DETERMINISTIC IMPACT STUDIES

SDRC 9.8 – VOLUME 4
DECEMBER 2015
### DOCUMENT ID | DOCUMENT TITLE
--- | ---
**SUMMARY REPORT**

- **Summary report**: An 18 page report summarising the outputs of the My Electric Avenue Project.

- **High level summary report**: A four page, high level summary of the My Electric Avenue Project outputs.

- **SDRC 9.1.1**: A report outlining key areas of learning and associated recommendations arising from the experience of a third party leading a Tier 2 bid.


- **SDRC 9.2.1**: The Management & Delivery Document created as part of the Novel Commercial Arrangement, published in support of SDRC 9.2.1.

- **SDRC 9.2.1**: This Principal Contract Template download remains available for reference purposes only, having been superseded by SDRC 9.2.3, an updated contract template incorporating the learning identified throughout Project Delivery.

- **SDRC 9.2.1**: The Partner / Supplier Task Order Template (PDF), created as part of the Novel Commercial Arrangement, published in support of SDRC 9.2.1 period.

- **SDRC 9.2.1**: The Partner / Supplier Task Order Template (MS Word) created as part of the Novel Commercial Arrangement, published in support of SDRC 9.2.1 period.

- **SDRC 9.2 & 9.3**: An SDRC report combining the planned relating to the contractual arrangements implemented to enable management of the Project by EA Technology on behalf of SEPD, and an assessment of how effective those arrangements were.

- **SDRC 9.2.3**: The updated ‘Principal Contract Template’ incorporating the learning from the Project following use of the initially developed commercial agreement.

- **SDRC 9.4**: Independent Project Reviews undertaken by Ricardo at Months 6 & 12, and the Project Team’s responses.

- **SDRC 9.4**: Independent Project Reviews undertaken by Ricardo at Months 18 & 24, and the Project Team’s responses.

- **SDRC 9.4**: Independent Project Reviews undertaken by Ricardo at Months 30 & 36, and the Project Team’s responses.

- **SDRC 9.5**: Confirmation of successfully achieving the SDRC target to recruit 3 Cluster Groups to Participate in the My Electric Avenue Project. In reality, 4 clusters were recruited by this point.

- **SDRC 9.5**: Confirmation of successfully achieving the SDRC target to recruit 5 Cluster Groups to Participate in the My Electric Avenue Project.

- **SDRC 9.5**: Confirmation of successful recruitment of participants for all Technical Trial Clusters.

- **SDRC 9.5**: Confirmation that all funding required for the establishment of Project Technical Clusters had been allocated.

- **SDRC 9.5**: Confirmation of successful recruitment of the necessary number of participants to the Project Social Trials.

- **SDRC 9.6**: A report assessing the public acceptance to Demand Side Response of EVs using the Esprit Type Technology.

- **SDRC 9.7**: An assessment of Esprit integration; Voltage Variance: The impact of EVs; Impact of Esprit on heat pumps; Impact of Esprit on cable thermal ratings.

- **SDRC 9.8**: Volume 1 An assessment of how much headroom this sort of technical solution would yield, considering different network topologies and load types.

- **SDRC 9.8**: Volume 2 This report sets out the My Electric Avenue project’s learning on the use of Powerline Carrier (PLC) communication for Low Voltage (LV) network.

- **SDRC 9.8**: Volume 3 Work Activity 1 - Evaluation of the Initial Trial. Report for University of Manchester Deliverables 1.1, 1.2 and 1.3. Low Voltage Networks. Report for University of Manchester Deliverables 2.1, 2.2 and 2.3. Work Activity 3 - Model Validation and Data Analysis. Report for University of Manchester Deliverables 3.1, 3.2, 3.3 and 3.4.


- **Technology White Paper**: This White Paper sets out EA Technology’s vision for Esprit, based on the key findings from My Electric Avenue.

- **Project Progress Reports**: The suite of Project Progress Reports, published at six monthly intervals through the duration of the My Electric Avenue Project.

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1. SECTION EXECUTIVE SUMMARY

This report corresponds to Deliverables 4.1 and 4.2 “Business as usual deterministic impact studies” part of the GB Ofgem’s Low Carbon Networks Fund Tier 2 project “My Electric Avenue” (MEA) run by EA Technology Ltd.

The aim of the MEA project is to implement and evaluate the performance of an innovative, cost-effective operational approach to control the charging points at which electric vehicles (EVs) are connected to: the low voltage (LV) distribution networks. This will allow more EVs to be connected to LV networks without the need of traditional reinforcement, thus deferring investment.

The following points have been thoroughly examined and discussed within this report:

— Scenario-based deterministic impact studies on validated and representative LV feeders considering business as usual integration of EVs; and,
— Assessment in economic terms of the network reinforcements needed to cope with high penetrations of EVs.

The main findings are summarised below.

DETERMINISTIC EV IMPACT STUDIES

— The studies on the LV feeders part of the MEA project show that voltages are never below the lower limit of 0.94 p.u. (216V), even when every house has an EV (100% EV penetration).
— It also shows that one MEA LV feeder presents thermal problems for a penetration as low as 30%. For penetrations above 60%, two feeders present thermal issues.

NETWORK REINFORCEMENT

— An economic assessment that quantifies as net present value the network reinforcement needed to cope with high EV penetrations is carried out considering the MEA feeders and the DECC scenarios for EV uptake.
— This assessment highlights that an investment of circa £10,200 (net present value) in Corney Road is needed to cope with EV penetrations up to 2043, i.e., 100%. The second feeder with issues, Cufaude Village, would require an investment of £4,800 (net present value).
— This assessment will also be used in the next report (Work Activity 5) to illustrate the economic benefits of using the ESPRIT technology to manage the demand from EVs.

FEEDER VALIDATION OF SSEN LV FEEDERS

— As part of Work Activity 3 – “Model Validation and Data Analysis”, three new SSEN LV feeder models have been produced considering data from March 2015 (not available previously) and feedback from SSEN in terms related to the demographics of two feeders.
— The six LV feeders previously produced in Work Activity 3 were checked again and successfully matched the new monitoring data.
— For all the nine residential LV feeders, the mismatches in the daily energy demand and the peak kilovolt-Ampere (kVA) were found to be smaller than the defined thresholds and can therefore be considered as validated models.
1.2 SECTION INTRODUCTION

In order to reduce greenhouse gas emissions by 2020 and beyond, the UK requires the decarbonisation of the entire energy system. Critical to this goal is the electrification of transport, particularly in the form of domestic-scale electric vehicles (EVs). The uncontrolled charging of EVs, however, might lead to technical impacts (low voltages and asset congestion/overload) on the very infrastructure they will be connected to: the residential low voltage (LV) networks.

In order to cope with these challenges, EA Technology, Scottish and Southern Electricity Networks (SSEN), and other Partners are involved in the “My Electric Avenue” (MEA) project (submitted and reported to Ofgem as “Innovation-Squared: Managing Unconstrained EV Connections”), which is funded through Ofgem’s Low Carbon Networks Fund Tier 2. The University of Manchester is also part of this project providing independent network modelling and analysis of the trial data.

The MEA project aims to implement and evaluate the performance of an innovative, cost-effective operational approach (i.e., the ESPRIT Technology) to control the EV charging points in the LV distribution networks. This will allow more EVs to be connected to LV networks without the need of traditional reinforcements, thus deferring investment.

This section, however, summarises the main findings on the EV impact assessment for the non-validated feeders involved in the MEA project, i.e., ‘Your Homes’. It is important to mention that full details of the seven LV feeders that were validated before can be found in previous reports (out of the original list of tasks). Appendix B.1 presents in details these EV impact studies.

