD

As shown in Section 4 EV load results in an increase in ADMD of 1.2 kW where large numbers of EVs are connected. Where customer numbers are smaller, such as for an LV feeder, a formula for EV demand can be given in a similar format to that produced by Northern Powergrid in the CLNR Project. These results are combined to give a total ADMD given by (6):

\[
ADMD = 4.6 \times n^{-0.22} + p2.585(np)^{-0.149}
\]

where \( n \) is number of customers and \( p \) is the proportion of customers with an EV.

Considering the combined result of CLNR and My Electric Avenue, the value for ADMD can be plotted as a function of customer number and EV penetration, as shown in Figure 42. This approach is possible due to the coincidence of peak demand for residential load and EV load which was shown in Section 4.
6.3.3.1.3 Variation in Load Profile with Increased Penetration

If known, the increase in ADMD is ideal for evaluating whether an LV network requires intervention. However, the proposed approach for Esprit deployment relies on short term monitoring which is unlikely to monitor the LV network over the peak winter period. Indeed, it is desirable to monitor to enable intervention prior to the winter peak. Therefore, a metric which indicates EV penetration without use of ADMD is desirable. Section 4.1.2 showed load profiles for different numbers of EVs based on My Electric Avenue participant behaviour. By comparing load profiles for an LV feeder with increasing EV penetration, it is possible to estimate the EV penetration level.

Figure 43 shows the winter feeder demand for increasing EV penetrations for 100 customers, based on My Electric Avenue participants and ELEXON residential load profiles (Section 4.2.6, Figure 15). There is a noticeable change in the shape of the load profile in addition to the expected change in peak load. Particular changes are:

- A reduction in the definition of the morning peak as the daytime average increases to a value close to the morning peak.
- An increase in variation between morning peak and evening peak.

The ratio of the load at evening peak to load at morning peak was calculated for the load profiles shown in Figure 43, and plotted in Figure 44. A clear linear relationship is seen between increased EV penetration and the ratio of loads at evening peak and morning peak. It is expected the quality of this fit would be reduced if a greater number of days were included, or if a smaller number of customers were used to calculate the underlying residential demand. However, this approach allows network planners to estimate the quantity of EV charging on a network without knowing the annual peak demand.
6.3.3.2 Decision Points

The process for deploying Esprit, summarised in Figure 39, includes the following four key decision points:

---

Figure 43: Variation in winter feeder load profile for 100 customers with EV Penetration.

Figure 44: Ratio of evening peak to morning peak for load profiles shown in Figure 43.
6.3.3.2.1 Business As Usual: Is there a possible need for intervention?

During the business as usual phase, DNOs have access to a number of information sources which indicate peak load, but which do not directly indicate EV usage. Customer complaints, fuse operations and maximum demand indicators are able to indicate a potential problem on the network. Future usage of network monitoring and “fit and inform” for EV charge points may improve this situation somewhat.

There is a potential need for intervention if any of the following questions can be answered “yes”:

1. Have we received unexplained customer complaints regarding power quality or voltage?
2. Have LV fuses operated with possible causes which include high demand?
3. Has the annual 11 kV/LV substation MDI reading shown an increase which, if associated with only one feeder, could cause the LV circuit rating to be exceeded?

In addition, the following questions may be included, subject to future increases in available data:

4. Does the load profile for the LV feeder indicate a penetration of greater than 40% where capacity per customer is less than or equal to 1.5 kW?
5. Do charging point installer notifications indicate an EV penetration of greater than 40% where capacity per customer is less than or equal 1.5 kW?

6.3.3.2.2 Business As Usual: Is there a reason not to install Esprit?

Esprit’s manufacturer currently estimates a 12 week lead time for the supply of the system. However, this can be easily overcome by holding small inventories of the necessary components. In the case where urgent intervention is required, Esprit may be rapidly deployed without the need to halt customer EV usage. Were the equivalent conventional reinforcement to be deployed, lead times associated with permitting, civil works, and specialist personnel would be incurred.

However, under certain scenarios emergency conventional reinforcement may be necessary. The requirement for urgent intervention is well defined by relevant DNO policies, procedures and working practices and is not discussed further in this report. However, one example would be a suspected live fault requiring emergency street works.

6.3.3.2.3 Monitoring: Is action required?

Having entered the monitoring phase, specific data is available concerning the operation of the suspect LV network. After a period of one to two weeks, the typical load profile for the feeder will have been ascertained. At that point, the data must be used to make a decision on the need for intervention. Ideally, this will include an assessment of the number of connected EV chargers as this influences the cost of DSR solutions including Esprit.

One method to estimate the requirement for intervention is using ADMD, as follows:

- Using the result shown in Figure 44, estimate the EV penetration from the ratio of morning to evening peak.
• Use the resulting EV penetration value to estimate the feeder’s ADMD using the formula
\[ ADMD = 4.6 \times n^{-0.22} + p2.585(np)^{-0.149}. \]
• As set out in ENA Engineering Recommendation P17\textsuperscript{33}, assess the suitability of the LV cable to deliver the required ADMD along its length. If the LV network is an overhead line system, follow the equivalent practice.

The alternative method for LV network planning is using DEBUT\textsuperscript{34}. DEBUT allows a more detailed approach, including seasonality. We suggest that the most appropriate method to model EV demand in DEBUT is to include an additional property, for each EV charger, using the load profiles set out in Section 4.1.2.

6.3.3.4 Intervention: Is Esprit cost effective?

In order to determine the most cost effective solution, both at installation and on an ongoing basis, designers review the available solutions to the network problem, considering costs, timescales and implications for the wider network. The addition of Esprit to the list of potential solutions does not significantly change the requirements on network designers; it adds another potential solution.

Results shown in Section 7, estimate that Esprit will be cost effective for up to 312,000 installations across GB through to RIIO-ED4 (ends 2047) (depending on scenario). The solution template published as a supporting document to this report gives the current costs and lead times for Esprit, which can be assessed against alternative solutions at a design level. Given the specific costs and network considerations for each network reinforcement, there is no value in considering a general case beyond that set out in Section 7. It is important to note that the cost-benefit calculation conducted by My Electric Avenue’s academic partners\textsuperscript{9} showed that Esprit could not compete on cost with the best-case conventional reinforcement (100 m of overlay at a cost of around £100 per meter). However, for many networks this is not a viable solution and Esprit can be more cost-effective than the best alternative.

The operational costs of running Esprit (or any other DSR) necessitates one variation to the approach of network designers in assessing the most cost effective solution. The presence of additional operational expenditure means that once the solution is fitted, it may not continue to be the most cost effective solution indefinitely. The comparison with alternative solutions should be made regularly to ensure customers receive value for money. In addition, the tolerance of customers may change in the future due to changes in behaviour, potentially due to increased familiarity with EVs, or changes to EV battery capacities and charge rates.

6.3.4 Summary

We propose a solution to the deployment of Esprit which addresses the lack of data regarding local EV uptake and network demand which is more applicable than an arbitrary intervention threshold. By operating in three modes (Business as Usual, Monitoring, and Intervention) this approach utilises the information available and will deploy low cost monitoring to understand if intervention is required. Once a decision is made, the most cost effective solution can be


\textsuperscript{34} EA Technology (2001) “Debut User Guide”
deployed based on local considerations; this should be monitored over time to ensure a cheaper alternative is used if available and to maintain customer satisfaction in the service provided by the DNO.

6.4 How Do the Needs of EV Charging (or Other Loads) Affect the Settings?

T1.2.4: How do the needs of EV charging (or other loads) affect the settings?

Technical Learning Outcome T1.2.4 was addressed in the delivery of SDRC 9.7, which drew the following conclusions:

- Vehicle manufacturers advise against using cycling times (i.e. the frequency of changes to Esprit control actions) of less than six minutes to preserve battery life.
- They also advise against interrupting charge during the final stages of a charge cycle when the battery cells are being balanced.
- Network models showed that power quality issues occurred where cycle times of less than two minutes were used or where more than five 3.5 kW chargers were switched simultaneously on the same phase.
- The trade-off between the effectiveness of the curtailment and customer acceptance led to the recommendation of minimum ‘on time’ of 15 minutes, maximum ‘off time’ of 60 minutes for each individual battery.
- Recommended cycle times are between two and thirty minutes.