1.3 SCENARIO-BASED DETERMINISTIC IMPACT STUDIES

This chapter assesses in a deterministic approach the impacts of different EV penetration levels on residential LV feeders. Section 2.1 summarises the validated residential LV feeders involved in the MEA project (see section 3 of Work Activity 3 [2] and Appendix A of this report) as well as the representative feeders without photovoltaic (PV) systems created in the industrial project “Low Voltage Network Solutions” (LVNS) [6-8] (see section 5 of [2]). The 1-min resolution residential and EV load profiles (see section 4 of [2]) are briefly presented in section 2.2. Section 2.3 introduces the impact assessment methodology. The impact metrics are illustrated in an example MEA LV feeder in section 2.4. The corresponding results using the MEA LV feeders and the LVNS feeders are presented in sections 2.5 and 2.6, respectively. Appendix B.1 presents in details these EV impact studies.

1.3.1 RESIDENTIAL LV FEEDERS

MEA Feeders

Figure 1 and Figure 2 show the feeder topology and the transformer location (black triangle) of the nine residential LV feeders involved in the MEA project (four LV feeders belong to Northern Powergrid and five to SSEN). Table 1 summarises the main features of these LV feeders as well as the available information for the commercial LV feeder involved in the MEA project, i.e., ‘Your Homes’. It is important to mention that full details on the EV impact assessment for the non-validated ‘Your Homes’ LV feeder are presented in Appendix B.1.9. This section, however, summarises the main findings on this LV feeder, which has not been analysed in previous reports (out of the original list of tasks).
While main path in Table 1 refers to the distance from the transformer to the last customer, total cable length indicates the sum of all cable lengths, i.e., including laterals and service cables. The cable ratings defined are based on feedback from the DNOs, i.e., maximum continuous for Northern Powergrid and winter sustained for SSEN.

**TABLE 1: SUMMARY OF THE FEATURES OF THE MONITORED LV FEEDERS**

<table>
<thead>
<tr>
<th>LV 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>NO. OF CUSTOMERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleadon Manor</td>
<td>418</td>
<td>1099</td>
<td>Waveform 300mm²</td>
<td>420</td>
<td>51 3 0</td>
</tr>
<tr>
<td>Gosforth Audley</td>
<td>670</td>
<td>1449</td>
<td>AL 0.3in²</td>
<td>350</td>
<td>56 1 0</td>
</tr>
<tr>
<td>Valley Lane East</td>
<td>556</td>
<td>1371</td>
<td>Cu 0.3in²</td>
<td>445</td>
<td>61 0 0</td>
</tr>
<tr>
<td>Wylam Dene</td>
<td>813</td>
<td>1988</td>
<td>Waveform 300mm²</td>
<td>420</td>
<td>71 1 0</td>
</tr>
<tr>
<td>Clydesdale Road</td>
<td>717</td>
<td>1732</td>
<td>Consac 185mm²</td>
<td>357</td>
<td>61 1 0</td>
</tr>
<tr>
<td>Corney Road</td>
<td>1152</td>
<td>2330</td>
<td>Waveform 185mm²</td>
<td>374</td>
<td>149 0 0</td>
</tr>
<tr>
<td>Cufaude Village</td>
<td>993</td>
<td>3120</td>
<td>Consac 185mm²</td>
<td>357</td>
<td>106 16 0</td>
</tr>
<tr>
<td>Forest Edge</td>
<td>621</td>
<td>1362</td>
<td>ABC 95mm²</td>
<td>242</td>
<td>20 2 0</td>
</tr>
<tr>
<td>Ryans Mount</td>
<td>546</td>
<td>1449</td>
<td>AL 0.3in²</td>
<td>392</td>
<td>56 1 0</td>
</tr>
<tr>
<td>Your Homes</td>
<td>-</td>
<td>-</td>
<td>Waveform 185mm²</td>
<td>320</td>
<td>- - -</td>
</tr>
</tbody>
</table>

While main path in Table 1 refers to the distance from the transformer to the last customer, total cable length indicates the sum of all cable lengths, i.e., including laterals and service cables. The cable ratings defined are based on feedback from the DNOs, i.e., maximum continuous for Northern Powergrid and winter sustained for SSEN.

**FIGURE 2: TOPOLOGY OF THE 5 SSEN LV FEEDERS INVOLVED IN THE MEA PROJECT**

**TABLE 1: SUMMARY OF THE FEATURES OF THE MONITORED LV FEEDERS**

<table>
<thead>
<tr>
<th>LV 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>NO. OF CUSTOMERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleadon Manor</td>
<td>418</td>
<td>1099</td>
<td>Waveform 300mm²</td>
<td>420</td>
<td>51 3 0</td>
</tr>
<tr>
<td>Gosforth Audley</td>
<td>670</td>
<td>1449</td>
<td>AL 0.3in²</td>
<td>350</td>
<td>56 1 0</td>
</tr>
<tr>
<td>Valley Lane East</td>
<td>556</td>
<td>1371</td>
<td>Cu 0.3in²</td>
<td>445</td>
<td>61 0 0</td>
</tr>
<tr>
<td>Wylam Dene</td>
<td>813</td>
<td>1988</td>
<td>Waveform 300mm²</td>
<td>420</td>
<td>71 1 0</td>
</tr>
<tr>
<td>Clydesdale Road</td>
<td>717</td>
<td>1732</td>
<td>Consac 185mm²</td>
<td>357</td>
<td>61 1 0</td>
</tr>
<tr>
<td>Corney Road</td>
<td>1152</td>
<td>2330</td>
<td>Waveform 185mm²</td>
<td>374</td>
<td>149 0 0</td>
</tr>
<tr>
<td>Cufaude Village</td>
<td>993</td>
<td>3120</td>
<td>Consac 185mm²</td>
<td>357</td>
<td>106 16 0</td>
</tr>
<tr>
<td>Forest Edge</td>
<td>621</td>
<td>1362</td>
<td>ABC 95mm²</td>
<td>242</td>
<td>20 2 0</td>
</tr>
<tr>
<td>Ryans Mount</td>
<td>546</td>
<td>1449</td>
<td>AL 0.3in²</td>
<td>392</td>
<td>56 1 0</td>
</tr>
<tr>
<td>Your Homes</td>
<td>-</td>
<td>-</td>
<td>Waveform 185mm²</td>
<td>320</td>
<td>- - -</td>
</tr>
</tbody>
</table>

While main path in Table 1 refers to the distance from the transformer to the last customer, total cable length indicates the sum of all cable lengths, i.e., including laterals and service cables. The cable ratings defined are based on feedback from the DNOs, i.e., maximum continuous for Northern Powergrid and winter sustained for SSEN.

**REPRESENTATIVE LOW VOLTAGE NETWORK SOLUTIONS (LVNS) FEEDERS**

The representative LVNS feeders were developed as part of a Tier 1 Low Carbon Networks Fund project [6-8]. These characterise 141 LV networks (i.e., 232 feeders) located in the North West of England and they are constructed based on their network parameters as well as monitoring data. The representative LVNS feeders without PV systems are also used in this report to investigate the impacts of different EV penetration levels. This study aims to investigate the EV impacts in a more diverse set of residential feeders that characterise a larger population in the North West of England (see [6-8] for more details). The main features of these LV feeders are summarised in Table 2. To consider more rural LV feeders, two additional (not validated) ones that belong to Scottish and Southern Electricity Networks (SSEN)* have been included within the set of representative LV feeders. Their characteristics are summarised in Table 3.