6.5 How Often Are Switching Routines Likely to be Initiated?

Technical Aim 5: Evaluate how often switch off routines are likely to be initiated from real life trials and extrapolation via modelling using the results.

6.5.1 Introduction

This section addresses technical aim 5 of the Project. In order to examine this issue, data from the technical trial and from modelling work will be provided to demonstrate the amount of switching necessary, and the impact this has had on EV charging for the participants.

6.5.2 Number of Switch Events During Trial

The following analysis has been conducted over a 12 month period of the technical trial (1st August 2014 – 31st July 2015) and is based on data recorded for 93 technical trial participants across the 10 My Electric Avenue clusters. During this period, Esprit settings were set at artificially low values to ensure switching. Therefore, this section is indicative of likely performance but cannot be directly applied to representative feeders.

The analysis considers the number of occasions when the load on the feeder exceeded the pre-defined threshold, making switching events possible. It then considers the number of switching events experienced by trial participants; both in total, and also those switching events specifically experienced at times when their EV was charging. In other words, it is not only important to consider the total number of times that the technology was called upon, but the likelihood that when called upon, this switching had a direct impact on the individual participant’s ability to charge their EV.
6.5.2.1 Number of Threshold Exceedances

For each of the LV feeders, the acceptable loading that could be supported by the feeder without the need to manage the demand has been configured. Over the course of the twelve months considered here, Table 13 displays the number of times that this limit was breached for each of the phases and each technical trial cluster.

Table 13: Number of threshold exceedances split by cluster and phase.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chineham</td>
<td>920</td>
<td>1933</td>
<td>1358</td>
</tr>
<tr>
<td>Chiswick</td>
<td>1346</td>
<td>2606</td>
<td>2586</td>
</tr>
<tr>
<td>Lyndhurst</td>
<td>433</td>
<td>99</td>
<td>463</td>
</tr>
<tr>
<td>Marlow</td>
<td>897</td>
<td>660</td>
<td>521</td>
</tr>
<tr>
<td>South Gosforth</td>
<td>1126</td>
<td>562</td>
<td>1175</td>
</tr>
<tr>
<td>South Shields1</td>
<td>3239</td>
<td>2741</td>
<td>2587</td>
</tr>
<tr>
<td>South Shields2</td>
<td>2666</td>
<td>2833</td>
<td>2346</td>
</tr>
<tr>
<td>Whiteley</td>
<td>1524</td>
<td>2378</td>
<td>2024</td>
</tr>
<tr>
<td>Wylam</td>
<td>1935</td>
<td>2135</td>
<td>1771</td>
</tr>
<tr>
<td>Your Homes</td>
<td>67</td>
<td>82</td>
<td>116</td>
</tr>
</tbody>
</table>

It can be seen that there is considerable variation, both between different clusters and between the phases on the same LV feeder. For example, the Lyndhurst cluster only experienced a maximum of 463 exceedances on the most heavily affected phase, whereas the South Shields clusters both experienced more than 2300 exceedances for all phases.

This is to be expected as the loading levels on feeders across the country are highly variable and hence this indicates that, in certain areas, the number of times that load needs to be managed will be far greater than that for other areas. Similarly, anecdotal evidence suggests that a large number of LV feeders have significant phase imbalance, meaning that the number of times that the threshold is exceeded can vary significantly between phases on the same feeder. This is a situation which may well be exacerbated by the connection of loads such as EV chargers because these large individual loads could have the effect of magnifying the imbalance between phases. Lyndhurst represents a good example of this as it can be seen that both Phases 1 and 3 experienced over 400 exceedances, yet Phase 2 reported less than 25% of this value (only 99 reported during the 12 months, see Table 13).

This imbalance could become more of an issue as EVs and managed demand become more common. The reason for this is that it is quite possible that two neighbours could be connected to different phases which have very different loadings. This could then have the consequence that one of the customers could have their demand constrained much more often than their neighbour, which could result in negative customer perceptions unless the issue of phase connection is clearly communicated to customers; something which has not previously been necessary.

It is also worth noting that the ‘Your Homes’ cluster experienced far fewer exceedances than other clusters. This was a consequence of this cluster being a commercial load, meaning it had a flat load profile (as discussed in Section 6.2). This led to a situation whereby the EV chargers were either allowed to charge without interruption, or had to be curtailed for effectively the whole day; unlike domestic feeders with a load profile that shows distinct peaks (where curtailment occurs) and troughs (where unconstrained charging is permitted). Following customer feedback the threshold
was adjusted to ensure that this all day curtailment did not occur and hence the total number of switch events over the trial was much lower than for domestic clusters.

6.5.2.2 Switching events

The figures shown in Table 13 indicate the total number of times that load exceeded the pre-defined threshold and hence could have resulted in switch events occurring. This section demonstrates the impact of these exceedances on trial participants.

For each of the 93\textsuperscript{35} technical trial participants, Figure 45 shows the average number of times per week that the participants experienced a switch event. It can be seen that there were 9 participants during this 12 months who never experienced a switch event. Of the 84 that did, almost half (40) were subject to less than 1 switch event per week across the 12 month period. At the opposite end of the scale, 16 participants experienced more than seven switch events per week on average, i.e. an average of at least one event per day.

Having established the average number of switch events experienced, it is necessary to drill down into this one stage further. Experiencing a switch event in itself has no impact on a participant unless the switch event occurs at a time when the participant is attempting to charge their EV. Figure 46 shows the average weekly number of switch events experienced per participant where the switch event interrupted the charging of the EV: i.e. “How many times per week did the participants have their preferred EV charging regime disrupted?”.

\textsuperscript{35} 93 of the technical trial participants received curtailment during the technical trial, the results presented in this section consider the amount of curtailment experienced by those participants. See Section 3 for details of the Project participants.
Figure 46: Average number of switch events experienced per week by a trial participant that interrupted EV charging.

It can be seen in Figure 46 that 25 of the 93 participants never had their charging interrupted. Earlier it was stated that nine participants experienced no switch events, meaning that 16 other participants did experience switch events. However, these never coincided with a time at which they were charging their EV. Therefore, only 68 of the participants (73%) experienced any disruption to charging over the twelve months. Of those 68 participants, the majority (45) experienced less than one switch event per week which affected their EV charging. In other words, only one in four participants had their charging disrupted more than once per week on average over the course of the monitored period.

At the other end of the scale, there are a small number of participants who experienced higher levels of disruption with four participants experiencing a switch event coinciding with their EV charging at least once per day on average.

An alternative method of viewing this level of interruption is to consider the total proportion of switch events that interrupted charging for each participant (shown in Figure 47).
It can be seen that the switching events experienced by 31 trial participants (one in three) interrupted charging less than 10% of the time. This includes the 25 participants who never had their charging interrupted. Furthermore, over two thirds of all participants were only subject to interruptions to charging less than 30% of the times that switching was initiated. This appears to show that the level of diversity in charging allows for the fact that at the time when switching was instructed, many participants were not drawing any charge.

It should be noted that in order to trial the equipment, lower thresholds were applied than the absolute limit of the LV cable. Therefore, it is unclear whether the proportions described here would be replicated exactly if the thresholds were applied at a higher level and the load was found to exceed that level owing to a high penetration of EVs. By artificially lowering the threshold, there is the possibility that other load types are assuming greater levels of dominance over the EV loads and could be triggering switches at times of day when few EVs are charging.

6.5.3 Modelling

The University of Manchester conducted modelling of the trial feeders to assess the likely loadings for different EV penetration levels and thereby indicate the times of day when curtailment is likely to be necessary. In order to further assess the impact of charging and the likely delays that customers could experience to their EV charging as a consequence of switch events, the University of Manchester conducted further modelling making use of some work previously conducted for the Low Voltage Network Solutions (LVNS) Project with Electricity North West.

6.5.3.1 Modelling of trial feeders

In order to quantify the likely need for controlled charging as EV penetration rises, the threshold for curtailment was set at the full rating of the LV assets and the trial feeders were modelled. This modelling clearly showed that domestic feeders are likely to experience their curtailment during the evening peak and this is likely to be most significant in winter.

Figure 48 shows modelling for one of the trial feeders (Chiswick) at an EV penetration level of 100% (i.e. one EV per household). This demonstrates the load profile in an unconstrained (business as usual – BaU) regime and also with controlled charging via the Esprit charging solution.
Figure 48: Winter weekday load profile with 100% EV penetration.
It can be seen that the load on different phases of the feeder are not uniform, with one of the phases not requiring constraint, as described earlier. Of the two phases that do necessitate controlled charging, it can be seen that this is for a period of approximately three hours during the evening peak.

6.5.3.2 Additional modelling

As part of the completed Low Carbon Networks Fund LVNS Project, ten representative feeders were constructed by University of Manchester. Of these ten feeders, it was found that six of them could adequately handle the connection of EVs up to a penetration level of 150%. In order to ensure the modelling was relevant, University of Manchester selected only those four feeders from the LVNS Project that encountered load related problems when EV penetration increased. The level of EV penetration that was found to cause threshold exceedances varied across the four feeders. These feeders all represented domestic loads and are, in many cases, somewhat similar to the feeders within the technical trial.

Table 14 provides some of the basic parameters associated with the modelled feeders.

<table>
<thead>
<tr>
<th>Feeder</th>
<th>No. customers</th>
<th>Total length (m)</th>
<th>Main feeding length (m)</th>
<th>Power consumption</th>
<th>Customer type and density</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVNS 2</td>
<td>108</td>
<td>1164</td>
<td>374</td>
<td>Highest</td>
<td>High density, mainly domestic</td>
</tr>
<tr>
<td>LVNS 4</td>
<td>108</td>
<td>2241</td>
<td>517</td>
<td>Medium – high</td>
<td>Mainly domestic with some low consumption non-domestic</td>
</tr>
<tr>
<td>LVNS 6</td>
<td>76</td>
<td>1664</td>
<td>360</td>
<td>Medium</td>
<td>Domestic</td>
</tr>
<tr>
<td>LVNS 7</td>
<td>169</td>
<td>2865</td>
<td>522</td>
<td>High</td>
<td>Domestic, longest circuit with highest customer numbers</td>
</tr>
</tbody>
</table>

By using these feeders, it was possible to consider the likely impacts on EV users in terms of both the frequency of switching and the associated charging delay that could be experienced through switching events as the penetration of EVs increases.

6.5.3.3 Frequency of switching

Analysis has been conducted on each of the four LVNS feeder types described in Table 14 and, for the purposes of this, it has been assumed that all connected customers are domestic. In reality a small number of light commercial customers are also likely to be present, but to demonstrate the likely amount of switching that will occur, this approximation has been taken as detailed information regarding domestic consumption patterns is available. Whereas, commercial consumption can vary more widely depending on the precise nature of the customer. It should also be noted that the EV load considered when constructing the profiles is diversified across a wide sample of customers (approximately 1000). Clearly if feeders with a small number of customers connected are to be considered, this may need to be adjusted to reflect the absence of such diversity in a smaller sample.

Assuming that all customers are residential, the total demand on each of these representative feeders can be constructed for varying levels of EV penetration. This is achieved through examining different times of year when different loading levels occur. For the purpose of this analysis, weekdays and weekends are considered separately across three representative times of year:
‘winter’, ‘summer’ and ‘shoulder’. It is assumed here that ‘winter’ and ‘summer’ each represent three months of the year, while ‘shoulder’ represents the spring and autumn times totalling six months of the year.

For each feeder, algorithms describing the necessary switching thresholds have been derived by University of Manchester. An example of these for LVNS Feeder 2 is shown in Table 15. Here, \( \alpha \) represents the amount by which the rating of the feeder should be multiplied to derive the Esprit switching threshold. This varies depending on the EV penetration level and the time of year.

<table>
<thead>
<tr>
<th>Winter</th>
<th>Shoulder</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha = \frac{1 - 0.7}{60 - 150} (EV_{penetration} - 60) + 1 )</td>
<td>( \alpha = \frac{1 - 0.75}{80 - 150} (EV_{penetration} - 80) + 1 )</td>
<td>( \alpha = \frac{1 - 0.75}{80 - 150} (EV_{penetration} - 80) + 1 )</td>
</tr>
</tbody>
</table>

If we now consider 100% EV penetration, i.e. the number of customers connected is equal to the number of EVs on the feeder, then the following results can be observed across these various times of year and days of the week (it should be noted that at a penetration of 100%, the values of \( \alpha \) for the various feeders range from 0.825 – 0.93).

In the case of Feeders 2 and 6, no switching events occur. At all times the demand is lower than the threshold. Figure 49, shows the winter load which represents the most onerous condition and it can be seen that the threshold is not exceeded. It should be remembered that this assumes all customers are domestic. In reality, a small number (up to 6) could be commercial and hence overall demand could be higher.

In the case of Feeder 4, the threshold is only exceeded during winter (and only on weekdays) as the demand during the summer and shoulder periods is calculated to be lower.
This level of exceedance (shown in Figure 50) corresponds to three EV owners being switched each winter weekday. Given that the number of customers on the feeder is 108, this corresponds to each EV owner being switched less than once per month (i.e. less than three times over the course of a year); a very modest level of switching, although it must again be noted that this neglects any commercial loads on the feeder which could increase the demand.

Feeder 7, on the other hand, experiences significant threshold exceedances, as demonstrated in Figure 51.
Figure 51: LVNS feeder 7 demand across each season for EV penetration of 100%.

In summer, approximately 20 customers per day would experience switching and this could last for around three hours. Of the 169 customers on the feeder, this means that during summer each customer is likely to experience switching on approximately one day per week.

During the shoulder periods, the switching could last for 4 – 5 hours and would affect some 28 customers per day; resulting in switching happening more than once per week for each customer. During a winter weekday, this increases further to 33 customers per day over a period of some 5 – 6 hours, while at the weekend in winter, the number of customers affected could be lower (at around
18), but the window over which switching may be required could be much longer (up to 9 hours) meaning cycling of switching is likely to be inevitable in winter, increasing the number of customers affected.

In summary, for Feeder 7, it is likely that an average customer would experience switching on approximately 70 days during the year (1 in 5), with 18 of these days during winter, 12 in summer and the remainder spread across spring and autumn.

It should be noted that this is heavily dependent on EV penetration and the modelling indicates that if the penetration is reduced to approximately 60%, then it is likely that very little or no switching would be required for each of these feeders (Figure 52 illustrates the demand at 60% penetration on Feeder 7). Clearly if penetration increases above 100% (with numerous households having multiple EVs) then the level of switching would further increase.

![Figure 52: Feeder 7 winter demand with 60% EV penetration.](image)

### 6.5.3.4 Charging delay through switching

In order to carry out this analysis, University of Manchester considered that EV chargers could be switched with 15 minute resolution and that the evening peak lasted from 17.30 – 20.30 (i.e. three hours), in line with the findings from the earlier modelling. It was therefore considered that the maximum time an EV would be disconnected was likely to be three hours.

It should be noted that this study did not consider the prioritisation of different EVs, i.e. it did not cycle those EVs which were disconnected and did not favour EVs for disconnection that had already received some charge. In reality these considerations would be important to ensure that the solution remained acceptable to customers. If these factors were considered then the delay times indicated here would be reduced but more work is needed to fully quantify this.