*Scottish and Southern Electric Power Distribution (SSEPD) now operates under the trading name, Scottish and Southern Electricity Networks (SSEN), as of 6th September 2016.
To illustrate how the diversified demand changes for different customer numbers, Figure 4 shows these for customer number values that are in the range of the LV feeders that are investigated in this report (i.e., 25, 50, 100 and 150 customers). As it can be observed, the lower the number of customers the higher the diversified peak demand given that diversity is lower.

Given that the LVNS feeders contain a number of non-residential customers (i.e., PC3 – PC8 in Table 2), Elexon-based profiles have been used to model this specific demand. It is worth noting that the load composition in the LVNS feeders is mainly residential in all the LVNS feeders except Feeder 5. In this context, it is expected that the influence of the non-residential customers will be limited and only Feeder 5 may present a different load behaviour when compared to the residential ones.

### Table 2: Summary of the Features of the LVNS Feeders

<table>
<thead>
<tr>
<th>LV 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>No. of Customers PC1</th>
<th>PC2</th>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeder 1</td>
<td>270</td>
<td>1207</td>
<td>Consac 185mm²</td>
<td>235</td>
<td>34</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Feeder 2</td>
<td>374</td>
<td>1676</td>
<td>Cu 0.25in²</td>
<td>355</td>
<td>96</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Feeder 3</td>
<td>370</td>
<td>1871</td>
<td>Cu 0.15in²</td>
<td>260</td>
<td>30</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Feeder 4</td>
<td>517</td>
<td>2963</td>
<td>Cu 0.30in²</td>
<td>400</td>
<td>91</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Feeder 5</td>
<td>253</td>
<td>962</td>
<td>Consac 240mm²</td>
<td>320</td>
<td>9</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>Feeder 6</td>
<td>360</td>
<td>1828</td>
<td>Cu 0.20in²</td>
<td>310</td>
<td>73</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Feeder 7</td>
<td>522</td>
<td>3673</td>
<td>Cu 0.50in²</td>
<td>525</td>
<td>161</td>
<td>6</td>
<td>0</td>
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<tr>
<td>Feeder 8</td>
<td>264</td>
<td>797</td>
<td>Consac 360mm²</td>
<td>360</td>
<td>19</td>
<td>12</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 3: Summary of the Features of the Two Additional Rural Feeders

<table>
<thead>
<tr>
<th>LV 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>No. of Customers PC1</th>
<th>PC2</th>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural 1</td>
<td>238</td>
<td>1154</td>
<td>AAC 0.05in²</td>
<td>214</td>
<td>16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rural 2</td>
<td>609</td>
<td>1678</td>
<td>ABC 95mm²</td>
<td>242</td>
<td>22</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### 1.3.2 Load Profiling

Synthetic 1-min resolution residential and EV load profiles are used in this report to investigate the impacts of different EV penetration levels. The creation of these profiles has been presented in section 4 of Work Activity 3 (2), and they are summarised in the next two subsections.

#### Residential Load Profiles

To create residential load profiles, the CREST tool is used [9]. This tool creates computational profiles for residential loads (i.e., profile class 1 and 2, PC1 and PC2, according to Elexon [10]) based on the domestic behaviour of British customers. It considers the number of people at home, the type of day, the month, and the use of the appliances. In this way, it is possible to have 1-min resolution profiles, indicating which appliances are on and how much power each of them demands.

A pool of profiles (for typical weekdays and weekends of each month) was created using this tool. The proportion of profiles with certain number of people is based on UK statistics [11]. In this case, the proportion of houses with one person, two people, three people and four or more is 23, 35, 16 and 20%, respectively. Figure 3 shows as an example individual residential/load profiles and the diversified demand from 1000 load profiles for typical weekdays and weekdays during January.
FIGURE 4: EXAMPLE OF DIVERSIFIED LOAD DEMAND (WINTER) FOR VARIOUS CUSTOMER NUMBERS

(a) Weekday – 25 Customers
(b) Weekend - 25 Customers
(c) Weekday – 50 Customers
(d) Weekend - 50 Customers
(e) Weekday – 100 Customers
(f) Weekend - 100 Customers
(g) Weekday – 150 Customers
(h) Weekend - 150 Customers

EV PROFILES

The time-series behaviour of the EVs is obtained using the probability distribution functions presented in Work Activity 3 [2], i.e., the start charging time, the initial state of charge (SOC) and the final SOC. The methodology to create these profiles is explained in [2]. The EV demand is considered to be 3.6 kW with a power factor of 0.98 (absorbing reactive power). A pool of 1,000 EV profiles has been created for each month (although no significant differences exist among seasons, see [2] for more details). Figure 5 shows as an example individual EV profiles and the diversified demand from 1,000 EV profiles for typical weekdays and weekdays during January (winter).

FIGURE 5: EXAMPLE OF INDIVIDUAL EV PROFILES AND DIVERSIFIED EV DEMAND DURING WINTER

(a) Weekday - Individual
(b) Weekend - Individual
(c) Weekday - Diversified
(d) Weekend - Diversified
(e) Weekday – 100 Customers
(f) Weekend - 100 Customers
(g) Weekday – 150 Customers
(h) Weekend - 150 Customers

Figure 6 further shows the diversified EV demand for different EV numbers (similar to the numbers illustrated above). Similar to the residential demand, the lower the number of EVs, the higher the diversified peak demand. Finally, Figure 7 finally shows the aggregated diversified demand of 1000 households and EVs for winter time. The diversified peak demand doubles when all houses have one EV compared to the case without EVs (see Figure 3).
1.3.3 DETERMINISTIC IMPACT STUDY METHODOLOGY

The objective of the methodology presented in this section is to assess in a deterministic approach the impacts of different EV penetration levels on the LV feeders introduced above. The LV feeders and profiles used in this section correspond to the ones presented in section 1.3.1 and 1.3.2, respectively.

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

- Different load profiles are allocated to each customer node in the feeder. The load profiles are randomly selected from the pool created in section 0 to represent properly the diversity among the residential customers.
- For a given penetration level (from 0 to 100% in steps of 10%), the houses to have an EV are randomly selected. In this report, the penetration level is defined as the percentage of houses with an EV. Note that only one EV per household is considered. Therefore, if the penetration level is 20%, then 20% of the houses are selected.
- When the residential and EV profiles are allocated in the feeder, a time-series three-phase four-wire power flow with 1 minute resolution data is executed by using OpenDSS. A line-to-line voltage of 424 V is considered at the secondary of the distribution transformer (which is aligned with Northern Powergrid and SSEN practices).

1.3.4 ASSESSMENT METRICS

To assess the deterministic EV impacts, three metrics are implemented in this report: voltage problems, thermal problems and energy losses. To illustrate the methodology, the EV impacts on the Corney Road LV feeder (the most populated LV feeder in the MEA project) are investigated per penetration level (from 0 to 100%). This particular feeder (see Figure 2(b)) supplies 149 customers through a network of 2.33 kilometres (including laterals and service cables).

Section 1.3.5 summarises the EV impacts on the remaining LV feeders involved in the MEA project for every penetration level, every season, and both weekdays and weekends. Appendix B.1 presents all the results for each LV feeder involved in the MEA project.

VOLTAGE PROBLEMS

To understand the EV impacts in terms of voltages on the LV feeders, the percentage of customers with voltage problems is calculated in each simulation. The methodology defines a voltage problem as a situation where the voltage at a customer node is not within the acceptable range specified by the British Standard BS EN 50160 [12].