Figure 53 and Figure 54 represent the best and worst case of the four LVNS feeders studied (noting, of course, that the remaining six LVNS feeders could accommodate the load with no delay to charging being necessary). Further details on these figures and other commentary on the modelling conducted are available in the University of Manchester report.\(^9\)
Figure 53: Charging delay experienced as EV penetration increases on LVNS feeder 2.

Figure 54: Charging delay experienced as EV penetration increases on LVNS feeder 4.
As seen in Figure 53 and Figure 54 and owing to the fact that the EV chargers are not cycled, the delay experienced tends to be either very low (tending to zero) or very large (tending to the three hours of the peak demand). Furthermore, as the penetration level increases, this delay also increases. In practice this would not be the case as the chargers would cycle and give priority to those EVs that had been without charge for longest. Furthermore, the next generation of EV chargers may well have the ability to adjust the charging level. This will mean that charging for all EVs on an affected feeder can be reduced rather than the binary nature of a charger being on or off. This is likely to be much more acceptable to customers and this area merits further consideration outside of this Project.

6.5.4 Conclusions

This analysis has focused on the findings from two sources: the technical trial and the additional modelling. It should be noted in all cases that these findings are based upon charging Nissan Leaf EVs at the normal ‘slow’ rate of 3.5kW. Variations to the type of EV or the rate of charge (such as 7kW) will have an impact on these findings, as will the increasing availability of public charging points as this study is predicated on domestic charging.

From the technical trials it has been noted that:

- The majority of participants experience less than one switch event per week.
- Of those experiencing switch events, the majority only experience one per week that affects their EV charging.
- Only 1 in 25 participants experienced an average of one switch event per day or more that affected their charging.
- Phase imbalance should be considered as the number of switch events occurring on different phases of the same feeder varied considerably.
- The thresholds for switching have been artificially lowered for the trial and further work would be required to confirm that these findings held true for more highly loaded assets.

From the additional modelling it has been noted that:

- Peak times for EV charging correspond with the traditional winter evening peak load for domestic customers.
- Feeders with very large numbers of customers can experience overloading issues with high EV penetration.
- If EV penetration is below 60%, the majority of feeders are likely to be able to handle the demand.

| A delay of up to three hours in charging is experienced if charging is not cycled or reduced. Even this delay is unlikely to pose a problem if the EV user does not require the vehicle until the following morning. If the vehicle is required that evening, this delay would be significant, but should be mitigated by more intelligent cycling or charge management in future EVs. |
7 Cost Savings Associated with Use of Esprit

| SDRC 9.8.1 (b): The Project will deliver an updated Solution template(s) specific to the Technology, and any updated EV charging profiles for use in the GB Smart Grid Forum Modelling. |
| SDRC 9.8.2: Potential cost savings and carbon emission savings using DECC published carbon intensity figures. If technology is unsuccessful, reasons why will be stated. |
| Deliverable 7.2: Cost-benefit analysis (on a GB scale and DNO licence scale) for the network using the Technology. This will be based on the approach developed under Work Stream 3 of the Smart Grids Forum to help validate this work. |

7.1 Introduction

The aim of this section of the report is to use the Transform Model® to estimate the overall cost benefit to the UK economy which could be achieved through implementation of an Esprit like technology through the period 2015 - 2050. The Transform model is used by all the GB DNOs to calculate projected smart grid costs and network benefits versus “Business As Usual” (BAU). The benefits are assessed assuming future scenarios for electricity use as laid down by DECC to satisfy the Fourth Carbon Budget. Further background information on Transform is set out in Section 7.1.1.

7.1.1 The Transform Model®

The Transform Model was developed by EA Technology with inputs from a number of Project Partners and with the full engagement of all British DNOs. It is now licensed to the DNOs, Ofgem, DECC and National Grid and has been used as part of all DNOs’ business plans for the new regulatory period (RIIO-ED1 (ends 2023)). The model uses DECC’s Fourth Carbon Budget scenarios to look at the potential costs associated with the proliferation of new Low Carbon Technologies (LCTs) such as EVs, PV and Heat Pumps.

The Transform Model was originally produced for the GB Smart Grid Forum. It considers the entire GB network at 33kV and below. It does this by using a number of representative network elements that can be replicated in the appropriate proportions to give an overall network that is a reasonable approximation to the GB distribution network.

The model considers the impact of LCTs on the representative networks. Technology uptake forecasts which are aligned to Government (DECC) scenarios are modelled for Heat Pumps (residential, business and public), EVs, Photovoltaics and Distributed Generation (taken from National Grid scenarios). Conventional load growth is also taken into account within the model alongside load growth attributed to the uptake of LCTs.

The model determines the “headroom” in terms of capacity of each representative network element. It then models the change in headroom with the uptake of Low Carbon Technologies, including distributed generation, and load growth. The model identifies the point at which headroom is consumed and investment is required. It considers many solutions (both conventional and “smart”) that could be applied to produce the additional headroom required. A “merit order stack” of solutions is defined in the model. This represents the relative merits of each solution in terms of its cost, the headroom it releases as well as any second order benefits or costs. All solutions are dynamically ranked for all network types annually to 2050.
7.1.2 Methodology and assumptions

For our work to calculate the cost benefit of an Esprit type technology we have developed a new solution template for Esprit. Transform provides two types of solutions, ones that provide additional voltage or thermal headroom, and ones which shift load (DSR, and storage). Esprit is effectively a DSR solution, but only at this stage for EVs so to model the benefit of Esprit accurately Transform has been adjusted in two key ways:

1. DSM solutions in Transform now apply to only specified technologies rather than all DSR capable loads. The general residential DSR solution was originally configured to control all loads in the scenario where Esprit occurred, but only non EV loads in the scenario without Esprit. However, the ‘local smart charging of EVs’ solution can now apply DSR to EVs only rather than providing a direct capacity uplift. This ensures that the capacity unlocked by the local smart charging solution is directly linked to the EVs present on the network and the co-incidence of peak load and high EV load.

2. Based on the My Electric Avenue learning, a new set of load profiles have been tailored for EVs. The new load profiles take three inputs: the power of loads connected at a particular time; the energy those loads require and the time they must complete by. Loads connecting at each hour are manipulated by DSR separately. This allows for a more accurate representation of EVs. The amount of load that can be shifted now varies between hours so for example, it could be easier to shift the load associated with a car that is connected at 11pm than one connected at 11am. This was not originally attempted within Transform because of a lack of data on EVs.

The solution template for Esprit can be found as a supporting document for the SDRC report.

7.1.3 DECC LCT Growth Projections

The Transform Model uses DECC’s Fourth Carbon Budget scenarios to project out to 2050, the amount of reinforcement required to the UK distribution network to accommodate the growth of Low Carbon electrical technologies such as heat pumps, PV and EVs. The UK Government has implemented a carbon budget which places a restriction on the total amount of greenhouse gases the UK can emit over a 5-year period. Under a system of carbon budgets, every tonne of greenhouse gases emitted between now and 2050 will count. The Government has set the first four carbon budgets in law, covering the period from 2008 to 2027 and has committed to halving UK emissions relative to 1990 during the Fourth Carbon Budget period (2023 to 2027). In order to meet the Fourth Carbon Budget the Government has laid out four possible scenarios:

1. High Abatement in Heat (i.e. significant uptake of heat pumps).
2. High Abatement in Transport (i.e. significant uptake of electric cars).
4. Carbon Credit Purchase.

These four scenarios of electricity growth have been used in the following analysis to predict the requirement for smart technologies to accommodate LCT driven load growth to 2050.

7.2 Benefit by Technology

In this section we look at the benefits based on actual installed costs and performance of the Esprit solution template developed. The benefits identified in this section are modelled against Business As Usual for the four DECC scenarios for ED1 (ends 2023) and to the end of ED4 (2046). All the benefits
estimated using the Transform Model are estimated looking only at LCT driven load growth and are presented as a range of potential benefits for the four DECC LCT growth scenarios. Benefits are presented both for the entire GB network and for the SEPD network area as a representative single licence area.