The methodology checks if the voltage at each customer node does not comply with the standard, then this customer is considered to have a voltage problem. All the customers with problems are added up, and this number is divided by the total number of customers in the feeder. In this way, the percentage of customers with voltage problems is calculated.
BS EN 50160 [12], adapted to the UK statutory limits, indicates that the nominal voltage (Un) in LV networks is 230 V (between phases and neutral) and:

"Under normal operating conditions, excluding situations arising from faults or voltages interruptions, during each period of one week 95% of the 10 min mean rms values of the supply voltage shall be within the range Un +10% / -6%.

All 10 min mean rms values of the supply voltage shall be within the range of Un +10% / -15%." [12].

Since the time-series profiles have a resolution of 1 minute, the daily voltage profiles for each customer in the feeder are averaged in 10 minutes to make the calculation according to BS EN 50160. Remark that a line-to-line voltage of 424 V is considered at the secondary of the transformer.

Considering a typical weekday during winter, e.g., January, Figure 8 shows the minimum voltage per phase among all houses at every 10 min for a 24 hours period. Both 0 and 100% penetration levels are presented. It can be observed that the voltages are all above the threshold (i.e., 0.94 p.u.), even when all customers have an EV. Thus, it can be concluded that Corney Road LV feeder does not present voltage problems at any penetration level during a typical weekday in winter.

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 considered to be similar and the EV charging behaviour does not significantly change among seasons (see Work Activity 3 [2]), only one of these is studied (e.g., spring, referred here as ‘shoulder’ season). Figure 9 shows the minimum voltage per phase among all houses at every 10 min for a 24 hours period. A 100% EV penetration is considered for both shoulder (e.g., April) and summer (e.g., July).

As it can be observed, voltages during weekdays of summer are slightly higher than the other two seasons. This is mainly due to the difference in the seasonality on the residential demand, i.e., the residential demand during summer is lower than any other season. More importantly, the results shown in Figure 8 and Figure 9 highlight that Corney Road LV feeder does not present voltage problems at any penetration level during typical weekdays in the year. This is mainly due to the characteristics of the main path (i.e., impedance) which is composed of a Waveform 185mm² cable.

In terms of potential voltage issues due to the adoption of EVs during typical weekends of each season, Figure 10 highlights that the most populated LV feeder involved in the MEA project (i.e., Corney Road LV feeder) does not present voltage problems for any weekend of the year.

Therefore, it can be concluded that Corney Road LV feeder does not have voltage problems at any season and day of the year. However, it must be mentioned that this LV feeder may experience in the future significant low voltages under some particular circumstances (i.e., uncertainties in the residential demand and EV demand and location) that cannot be catered for using a deterministic approach, but a stochastic one [13], which is out of the scope of this report.
1.1.1 THERMAL PROBLEMS

To understand the impacts of EVs in the headroom (capacity to supply demand) of LV feeders, the utilization factor at the head of the feeder is calculated in each simulation.

Utilization Factor at the head of the Feeder

This metric assesses the utilization level in the first segment of the feeder (i.e., head of the feeder). This index is calculated as the 10-minute maximum current divided by the ampacity (cable rating) of the main segment of the feeder. To calculate the 10-minute maximum current, the current in the main feeder calculated from the power simulation (1-minute resolution) is averaged in 10 minutes.

The idea of this index is to show how the utilization of the network behaves with different EV penetration levels. Considering a typical weekday during winter, Figure 11 shows the phase current for a 24 hours period for both 0 and 100% penetration levels. For a full adoption, the phase current in all the phases exceeds the capacity of the cable (i.e., 374 A). Indeed, the feeder utilization factor for a 100% penetration is 135% (i.e., 35% over the cable capacity). Thus, it can be concluded that Corney Road LV feeder presents overloads for the highest penetration during typical weekdays in winter.

Figure 12 further shows the phase current for a 24 hours period for a 100% penetration level for typical weekdays in both shoulder and summer seasons (e.g., April and July, respectively). The utilization factor for these seasons is 129 and 119%, respectively (i.e., shoulder season has higher utilization level). These results highlight that during typical weekdays Corney Road LV feeder does also present overloads during shoulder and summer period when all houses have an EV.
In terms of thermal issues during weekends, Figure 13 finally shows that for a full EV deployment weekends will also be overloaded throughout the year. Considering a full adoption, it was found that weekends in winter represent the worst case scenario and weekends in summer the less problematic.

The analysis presented above focused on two cases (i.e., without EVs, 0% penetration, and full adoption, 100%) during typical weekdays and weekends. However, it is important to investigate the penetration level at which feeder overloads are experienced first. This is critical to define the hosting capacity of the LV feeder (in this particular case, the Corney Road LV feeder).

Therefore, the analysis for each season (i.e., winter, shoulder and summer) has been extended for every penetration level (from 0 to 100% in steps of 10%). Figure 14 highlights that the utilisation level of this feeder increases linearly with the penetration level. More importantly, it shows that the feeder utilisation level in winter is higher compared to the other two seasons. Crucially, Figure 14 highlights that Corney Road LV feeder is constrained overall to an EV penetration level of approximately 30% (~45 houses with an EV), given that at 40% penetration level the cable ampacity is exceeded by 0.2%. The potential use of cycle ratings is not assessed in the MEA project.
ENERGY LOSSES
It is expected that the energy losses increase with the EV penetration level in LV feeders. To understand this effect, the energy daily losses are calculated.

Energy daily losses
This metric assesses 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 at the head of the feeder (energy imported) and the power consumption in each load is calculated in each time period [14]. Since the time period of the power consumption is known (i.e., 1 minute) it is possible to determine the corresponding energy losses. This value is then divided by the total energy consumption in the feeder, thus the energy losses in percentage of the total energy demanded.

For each penetration and season, Figure 15 highlights that the energy losses increase (to the square of the current) as the penetration increases (the higher the penetration, the higher the current, see Figure 14). In general, the losses are higher in winter. Losses are lower in summer. For every season, Figure 15 highlights that the highest EV penetration level results in double (from ~0.25% to ~0.5%) the energy losses compared with the scenario without EVs (i.e., 0% penetration level).

1.3.5 MULTI-FEEDER ANALYSIS
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 a different one. Two feeders can present different technical problems at different EV penetration levels. For this purpose, all the feeders involved in the MEA project are analysed in this section to assess the impacts from EVs. This analysis is carried out for each season (i.e., winter, shoulder and summer) and for typical weekdays and weekends.

FIGURE 14: EXAMPLE OF FEEDER UTILIZATION ANALYSIS PER PENETRATION AND SEASON

FIGURE 15: DAILY ENERGY LOSSES PER PENETRATION AND SEASON
The number of feeders that presents voltage and/or thermal problems for each EV penetration level is illustrated in Figure 16. Thermal problems occur for penetration levels larger than 30% (overloads are experienced for a 40% penetration in at least one feeder, Corney Road, in winter). More importantly, Figure 16 highlights that the LV feeders involved in the MEA project only experience overloads (i.e., none of the LV feeder involved in the project presents voltage issues due to the adoption of EVs).

**YOUR HOMES FEEDER**

This section summarises the results presented in Appendix B.1.9 for Your Homes LV feeder – the commercial LV feeder involved in the MEA project. The methodology to analyse this feeder, which differs from the residential LV feeders, is detailed in Appendix B.1.9. Only the first section of the feeder (head of the feeder) was available; thus, only thermal issues can be assessed.

The analyses on this commercial LV feeder considering a typical weekday during winter season have concluded that this feeder is constrained to approximately 52 EVs. Note that absolute numbers are used to indicate the number of EVs that are connected. However, this study highlights that if the highest demand in winter is considered, the maximum number of employees that can have an EV is reduced to approximately 45. More details are provided in Appendix B.1.9.