To estimate benefits, two modelling runs were completed. The first with Esprit benefits “switched off” and the second with benefits included. The marginal benefit is then given by the reduction in expenditure achieved through DNOs having Esprit type solutions available to them. This reduces the chance of overestimating the benefits of Esprit as it competes against other developing smart grid technologies.

### 7.2.1 Benefits

The Transform model suggests that Esprit will be an economic solution and will start to be deployed around 2021 dependent on the EV growth scenario. The number of feeders on which Esprit would be deployed, per review period, are shown in Table 16. It should be noted that, as with all results presented in this report, the number of interventions assumes 3.5 kW charging with of the Nissan Leaf Mark 2. It is likely that the number of interventions will increase with 7 kW charging.

**Table 16: New Deployments per review period.**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>ED1 (to 2023)</th>
<th>ED2 (to 2031)</th>
<th>ED3 (to 2039)</th>
<th>ED4 (to 2047)</th>
<th>Total Cost Saving £m to end of ED4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (High Heat)</td>
<td>0</td>
<td>3,102</td>
<td>97,442</td>
<td>112,092</td>
<td>2,225</td>
</tr>
<tr>
<td>2 (High Transport)</td>
<td>0</td>
<td>605</td>
<td>97,442</td>
<td>112,092</td>
<td>2,242</td>
</tr>
<tr>
<td>3 (High Heat &amp; Transport)</td>
<td>25</td>
<td>4,972</td>
<td>65,555</td>
<td>84,110</td>
<td>2,215</td>
</tr>
<tr>
<td>4 (Low)</td>
<td>0</td>
<td>0</td>
<td>943</td>
<td>1,976</td>
<td>197</td>
</tr>
</tbody>
</table>

Each feeder serves an average of around 20 homes, thus Esprit could be controlling over 2 million homes by the end of ED4 if both heat pumps and EVs take off in large numbers. It is interesting to note that the prevalence of heat pumps (scenario 1) could be a driving force for Esprit just as much as higher uptake of EVs (Scenario 2) due to spare capacity in the network being taken up by either of these technologies. Indeed the scenario where Esprit provides most benefit is where the feeder has a small additional growth of load to cope with. If load growth is very large then more expensive solutions are required.

**Table 17: Transform Results – Cost Savings through Use of Esprit.**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cost Saving (£million)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ED1 (to 2023)</td>
</tr>
<tr>
<td>1 (High Heat)</td>
<td>0</td>
</tr>
<tr>
<td>2 (High Transport)</td>
<td>0</td>
</tr>
<tr>
<td>3 (High Heat &amp; Transport)</td>
<td>14</td>
</tr>
<tr>
<td>4 (Low)</td>
<td>0</td>
</tr>
</tbody>
</table>
In terms of the economic benefit of Esprit we find the discounted Totex network reinforcement savings compared to a world without Esprit are relatively consistent in all LCT load growth scenarios at around £2.2 billion to the end of ED4.

Most of the financial benefits occur in ED3 and ED4 and indeed it looks unlikely that Esprit would be a solution in any numbers until ED2. The benefits by ED period are shown in Table 17.

The benefits can be seen to be a maximum of nearly £1,400m in a single review period or nearly £100m per licence area.

Overall we see that Transform suggests that Esprit could benefit the GB DNOs by £2.2 billion if LCTs take off as they will need to for the GB to meet its carbon commitments. This translates to a benefit of £150 million per licence area and installations on around 15,000 feeders in each licence area.

Whilst a small number of interventions are required in ED1, it should be noted that even one outage due to high EV penetration could result in reputational damage for a DNO and the wider EV industry. Therefore, it is imperative that measures to mitigate increased EV penetration are available within the ED1 period.
8  Environmental Impact of Esprit Type Control of Electric Vehicle Charging

SDRC 9.8.2: Potential cost savings and carbon emission savings using DECC published carbon intensity figures. If technology is unsuccessful, reasons why will be stated.

Deliverable 7.3: Likely carbon savings of using the Technology.

8.1  Environmental Impact of EV Charging on Electricity Distribution Networks

The existing network has a set capacity and capability to accommodate a certain number of EVs without any intervention (as set out in Section 4.3). Allowing additional EVs onto the network shifts the energy used in transportation from petrol/diesel to electricity, and this has an associated environmental benefit. The positive impact associated with the conversion from petrol and diesel to electricity is the same, regardless of the method used to enable additional EVs to charge from the grid but the carbon cost differs. These concepts are illustrated in Figure 55 and Figure 56.

Above a certain penetration level network reinforcement cannot be avoided, though the use of Esprit would extend the utility of reinforcements allowing them to accommodate a larger number of vehicles.

![Diagram](attachment:esprit_diagram.png)

**Figure 55:** Illustration of the “base case” versus the positive (green) and negative (orange) impacts of enabling further EVs onto the network using either conventional reinforcement or Esprit.
8.2 Direct Trial Benefits

During the 18 month trial to 18th September 2015 the total distance travelled by all 213 participants with their Nissan Leaf EVs equated to 3,081,328 km. This represents a saving in direct emissions of around 105 tonnes of CO$_2$e as compared to the next best alternative, a new diesel vehicle.$^{36}$

Direct carbon savings were calculated based on the EV electricity consumption per km, 0.211 kWh/km, which was achieved by the My Electric Avenue participants. Information on what vehicle would have been chosen instead of the EV was not available, so the ‘fleet average’ diesel vehicle emission factor of 0.12 kgCO$_2$e/km, was used for comparison; this figure published by SMMT$^{36}$ is based on New European Driving Cycle data for 2014 vehicles. The results were adjusted to include an uplift factor (15% as recommended by the DECC$^{37}$) to accommodate for ‘real-life’ use of the vehicle. Finally, the carbon associated with delivering fuel to consumers was accounted for by using

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a well-to-tank emissions figure, 0.025 kgCO$_2$e/km$^{38}$; this allowed comparison with the equivalent figures for EVs which include carbon emissions associated with the transmission and distribution networks.

It should be noted that had the alternative vehicle for all participants been a new diesel vehicle of equivalent size to the Nissan LEAF, the total carbon emissions would have been reduced. However, it is unlikely that all participants would have adopted new diesel vehicles without the My Electric Avenue Project. In addition, the well-to-tank figure relies on an assumed fuel economy across the diesel fleet which may not have been representative of My Electric Avenue participants, or the vehicles used to calculate tailpipe emissions.

To calculate carbon emissions associated with EV usage, the best available figure of 0.0689 kgCO$_2$e/kWh for the ‘production, transport and distribution of fuels used in electricity generation’ was used, in addition to direct emissions which were calculated to be 0.4877 kgCO$_2$e/kWh. The direct emissions were calculated from grid average data for consumption-based emissions$^{37}$ which include transmission and distribution losses and accommodate the proportion of home (90.85%) and work (9.15%) charging (domestic versus commercial/public sector) recorded during the trial. These results are summarised in Table 18.

Table 18: Operational Carbon Savings from Using EVs instead of Diesel Vehicles during My Electric Avenue

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total distance covered by all EVs in trial (km)</td>
<td>3,081,328</td>
</tr>
<tr>
<td>2014 emissions factor for diesel cars with uplift factor (kgCO$_2$e)</td>
<td>425,223</td>
</tr>
<tr>
<td>Well-to-pump emissions (kgCO$_2$e)</td>
<td>77,033</td>
</tr>
<tr>
<td>Diesel emissions saved (kgCO$_2$e)</td>
<td>502,256</td>
</tr>
<tr>
<td>EV electricity consumption (kWh/km)</td>
<td>0.211</td>
</tr>
<tr>
<td>Grid electricity intensity (direct and indirect emissions) (kgCO$_2$e/kWh)</td>
<td>0.557</td>
</tr>
<tr>
<td>Carbon emissions per km for EVs (kgCO$_2$e/km)</td>
<td>0.117</td>
</tr>
<tr>
<td>EV emissions (kgCO$_2$e)</td>
<td>361,864</td>
</tr>
<tr>
<td>Total running emissions saved (kgCO$_2$e)</td>
<td>104,393</td>
</tr>
<tr>
<td>Annual savings per car (kgCO$_2$e)</td>
<td>439</td>
</tr>
</tbody>
</table>

8.3 Carbon Savings from the Use of Esprit

Additional EVs can be accommodated either by increasing the network’s capacity or by implementing Esprit like technology. These two options have different environmental costs. This section sets out likely carbon savings which can be expected from deployment of the Esprit like system.