**1.3.6 REPRESENTATIVE LUNS FEEDERS**

This section investigates the EV impact on the LUNS feeders (detailed in [6-8] and summarised in Table 2) and the two rural feeders (summarised in Table 3). The methodology presented in section 1.3.3 is used.

The analysis has been carried out for each season as well as weekdays and weekends. Appendix B.1.9 shows the results for all the LV feeders and the two (non-validated) rural SSEN LV feeders.

Table 4 shows the penetration level for which each feeder presents the first technical problem. A 100% indicates that no problems occur on the feeder (i.e., the feeder can cope with the highest penetration level). Only one feeder, Feeder 6, presents a technical problem for a penetration as low as 30%. Three of the feeders present a problem for EV penetrations lower or equal to 50%. Nonetheless, Table 4 highlights that four of the LV feeders do not present technical problems at any penetration.

Figure 17 finally shows the number of feeders with technical problems for each day and season. It highlights that thermal problems are experienced first (at lower penetration levels) in every scenario. In general, weekdays cause more problems than weekends, and technical problems in winter are experienced first than any other period of the year (as expected).

**Table 4: Penetration level of EVs (%) for first problem in LUNS and rural feeders**

<table>
<thead>
<tr>
<th>LV FEEDER NAME</th>
<th>WINTER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WEEKDAY</td>
</tr>
<tr>
<td>Feeder 1</td>
<td>100</td>
</tr>
<tr>
<td>Feeder 2</td>
<td>50</td>
</tr>
<tr>
<td>Feeder 3</td>
<td>100</td>
</tr>
<tr>
<td>Feeder 4</td>
<td>40</td>
</tr>
<tr>
<td>Feeder 5</td>
<td>100</td>
</tr>
<tr>
<td>Feeder 6</td>
<td>30</td>
</tr>
<tr>
<td>Feeder 7</td>
<td>80</td>
</tr>
<tr>
<td>Feeder 8</td>
<td>100</td>
</tr>
<tr>
<td>Rural 1</td>
<td>100</td>
</tr>
<tr>
<td>Rural 2</td>
<td>100</td>
</tr>
</tbody>
</table>

**SUMMER**

<table>
<thead>
<tr>
<th></th>
<th>WEEKDAY</th>
<th>WEEKEND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeder 1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Feeder 2</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>Feeder 3</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Feeder 4</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Feeder 5</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Feeder 6</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>Feeder 7</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>Feeder 8</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Rural 1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Rural 2</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
1.3.7 REMARKS

MEA LV FEEDERS

— The LV feeders monitored in the MEA project do not present voltage problems at any penetration level, neither on weekdays or weekends at any period of the year.

— During weekdays in winter, however, one LV feeder involved in the MEA project (Corney Road) presents thermal problems for a penetration level as low as 40%. Two LV feeders involved in the MEA project present thermal problems for high penetration levels.

— While Corney Road LV feeder is constrained to very low penetration levels (30%), Cufaude Village LV feeder can cope with EV penetrations of up to 60%.

— In terms of energy losses, as expected, these are higher in winter season, given that the demand is higher for this period. Summer represents the period with the lowest energy losses.

— Your Homes LV feeder – the commercial feeder involved in the MEA project – is constrained to 52 EVs when typical weekdays in winter are considered. This is reduced to 45 EVs when maximum demand is taken into account.

REPRESENTATIVE LVNS FEEDERS

— One LVNS feeder, Feeder 6, experienced technical problems (thermal) for a penetration level as low as 30%. This is likely to be the case of similar feeders, i.e., long and highly loaded.

— Overall, it was found that feeders that could present a technical problem for EV penetrations lower or equal to 50% are those with the following characteristics: (i) small/medium and highly load (Feeder 2); (ii) Long and medium/high demand (Feeder 4); and (iii) Long and highly loaded (Feeder 6).

— It was also found that feeders that do not present technical problems at any penetration are those with the following characteristics: (i) Small and lightly loaded (Feeder 1); (ii) Small and Medium demand (Feeder 3); (iii) Small and lightly loaded rural (Rural 1); and (iv) Long and lightly loaded rural (Rural 2).

1.4 TECHNICAL AND ECONOMIC CHALLENGES OF FUTURE EV PENETRATIONS

To understand the cost-effectiveness of potential active management solutions such as the ESPRIT technology (to be formally presented in the next report for Work Activity 5), first it is important to understand the traditional alternatives and their corresponding cost. This chapter presents an economic assessment of the network reinforcement needed to cope with high penetrations of EVs. This chapter focuses on the two MEA feeders that have thermal overloads at some penetration level (as shown in section 2), i.e., Corney Road and Cufaude Village. The scenarios produced by DECC for EV uptake in the UK [3] are adopted.

1.4.1 REINFORCEMENT COST

The network reinforcement is the traditional approach used by DNOs to cope with increasing demand. This consists of replacing the conductors for bigger ones to supply the demand without violating the thermal rating of the cables. Replacing the conductors can also be implemented to solve voltage problems, given that a bigger cable has lower resistance, and thus, smaller voltage drops. Replacing the conductors could be seen as the BaU approach to mitigate the EV impacts on LV feeders.

To assess the cost of this practical alternative, the simplified network reinforcement methodology presented in [15] is adapted here. This methodology calculates the investment cost (investment plus installation) required to enable certain EV penetration level. Therefore, it is possible to determine the reinforcement cost for each simulation presented in section 1.3 (each penetration level is independently assessed). When the investment cost is defined, the EV uptake rates defined in [3] (report produced for the Department of Energy and Climate Change, DECC) are utilised to determine the year in the future at which such reinforcement will be needed. When the moment in the future is defined, the investment as a net present value (in fact net present cost) is quantified.

The installation plus investment cost used in this analysis corresponds to the average value provided by SSEN. This value is currently (2015) equal to £106.07 per meter for LV main cable and £760 per installation of service cable, both for urban areas. It is important to mention that these costs are based on Ofgem’s allowable costs. As such, they may not be appropriate for all networks and other solutions are likely to have higher associated costs.
**REINFORCEMENT METHODOLOGY**

The simplified network reinforcement methodology presented in [15], which is implemented per feeder, can be summarised as below. Given that thermal problems are larger in the case of EVs, the actual methodology presented in [15] has been adapted accordingly.

1. The thermal problems are checked for the main section of the cable. If there is a thermal problem, the first 100m of the main path (i.e., the route between the transformer and the last customer, e.g., red line in Figure 18) is replaced by a conductor with the next size for the rating required. It is assumed that a contractor will carry out the works for no less than 100m.

2. A new power flow is run and the voltages are checked.

3. If there are still voltage problems, determine all the customers with voltage problems (e.g., red circles in Figure 18) according to BS EN 50160 [12].

4. Identify the customer with the lowest voltage.

5. Identify the main path between the transformer and the customer with the lowest voltage (e.g., green line in Figure 18). The main path is divided in segments of 100 metres.

   a) If there are more feasible cables, go to step 1 and replace for the next (larger) cable.

   b) If there are not more feasible cables, go to step 1 but for the next segment (next 100m).

It is important to highlight that this simplified reinforcement methodology only analyses the replacement of conductors along the main path. Because of this in some of the simulations the voltage problems might not be completely solved. Nonetheless, this is not the case of the MEA feeders given that thermal problems are the only technical issue.