It should be noted that the likely carbon savings are calculated as the difference between deploying conventional reinforcement techniques and deploying an Esprit-like technology. Whilst very significant carbon savings can be associated with increased EV uptake, this will occur regardless of the means used to connect EVs to the network. Using Esprit will offset or delay the need for network reinforcement.

My Electric Avenue’s academic partners published calculations for the carbon impact of Esprit versus reinforcement for two of the example feeders in the My Electric Avenue trials (Chiswick and Chineham)\(^9\). The calculations set out in this section apply to the representative LVNS feeders. Therefore, these two results cannot be compared directly and the values for the representative feeders are given as the most representative of the wider distribution networks. However, these results are presented as an estimate, sensitive to future developments of Esprit, the GB electricity generation mix, and EV uptake rates.

8.3.1 Method

To calculate the carbon savings of using Esprit compared to conventional reinforcement only the installation carbon costs are considered, the University of Manchester showed that the savings from maintenance activities are negligible\(^9\). The reinforcement is assumed to be 100 m lengths of 300 mm\(^2\) aluminium triplex cable to meet the requirements of a cable with a higher rating that is commercially readily available. The upper and lower estimates of the carbon emission figures, 49 and 95 tons CO\(_2\)/km are taken from a Tyndall Centre Life Cycle Assessment\(^9\). When considering Esprit, the same carbon emissions for similar technologies are used, as in the Work Activity 5 report\(^9\): 73.5 kgCO\(_2\)e/device for the Controller and 33.6 kgCO\(_2\)e/device for the ICB and communications.

In order to estimate the environmental cost-benefit for GB, the Government defined scenario in which there is High Abatement in Transport is used to forecast figures for EV uptake in Transform\(^40\).

It should be noted that the variation in losses between Esprit and conventional reinforcement has not been considered in this carbon estimate (although it is considered in the supporting work\(^9\)). The reduction in network losses as a result of conventional reinforcement, regardless of network load, results in significant carbon savings. However, over the long term, the decarbonisation of electricity generation is likely to reduce this factor considerably. Therefore, this section considers carbon associated with installation of the different solutions, and excludes the impact of losses.

The following steps are used to calculate the carbon costs of each technology:


1. The number of each LVNS feeder type needing intervention was calculated by considering the proportion of each relevant feeder (LVNS 2, 4, 6 and 7) to all GB feeders (for the figures see Appendix C, Table 23).
2. The number of households with EVs per feeder was calculated, using number of households per feeder and the penetration level at which thermal or voltage limit is surpassed (Appendix C, Table 23).
3. Using Transform model predictions for the number of feeders for which Esprit is the most economic option for intervention and each LVNS feeder type's maximum penetration levels, the total number of each LVNS feeder type and hence the number of EVs was calculated. The total number of feeders needing intervention translates exactly to the number of controllers or the number of network reinforcements needed. The total number of EVs translates to the number of ICBs (see Appendix C, Table 24 and Table 25).

8.3.2 Results

A need for intervention in which Esprit can help was found across four LVNS Feeders types which make up 22% of the LV feeders within one license area (based on the characterization and mapping work carried out for ENWL’s Low Voltage Network Solutions Project41).

Assuming the proportion of the networks made up of each feeder type and the penetration levels at which intervention is needed, it can be shown that the application of Esprit in place of network reinforcements is projected to save between 11.4 and 19.4 tons CO$_2$e emissions by the end of 2030 depending on the reinforcement required. By 2050 the carbon emissions savings are expected to be between 814 and 1,390 tons CO$_2$e.

These figures include the embodied carbon cost of ICBs, estimated at 33.6 kgCO$_2$9 per device, but underestimates the total number of ICBs deployed as it does not account for additional ICBs needed for EVs above the intervention penetration level. However, it is expected that the total number of ICBs will be dominated by new installations rather than organic growth of existing installations. In addition ICBs are unlikely to be used in the final design of the product as their functionality can be incorporated into the charging unit. This will reduce costs and improve environmental impact. Without the ICBs the benefit would increase to between 15.0 and 23.0 tons of CO$_2$e of emissions saved by 2030 or between 1,071 and 1,648 tons of CO$_2$e of emissions saved by 2050.

The use of Esprit technology not only delays the need for reinforcement, it also enables smaller scale reinforcements to deliver greater headroom. It is anticipated that delaying reinforcements could offer further carbon savings as a result of lower carbon materials and innovations in transport and more Smart solutions.

9 Additional Learning

Throughout the My Electric Avenue trials there have been a number of areas of learning which have exceeded the requirements of SDRC 9.8. This section captures these learning points are captured.

9.1 Customer Learning Period

It is useful to understand the time required for customers to adjust to an EV. This has an impact on the mechanisms which may be deployed to encourage uptake of EVs. For instance, the length of a test drive period can be adjusted to allow customers to settle their behaviour and overcome phenomena such as ‘range anxiety’

My Electric Avenue results showed that customers typically spend seven days adapting to their EV, after which time behaviour is largely unchanged (see Figure 6, or My Electric Avenue’s academic outputs for detail of the method). During the first seven days of usage, a number of unexpected behaviours were observed, including:

- 10% of the EVs are connected when the battery is already full.
- About 40% of the EVs are charged more than once a day.

After seven days most participants adopted a repetitive charging behaviour with fewer connections per day and lower state of charge upon connection. Behaviour during the first seven days was significantly different. Therefore, we conclude it takes customers seven days to adjust their usage pattern to accommodate the characteristics of an EV into their normal behaviour.

9.2 Impact on 11 kV / LV Transformers

My Electric Avenue was limited in scope to mitigating the impact of EVs on LV feeders. However, the results are evidently relevant to equipment at higher voltages and at 11 kV / LV substations, including transformers. The University of Manchester, My Electric Avenue’s academic partner, has published a detailed consideration of the impact of unconstrained EV usage on 11 kV/LV transformers which delivers significant additional learning to the My Electric Avenue outputs.

In this work, two LV networks in the North West of England were modelled, and the probability of thermal and voltage problems on the LV feeder was calculated, with the probability of thermal exceedance on the 11 kV/LV transformer. It should be noted that these results present two examples, rather than a representative sample. However, both LV networks present technical problems.

One of the LV networks studied presented voltage problems on two of five feeders at 50% EV penetration. The other LV network presented thermal problems for the transformer at between 40% and 50% EV penetration.

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These results highlight the need to consider each element of the LV network, and to note that the 11 kV/LV transformer may be the first asset to require reinforcement.

9.3 “Rule of Thumb” for Identifying Networks Susceptible to EV Uptake

Section 6.3 of this report set out a formula for after diversity maximum demand (ADMD) of a residential EV charger was set out in \( EV_{\text{ADMD}} = 2.585 \times n^{-0.149} \) where \( n \) is the number of chargers) which corresponds to an ADMD of 1.3 kW for 100 customers. Section 6.2 of this report discussed the types of network on which Esprit can be deployed, with the conclusion that Esprit has been shown to be effective on all network types; except commercial networks with flat profiles and peak values close to the threshold limits. In reviewing the My Electric Avenue clusters, and the representative LVNS feeders, it was shown that feeders which exhibit technical problems due to increase EV penetration are those with space capacity of less than 1.5 kW per customer.

Therefore, we have been able to show a “rule of thumb” that circuits with spare capacity of less than 1.5 kW per customer are susceptible to increasing EV penetration.

9.4 Development of the Transform Model® to Accommodate Esprit Type Solutions

One supporting output for SDRC 9.8 is an updated solution template for Esprit for use in Smart Grid Forum modelling. However, in order to model Esprit effectively, an update to the EA Technology Transform model has been produced. This allows the load which may be controlled by Esprit to be defined, according to customer EV usage, and limited to EV load. Specifically Transform has been adjusted in two key ways as described in Section 7.1.2.

1. DSR solutions in Transform now apply to only specified technologies rather than all DSR capable loads. The general residential DSR solution was originally configured to control all loads as before in the scenario where Esprit occurred, but only non EV loads in the scenario without Esprit. However, the ‘local smart charging of EVs’ solution can now apply DSR to EVs rather than providing a direct capacity uplift. This ensures that the capacity unlocked by the local smart charging solution is directly linked to the EVs present on the network and the co-incidence of peak load and high EV load.

2. Based on the My Electric Avenue learning, a new set of load profiles have been tailored for EVs. These profiles take three inputs, the power of loads connected at a particular time, the energy those loads require and the time by which they must be complete. Loads connecting at each hour are manipulated by DSR separately. This allows for a more accurate representation of EVs. The amount of load that can be shifted now varies between hours so for example, it could be easier to shift the load associated with a car that is connected at 11pm than one connected at 11am. This was not originally attempted within Transform because of a lack of data on EVs. These profiles have been factored into the GB dataset used
in Transform, building upon results delivered by UK Power Network’s Low Carbon London Project\textsuperscript{43}.

### 9.5 Understanding of Powerline Carrier Communications

The implementation of Esprit trialled by My Electric Avenue used Powerline Carrier (PLC) communication to enable instructions and measurements to be relayed between the different system components. PLC has been used in a number of utility sector applications. However, the implementation during My Electric Avenue provided an opportunity to learn more about PLC performance. A report outlining My Electric Avenue’s learning on PLC has been produced\textsuperscript{21}, with the following key conclusions:

1. The implementation of PLC within My Electric Avenue – using sparsely populated networks with relatively long communication distances – is not capable of delivering highly reliable communication.

2. There is an exponential correlation between distance and reduced reliability of communications for the participants where distance could be isolated. However, the certainty of this correlation is low due to the relatively low number of participants.

3. The system implemented by My Electric Avenue allowed units to relay messages along the LV network. It was found that increasing the number of units relaying messages increased communication reliability and allowed communication with participants at distances of up to 300 meters.

4. The correlation between distance and communication reliability was weak and a significant number of other factors influenced the results.

5. The presence of cable joints on the network was generally found not to influence PLC communication reliability. However, in one instance (South Shields 1) a particular cable joint on the network was found to cause communications failure in all downstream properties.

6. PLC communication reliability was shown to improve with an increase in the number of viable signal paths, at least over the range from one to five paths. However, the results were not conclusive for higher numbers of signal paths.

7. There was a strong correlation between the PLC communication reliability and the load on the network. PLC communication reliability was found to reduce with increased network load.

8. The interference caused by solar PV generation was generally not found to reduce the PLC communication reliability. However, for one participant a definite correlation with daylight hours was found.

9.6 Stochastic Analysis

The My Electric Avenue scope included deterministic analysis of trial clusters and representative networks. However, further understanding was gained through performance of a stochastic analysis. The stochastic analysis, conducted by My Electric Avenue’s academic partners at The University of Manchester created a methodology which assigned probabilities to the various factors affecting network performance; including location of EVs, and customer behaviour. Having created this probability map, a Monte Carlo model was run which allowed assessment of the likelihood of an LV network requiring reinforcement, for a range of EV penetration levels. Results such as those in Figure 57 have been produced, the presence of error bars indicates the power of this method in delivering greater levels of insight on the impact of EVs. It is recommended that this method is applied to a representative sample of GB networks to build upon the My Electric Avenue outputs. These results show indicative results, which demonstrate the power of the analysis, but cannot be used to infer impact of EVs on GB networks as a whole.

Figure 57: Example stochastic analysis results, required asset utilization for increasing EV penetrations for an example LV network (comprising six feeders and one transformer).
10 Conclusions
This report sought to provide a response to questions and learning aims provided in the Project Direction. This section draws out the relevant learning and key points for each question listed in the Project Direction with references to further details within this document. The following limitations should be noted with all results presented in this section:

- The EVs used for My Electric Avenue used 3.5 kW charging, with a 24 kWh battery capacity. Charging behaviour for different battery capacities and charging powers will vary.
- The only network components considered were low voltage feeders. As discussed in Section 9.2, other network components will be affected by EV charging.
- Customers with different vehicle usage, personal preferences and tolerances may behave differently to the customers who participated in My Electric Avenue. Therefore, requirements on the network may vary.

9.8 An assessment of how much headroom this sort of technical solution would yield, considering different network topologies and load types.

For the purposes of this report, this SDRC has been broken down into distinct topics, as follows:

9.8.1 Modelling to understand additional headroom available / other network benefits from using the Technology.

a) The models will assess the % of thermal and voltage headroom estimates produced.

T1.2.1 How much headroom is released?

Related Technical Aim:

- From the results and extrapolation via modelling, estimate the typical and maximum thermal capacity gained.

And related Deliverables:

7.1 Network models of the impact of EV charging and the Technology.

Network models for the My Electric Avenue clusters and the representative Low Voltage Network Solutions (LVNS) feeders have been set out in Section 4.2 and the outputs supporting this SDRC. Section 4.3 showed that increased EV penetration is likely to cause problems in four of the ten representative feeders, corresponding to approximately 22% of LV feeders in one license area, and approximately 312,000 circuits across GB.

Section 6.1 showed that, with the use of dynamic settings, Esprit can mitigate thermal problems on all residential network types. Total mitigation of thermal problems caused by increased EV penetration corresponds to thermal headroom of between 12% and 46% depending on the headroom required by the different types of network.

The Esprit algorithm demonstrated in the My Electric Avenue modelling work prioritised delivering thermal headroom. However, Esprit was still shown to mitigate some voltage problems; typically an additional 10% EV penetration was achieved by using Esprit. Greater headroom is technically feasible, particularly at higher penetrations, but more work is required to demonstrate this sufficiently.
One ‘additional network benefit’ was also found through using Esprit. At high EV penetrations (i.e. above 90%) shifting EV load was found to reduce network losses by around 9%.

### Technical Learning Outcomes:

**T1.2.2** How close to the thermal rating should load be before deployment?

The results of My Electric Avenue showed no reason to deploy Esprit prior to demand reaching the capacity of an LV feeder. Therefore, Esprit can be deployed ‘just in time’ to mitigate network problems, as they arise. However, anticipating first required usage was found to be difficult: requiring knowledge of EV penetration; local rate of uptake; and the penetration causing network problems. In Section 6.3 we proposed an approach to determine when to install Esprit, in connection with the procedures recommended in the SDRC 9.2 and 9.3 report. This approach was based on available information, and information which may become available, to deliver a nuanced mechanism applicable to network designers.

### Technical Learning Outcomes:

**T1.2.3** On what type of networks can the technology be used?

Section 6.1 showed that Esprit can mitigate thermal problems on all network types, except for commercial networks with flat load profiles operating with peak load close to the threshold limits. In such a situation, Esprit could be deployed for the purposes of network protection but this would only be effective as a temporary measure as customers did not accept the level of control required to mitigate these problems in this circumstance. Further development of Esprit is recommended to ensure customer satisfaction prior to long term deployment of Esprit on commercial networks with little spare capacity for EV charging.

### Related Technical Aims:

- Evaluate how often switch off routines are likely to be initiated from real life trials and extrapolation via modelling using the results.

Section 6.5 considered the number of switch events which occurred throughout the technical trials, and those projected to be required through modelling. Key outcomes from the technical trials were:

- The majority of participants experience less than one switch event per week.
- Of those experiencing switch events, the majority only experience one per week that affects their EV charging.
- Only one in 25 participants experienced an average of one switch event per day or more that affected their charging.