**1.4.2 ECONOMIC ASSESSMENT**

The results after the application of the reinforcement algorithm in the MEA feeders (those with problems) are presented in this section. The EV uptake rates used in this report correspond to the EV uptake scenarios 2-3 (highest uptake) as defined in [3] and shown in Figure 19. The discounted rates are 3.5% if the investment is within the next 30 years or 3.0% if it is larger than 30 years as defined by Ofgem in [16]. It is important to note that the analyses presented here have considered that the EVs are connected at home using a slow charging mode and their characteristics are similar to those of the Nissan LEAF (i.e. 24 kWh, 3.6 kW with a power factor of 0.98 – absorbing reactive power).

The reinforcement algorithm was applied considering the winter-weekday scenario, given that this period was found to be the bottleneck in all the MEA feeders. Moreover, given that MEA feeders present thermal problems, only step 1 of the reinforcement methodology is required.

It is important to highlight that, considering the initial year as 2015, the total net present cost considers the sum of all the reinforcements needed along the years up to 2043 (100% EV penetration).

For the two MEA feeders with thermal problems (i.e., Corney Road and Cufaude Village LV feeders), Table 5 presents the net present cost of the reinforcements required. For instance, the net present cost to upgrade the cable in Corney Road is about £10,200. This corresponds to £6,100 by 2031 (40% of penetration level) and £4,100 by 2043 (100% of penetration level).

**1.4.3 REMARKS**

- An economic assessment that quantifies as net present value the network reinforcement needed to cope with high EV penetrations is carried out considering the MEA feeders and the DECC scenarios for EV uptake.

- The economic assessment considers a network reinforcement methodology (modified from [15]), EV uptake rates defined by DECC in [3], and quantifies the investment as a net present value considering discounted rates defined by Ofgem [16].

- This assessment highlights that an investment of circa £10,200 in Corney Road is needed to cope with EV penetrations up to 2043, i.e., 100%. The second feeder with issues, Cufaude Village, would require an investment of £4,800.

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**TABLE 5: PENETRATION LEVEL OF EVS (%) FOR FIRST PROBLEM IN LUNS AND RURAL FEEDERS**

<table>
<thead>
<tr>
<th></th>
<th>CORNEY ROAD LV FEEDER</th>
<th>CUFUADE VILLAGE LV FEEDER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of 1st problem</td>
<td>2031 (40% EV penetration)</td>
<td>2038 (70% EV penetration)</td>
</tr>
<tr>
<td>Net present cost (1st investment)</td>
<td>£6,100</td>
<td>£4,800</td>
</tr>
<tr>
<td>Year of 2nd problem</td>
<td>2043 (100% EV penetration)</td>
<td>-</td>
</tr>
<tr>
<td>Net present cost (2nd investment)</td>
<td>£4,100</td>
<td>-</td>
</tr>
<tr>
<td>Total Investment</td>
<td>£10,200</td>
<td>£4,800</td>
</tr>
</tbody>
</table>

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**FIGURE 19: EV UPTAKE SCENARIOS 2-3 [3]**

**FIGURE 18: VISUALISATION OF THE MAIN COMPONENTS IN THE REINFORCEMENT ALGORITHM [15]**

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This assessment will also be used in the next report (Work Activity 5) to illustrate the economic benefits of using the ESPRIT technology to manage the demand from EVs.

**1.5 CONCLUSIONS**

This report corresponds to Deliverables 4.1 and 4.2 “Business as usual deterministic impact studies” part of the GB Ofgem’s Low Carbon Networks Fund Tier 2 project “My Electric Avenue” (MEA) run by EA Technology Ltd.

The aim of the MEA project is to implement and evaluate the performance of an innovative, cost-effective operational approach to control the charging points at which electric vehicles (EVs) are connected to: the low voltage (LV) distribution networks. This will allow more EVs to be connected to LV networks without the need of traditional reinforcements, thus deferring investment.

The following Deliverables are discussed within this report:

- Deliverable 4.1 “Scenario-based deterministic impact studies on validated and representative LV feeders considering BAU integration of EVs”.
- The LV feeders monitored in the MEA project do not present voltage problems at any penetration level, neither on weekdays or weekends at any period of the year.
- During weekdays in winter, however, one LV feeder involved in the MEA project (Corney Road) presents thermal problems for high EV penetrations up to 60%.
- The EV feeders monitored in the MEA project do not present voltage problems at any penetration level, neither on weekdays or weekends at any period of the year.
- During weekdays in winter, however, one LV feeder involved in the MEA project (Corney Road) presents thermal problems for a penetration level as low as 40%. Indeed, up to two LV feeders involved in the MEA project present thermal problems for high penetration levels.
- While Corney Road LV feeder is constrained to very low penetration levels (30%), Cufaude Village LV feeder can cope with EV penetrations of up to 60%.
In terms of energy losses, these are higher in winter season, given that the demand is higher for this period. Summer represents the period with the lowest energy losses.

One LVNS feeder, Feeder 6, experienced technical problems (thermal) for a penetration level as low as 30%. This is likely to be the case of similar feeders, i.e., long and highly loaded.

Overall, it was found that feeders that could present a technical problem for EV penetrations lower or equal to 50% are those with the following characteristics: (i) Small/medium and highly load (Feeder 2); (ii) Long and medium/high demand (Feeder 4); and (iii) Long and highly loaded (Feeder 6).

It was also found that feeders that do not present technical problems at any penetration are those with the following characteristics: (i) Small and lightly loaded (Feeder 1); (ii) Small and Medium demand (Feeder 3); (iii) Small and lightly loaded rural (Rural 1); and (iv) Long and lightly loaded rural (Rural 2).

— Deliverable 4.2 “Assessment in economic terms of the network reinforcement needed to cope with high penetrations of EVs”.

— An economic assessment that quantifies as net present value the network reinforcement needed to cope with high EV penetrations has been carried out considering the MIEA feeders and the DECC scenarios for EV uptake.

This assessment highlights that an investment of circa £10,200 in Corney Road is needed to cope with EV penetrations up to 2043, i.e., 100%. The second feeder with issues, Cufaude Village, would require an investment of £4,800.

This assessment will also be used in the next report (Work Activity 5) to illustrate the economic benefits of using the ESPRIT technology to manage the demand from EVs.

As part of Work Activity 3 – “Model Validation and Data Analysis”, this report has been extended to create updated computer-based models of three LV feeders that belong to SSEN that could not be validated in the previous report. All the computer-based models of the LV feeders involved in the MEA project have been successfully validated against monitoring data. Mismatches in the daily energy demanded and the peak kilovolt-Ampere (kVA) smaller than the thresholds have been obtained in all the studied cases.

1.6 REFERENCES


This appendix updates section 3 of [2] (i.e., the validation of the nine residential computer-based models of the LV feeders involved in the MEA project).

The updates presented here focus on:
— the validation of the previously non-validated LV feeders (see [2] for more details); and,
— the comparison of the peak kilovolt-Ampere (kVA) demand between the monitored data and the simulation results.

However, this appendix also illustrates the performance of the previously validated LV feeders considering new monitored data for March 2015. Details are thoroughly presented for the previously non-validated LV feeders and a summary of the performance of the already validated LV feeders is given at the end of this appendix.

A.1 BACKGROUND

The validation of the LV feeders corresponded to the Deliverable 3.3 of Work Activity 3. The validation of the LV feeders consists of comparing the simulation results for the computer-based models created in Work Activity 2 “Low Voltage Networks” [1] against the monitored data measured by the monitors and stored in iHost.

More specifically, this validation focused in Work Activity 3 [2] on comparing four energy metrics, i.e., single-phase and three-phase errors for both throughout the day, $E_{\Delta,\text{all day}}(a,b,c)$ and $E_{\Delta,\text{all day}}(3\text{ph})$, and during peak demand, $E_{\Delta,\text{5-8pm}}(a,b,c)$ and $E_{\Delta,\text{5-8pm}}(3\text{ph})$.

Given these energy metrics, six out of nine LV feeders were successfully validated in [2] (i.e., Cleadon Manor, Gosforth Audley, Valley Lane East, Wylam Dene, Cleadon Manor and Corney Road). However, three LV feeders could not be validated due to lack of monitored data or significant mismatches among the energy metrics (i.e., Cufaude Village, Forest Edge and Ryans Mount).

Fortunately, monitors have been successfully installed in Forest Edge LV feeder, and thus monitored data has been made available. In addition, feedback from SSE, particularly in terms of the demographics of the LV feeders, enabled the validation of these.

Although the validation carried out in [2] focused on the energy consumption, it has been found that the peak kVA demand is important given that the ESPRIT technology operates based on this value. Thus, the analysis presented in [2] is extended in this appendix to consider this maximum value. In this analysis, it was aimed to achieve a maximum peak kVA error (per phase) of 30%.

A.1.1 MONITORED DATA

As it was detailed in [2], the methodology to validate the computer-based models uses data available in iHost (the platform used in the project to store monitored data). It must be highlighted that this data now represents the 10-min average, instead of instantaneous values that were available in [2].

Monitoring data for March 2015 for each LV feeder has been used in this appendix. Although this data initially included the demand from the EVs in the corresponding LV feeder (given that they are in use by EV participants), CARWINGS data (information that is available in the MEA project and represents the charging behaviour of EV participants) have been used to subtract the EV demand and obtain only the domestic demand at the head of the feeder (i.e., at the first segment of the residential LV cable). This domestic demand is finally used to compare the simulation results and the monitored data.

A.1.2 RESIDENTIAL LOAD PROFILES

The proposed methodology uses residential load profiles based on the CREST tool [9] (considering profile classes 1 and 2 as defined by Elexon [10]) for each of the customers modelled in a given feeder (see [2] for more details). The profiles consider UK statistics in terms of number of occupants per house and are linked to the corresponding date of the monitoring data (weekday/weekend and month). It must be mentioned that the month used in the analysis is March, as previously mentioned. Once all these load models are defined, a power flow analysis is carried out.
A.2 FEEDER VALIDATION: METHODOLOGY

As it was detailed in [2], the validation methodology compares the total energy consumed (single-phase and three-phase errors for both throughout the day and during peak demand) between the simulated feeder and that derived from the corresponding monitoring data. These errors are based on a single random simulation of a day in March (or multiple days), as further detailed below.

Single-phase errors of up to 30% and three-phase errors of up to 20% are considered acceptable values (see [2] for more details), taking into account the number of assumptions that were made when creating the computer-based models: phase connection, service cable type, three-phase cables, impedance, etc. If errors exceed the above thresholds, actions are taken to improve the corresponding LV feeder model. In particular, phase connections of customers are modified to minimise mismatches. The number of customers that should be changed from one phase to another is done considering average daily energy consumptions. The selection of those customers to be changed is done randomly.

As previously mentioned, the peak kVA demand between the simulations and the monitored data is also compared to highlight the errors between the computer-based models and the real LV feeder in terms of maximum demand (i.e., at night when load conditions are higher).

A.3 CUFAUDE VILLAGE LV FEEDER: SIMULATION VS MONITORING DATA

This section validates the Cufaude Village LV feeder, one of the LV feeders that could not be validated in [2]. Monitored data and CARWINGS data for March 2015 have been used. As previously detailed, the monitored data may contain demand from the EVs that are used by users. Therefore, it was necessary to subtract the demand from EVs from the monitored data.

As an example, Figure 20 shows the information on ‘phase A’ obtained from the monitor at the head of the LV feeder (5/3/2015). It also shows the EV demand found using the CARWINGS data for the same day, and it finally presents the domestic demand, which is the result of subtracting the EV demand from the monitored data. The domestic demand is compared in the validation procedure presented below against the simulation data.

The final values of the validation metrics of Cufaude Village LV feeder are given in Table 6. According to the energy criteria and the peak kVA demand, all energy metrics per phase are smaller than 30%. Moreover, the variations of the three-phase energy metrics are smaller than 20%. In addition, it can be observed that the peak kVA demand is significantly small (less than 15%). Therefore, it can be concluded that the new model of the Cufaude Village LV feeder is valid for this particular day.

A.3.1 SINGLE-DAY ANALYSIS

The validation methodology uses the domestic demand (i.e., monitored data minus EV demand). Since the monitoring devices only measure the current at the head of the LV feeders, it was necessary to assume 424 V line-to-line (i.e., 245 V line-to-neutral).

An arbitrary day (16/03/2015) has been selected from the weekdays of March. The domestic demand found using the monitored data for this LV feeder is shown per phase in Figure 21.

Synthetic load profiles were then created for the same day using the CREST tool. However, given that this LV feeder presents particular demographics (it was found that houses are occupied mostly for one or two persons), the load profiles created for this feeder are constrained to one or two residents.

As it was detailed in [2], the initial mismatches considering the energy metrics, particularly for energy values per phase, led to the re-distribution of a few customers to other phases.

To illustrate the performance of the new LV feeder model for Cufaude Village, the corresponding 10-min average power flow results are also shown per phase in Figure 21. It can be observed that the patterns show an overall good match.
A.3.2 MULTIPLE-DAY ANALYSIS
To validate the new LV feeder model for Cufaude Village, the analysis presented above (for the 16/03/2015) has been carried out for multiple random days (up to 10 days). Table 13 highlights that the new computer-based model of Cufaude Village LV feeder is valid, even 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 (i.e., Total Error). Moreover, during peak time (from 5pm-8pm), it can be observed that all the phases present errors smaller than 30%. Important for understanding the peak kVA demand, it can be seen in Table 13 that the difference in the peak kVA demand between the monitored data and the simulations is smaller than 25% in all the cases (considering one standard deviation). Therefore, it can be concluded that the new model of Cufaude Village LV feeder is valid, even when multiple days are taken into account.

<table>
<thead>
<tr>
<th>% Error (all day)</th>
<th>11.8</th>
<th>3.6</th>
<th>3.4</th>
<th>0.04</th>
</tr>
</thead>
<tbody>
<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>

A.3.3 REMARKS
— A new model for the Cufaude Village LV feeder has been produced and successfully validated.
— Feedback from SSEN was used to validate this computer-based model. Demographics were considered and synthetic load profiles considering up to two residents were used.
— Initial mismatches in the energy per phase led to changes in the phase connections of a few customers.
— Multiple monitored days were compared against simulations results to demonstrate the validity of the new computer-based model considering a set of energy-based metrics and the peak kVA demand. Good matches were found in all the cases.

A.4 FOREST EDGE LV FEEDER: SIMULATION VS MONITORING DATA
Similar analysis has been carried out for the Forest Edge LV feeder. Monitors were installed on this LV feeder on 19/01/2015, and information for March 2015 was used. It is important to mention that the composition of the load in this LV feeder presents different patterns compared to the other LV feeders. This is due to the characteristics of the LV feeder (i.e., rural area with a significant number of cottages and few commercial premises), which in turns causes significant load changes over the year as the load depends on the number of people staying in the cottages.