For the modelled outputs:

- A delay of up to three hours in charging is experienced, particularly if available capacity is not allocated evenly between customers.
- This delay is unlikely to pose a problem if the EV user does not require the vehicle until the following morning.
- If the vehicle is required that evening, this delay would be significant, but should be mitigated by more intelligent cycling or charge management in future EVs.

In summary, curtailment is likely to occur at traditional winter evening peak times for domestic customers with a delay in EV charging of up to three hours. The level of disruption will depend on whether customers intend to use their EVs during, or shortly after, this three hour window. Further
development of Esprit to anticipate customers’ individual requirements would go some way to mitigating this.

SDRC 9.8.1b  The Project will deliver an updated Solution template(s) specific to the Technology, and any updated EV charging profiles for use in the GB Smart Grid Forum modelling

Section 4.3 set out improved EV charging profiles based on My Electric Avenue results. These represent a significant step forward in understanding from the outset of the Project. An updated solution template is provided as a supporting document for this report, and updates to the Transform Model® were reported as additional learning in Section 9.4.

SDRC 9.8.2  Potential cost savings and carbon emission savings using DECC published carbon intensity figures. If technology is unsuccessful, reasons why will be stated.

And related Deliverables:

7.2  Cost-benefit analysis (on a GB scale and DNO licence scale) for the network using the Technology. This will be based on the approach developed under Work Stream 3 of the Smart Grids Forum to help validate this work.

7.3  Likely carbon savings of using the Technology.

A cost-benefit analysis has been conducted using the updated Transform model. Section 7 sets out the methodology and results, based on a number of EV uptake scenarios. In terms of economic benefit of Esprit we find the discounted Totex network reinforcement savings compared to a world without Esprit are relatively consistent in all Low Carbon Technology load growth scenarios at around £2.2 billion to the end of ED4 (to 2047).

The benefits can be seen to be a maximum of nearly £1,400m in a single review period or nearly £100m per licence area.

Likely carbon savings have been calculated based on the best published life cycle analyses, considering typical consumer electronics and network reinforcement in Section 8. Carbon savings are quoted as likely total emissions comparing conventional reinforcement and deployment of Esprit. Uptake in EVs is not considered as this can be applied regardless of the means used to support the LV network.

The application of Esprit (in its current state as a system with a controller and ICB) in place of network reinforcements is projected to save between 11.4 and 19.5 tons CO₂e emissions by the end of 2030 depending on the reinforcement required. By 2050 the carbon emissions savings are expected to be between 814 and 1,390 tons CO₂e. The carbon emission savings should the design not require ICBs (i.e. through charging points integrating the technology) would be more significant.
Appendix A. My Electric Avenue Document Map

Final Close-down Report

Esprit White Paper
Appendix B. Results Showing Esprit’s Impact of Thermal and Voltage Problems

LVNS Feeder 2

Table 19: Esprit Threshold Settings for LVNS Feeder 2

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<tr>
<th></th>
<th>Winter</th>
<th>Shoulder</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
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<td>Equation</td>
<td>( \alpha = \frac{1 - 0.7}{60 - 150} (EV_{\text{penetration}} - 60) + 1 )</td>
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</tr>
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Figure 58: Impact of Esprit on LVNS Feeder 2 at varying EV penetration levels.
LVNS Feeder 4

Table 20: Esprit Threshold Settings for LVNS Feeder 4.

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<th>Season</th>
<th>Equation</th>
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<td>[ \alpha = 1 - 0.7 \left( \frac{EV_{\text{penetration}} - 30}{30 - 150} \right) + 1 ]</td>
</tr>
<tr>
<td>Shoulder</td>
<td>[ \alpha = 1 - 0.75 \left( \frac{EV_{\text{penetration}} - 50}{50 - 150} \right) + 1 ]</td>
</tr>
<tr>
<td>Summer</td>
<td>[ \alpha = 1 - 0.75 \left( \frac{EV_{\text{penetration}} - 40}{40 - 150} \right) + 1 ]</td>
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Figure 59: Impact of Esprit on LVNS Feeder 4 at varying EV penetration levels.
LVNS Feeder 6

Table 21: Esprit Threshold Settings for LVNS Feeder 6.

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<td>$\alpha = \frac{1 - 0.7}{40 - 150} (EV_{penetration} - 40) + 1$</td>
</tr>
<tr>
<td>Shoulder</td>
<td>$\alpha = \frac{1 - 0.75}{40 - 150} (EV_{penetration} - 40) + 1$</td>
</tr>
<tr>
<td>Summer</td>
<td>$\alpha = \frac{1 - 0.75}{50 - 150} (EV_{penetration} - 50) + 1$</td>
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Figure 60: Impact of Esprit on LVNS Feeder 6 at varying EV penetration levels.
Table 22: Esprit Threshold Settings for LVNS Feeder 7.

<table>
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</tr>
<tr>
<td>Shoulder</td>
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</tr>
<tr>
<td>Summer</td>
<td>$\alpha = \frac{1 - 0.75}{80 - 150} (EV_{\text{penetration}} - 80) + 1$</td>
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</table>

Figure 61: Impact of Esprit on LVNS Feeder 7 at varying EV penetration levels
### Appendix C. Carbon Calculation Detail

Table 23: Proportions of LVNS feeders requiring intervention and corresponding number of households with EVs.

<table>
<thead>
<tr>
<th>LVNS Feeder</th>
<th>Proportion of one license area's feeders represented (%)</th>
<th>Proportion of feeder type in relation to all feeders requiring intervention</th>
<th>Penetration level at which thermal limit surpassed (i.e. Esprit needed) ( ^{(*)} )</th>
<th>No. of Households per Feeder [PC1 and PC2 customers]</th>
<th>No. of Households with EVs per Feeder (equals number of controllers)</th>
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<tr>
<td>2</td>
<td>1%</td>
<td>4.55%</td>
<td>70%</td>
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<td>77.27%</td>
<td>50%</td>
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Table 24: Calculation of number of Affected Feeders and Connected EVs, considering a high uptake of EV scenario.

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<th>LVNS Feeder 2</th>
<th>LVNS Feeder 4</th>
<th>LVNS Feeder 6</th>
<th>LVNS Feeder 7</th>
<th>EVs at LVNS 2</th>
<th>EVs at LVNS 4</th>
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</tbody>
</table>

126
Table 25: Carbon cost of Esprit technology and network reinforcement for high EV uptake scenario (forecast by Transform*).

<table>
<thead>
<tr>
<th>Year</th>
<th>Times Esprit Deployed (from Transform)</th>
<th>Controller (tCO₂)</th>
<th>ICB and Comms (tCO₂)</th>
<th>Total Esprit Carbon Cost (tCO₂)</th>
<th>Cable Reinforcement (lower estimate) (tCO₂)</th>
<th>Cable Reinforcement (higher bound) (tCO₂)</th>
<th>Difference between Reinforcement (lower estimate) and Esprit with ICB (tCO₂)</th>
<th>Difference between reinforcement (upper estimate) and Esprit with ICB (tCO₂)</th>
<th>Difference between reinforcement (lower estimate) and Esprit without ICB (tCO₂)</th>
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<td>Times Esprit Deployed (from Transform)</td>
<td>Controller (tCO₂)</td>
<td>ICB and Comms (tCO₂)</td>
<td>Total Esprit Carbon Cost (tCO₂)</td>
<td>Cable Reinforcement (lower estimate) (tCO₂e)</td>
<td>Cable Reinforcement (higher bound) (tCO₂e)</td>
<td>Difference between Reinforcement (lower estimate) and Esprit with ICB (tCO₂e)</td>
<td>Difference between reinforcement (upper estimate) and Esprit with ICB (tCO₂e)</td>
<td>Difference between reinforcement (lower estimate) and Esprit without ICB (tCO₂e)</td>
<td>Difference between reinforcement (upper estimate) and Esprit without ICB (tCO₂e)</td>
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