A preliminary and extensive analysis determined that the composition of the demand in this LV feeder does not totally follow that of the CREST tool (which uses UK Statistics). Indeed, no information was found in the literature about the modelling of a cottage demand. Therefore, and given that cottages consist mainly of individual bedrooms, each equipped with the characteristics of small (one person) bedrooms, the initial analysis consisted in finding an adequate number of one person load profiles from the CREST tool that could be used to model the demand of each cottage. To determine this number, the three-phase daily energy monitored at the head of the LV feeder was used. For March 2015, it was found that the energy consumption per house (22 in total) in this LV feeder was 40.5±3.3 kVArh (assuming a constant of 424V line-to-line). Then, a random number ‘X’ of CREST profiles considering only one person was selected and the total energy consumption was calculated. This process was repeated a thousand times for each value of “X”. At this stage of the validation, only the three-phase energy is compared. Table 8 shows that a similar value is obtained when five or six one person profiles are considered to represent each cottage. In this report, five one person profiles have been used to represent the demand of each cottage, given that six one person load profiles caused high peak demand compared to the monitored data.

<table>
<thead>
<tr>
<th>VALUE OF X</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>E3Ø (mean)</td>
<td>7.2±3.7</td>
<td>14.1±5.0</td>
<td>21.1±6.0</td>
<td>28.1±7.2</td>
<td>35.8±8.4</td>
<td>42.3±8.9</td>
<td>49.4±9.8</td>
</tr>
</tbody>
</table>
A.4.1 SINGLE-DAY ANALYSIS

Once the load demand of a cottage was found to be represented by five one person load profiles from CREST tool, the single day analysis was carried out. Figure 22 and Table 9 highlight that the errors in the energy metrics and the peak kVA demand are significantly small for this particular (13/3/2015). Therefore, it can be concluded that the new model of the Forest Edge LV feeder is valid for this day.

Figure 22: Comparison of real-data and simulation data for Forest Edge LV Feeder

Table 9: Network validation metrics for Forest Edge LV Feeder

<table>
<thead>
<tr>
<th>E Ø,A (MEAN)</th>
<th>E Ø,B (MEAN)</th>
<th>E Ø,C (MEAN)</th>
<th>E3Ø (MEAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Error (all day)</td>
<td>3.8</td>
<td>1.4</td>
<td>2.1</td>
</tr>
<tr>
<td>% Error (5-8pm)</td>
<td>20.8</td>
<td>0.6</td>
<td>3.5</td>
</tr>
<tr>
<td>% Error Peak kVA</td>
<td>18.2</td>
<td>10.6</td>
<td>9.9</td>
</tr>
</tbody>
</table>

A.4.2 MULTIPLE-DAY ANALYSIS

Table 10 highlights that the new computer-based model of Forest Edge LV feeder is valid, even when different days are considered. It can be observed that the single-phase energy errors are all below 30%, even when a standard deviation is considered. In addition, the three-phase energy errors are below 20% and the peak kVA demand is significantly small (less than 25% if one standard deviation is considered). Therefore, it can be concluded that the new model of Forest Edge LV feeder is valid, even when multiple days are taken into account.

Table 10: Network validation metrics for Forest Edge LV Feeder – Multiple Days

<table>
<thead>
<tr>
<th>E Ø,A (MEAN)</th>
<th>E Ø,B (MEAN)</th>
<th>E Ø,C (MEAN)</th>
<th>E3Ø (MEAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Error (all day)</td>
<td>4.3±3.0</td>
<td>8.3±7.3</td>
<td>7.2±7.5</td>
</tr>
<tr>
<td>% Error (5-8pm)</td>
<td>14.0±11.4</td>
<td>8.5±14.5</td>
<td>14.3±8.2</td>
</tr>
<tr>
<td>% Error Peak kVA</td>
<td>14.2±10.0</td>
<td>10.1±11.0</td>
<td>11.0±8.2</td>
</tr>
</tbody>
</table>

A.4.3 REMARKS

— A new model for the Forest Edge LV feeder has been produced and successfully validated.
— Given that the load composition for this LV feeder is difficult to find, monitored data was used to successfully determine the number of one person load profiles that could be used to model the demand of this very particular LV feeder with many cottages.
— Initial mismatches in the energy per phase led to changes in the phase connections of a few customers.
— Multiple monitored days were compared against simulations results to demonstrate the validity of the new computer-based model considering a set of energy-based metrics. Good matches were found in all the cases.

A.5 RYANS MOUNT LV FEEDER: SIMULATION VS MONITORING DATA

Similar analysis has been carried out for the Ryans Mount LV feeder. Feedback from SSEN highlighted that a minimum of three residents should be considered. Thus, synthetic load profiles taking into account these characteristics were created.

A.5.1 SINGLE-DAY ANALYSIS

The single day analysis was carried out for the 6/3/2015. Figure 23 and Table 11 highlight that the errors in the energy metrics and the peak kVA demand are significantly small for this particular day. Therefore, it can be concluded that the new model of the Ryans Mount LV feeder is valid for this day.

A.5.2 MULTIPLE-DAY ANALYSIS

Table 13 highlights that the new computer-based model of Ryans Mount LV feeder is valid, even when different days are considered. It can be observed that the single-phase energy errors are all below 30%, even when a standard deviation is considered. In addition, the three-phase energy errors are below 20% and the peak kVA demand is significantly small (less than 25% if one standard deviation is considered). Therefore, it can be concluded that the new model of Cufaude Village LV feeder is valid, even when multiple days are taken into account.

A.5.3 REMARKS

— A new model for the Ryans Mount LV feeder has been produced and successfully validated.
— Feedback from SSEN was used to validate this computer-based model. Demographics were considered and synthetic load profiles considering a minimum of three residents were used.
— Initial mismatches in the energy per phase led to changes in the phase connections of a few customers.
— Multiple monitored days were compared against simulations results to demonstrate the validity of the new computer-based model considering a set of energy-based metrics. Good matches were found in all the cases.
A.6 PERFORMANCE OF PREVIOUSLY VALIDATED LV FEEDERS: MARCH 2015

The performance of the previously validated LV feeders is presented in this section. Table 13-Table 18 highlight that all the previously validated LV feeders present a very good performance (in terms of the metrics used above), and thus their validity is confirmed.

TABLE 12: NETWORK VALIDATION METRICS FOR RYANS MOUNT LV FEEDER – MULTIPLE DAYS

<table>
<thead>
<tr>
<th></th>
<th>E Ø,A (MEAN)</th>
<th>E Ø,B (MEAN)</th>
<th>E Ø,C (MEAN)</th>
<th>E3Ø (MEAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Error (all day)</td>
<td>9.1±5.8</td>
<td>8.8±5.55</td>
<td>13.1±13.2</td>
<td>1.8±1.1</td>
</tr>
<tr>
<td>% Error (5-8pm)</td>
<td>12.8±10.8</td>
<td>13.4±12.5</td>
<td>19.6±8.9</td>
<td>5.6±4.0</td>
</tr>
<tr>
<td>% Error Peak kVA</td>
<td>11.8±9.1</td>
<td>16.9±13.5</td>
<td>15.3±8.4</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE 13: NETWORK VALIDATION METRICS FOR CLEADON MANOR LV FEEDER – MULTIPLE DAYS

<table>
<thead>
<tr>
<th></th>
<th>E Ø,A (MEAN)</th>
<th>E Ø,B (MEAN)</th>
<th>E Ø,C (MEAN)</th>
<th>E3Ø (MEAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Error (all day)</td>
<td>9.0±4.7</td>
<td>12.0±7.0</td>
<td>8.6±5.9</td>
<td>2.5±1.2</td>
</tr>
<tr>
<td>% Error (5-8pm)</td>
<td>16.4±9.4</td>
<td>17.6±10.8</td>
<td>14.2±9.9</td>
<td>8.8±6.9</td>
</tr>
<tr>
<td>% Error Peak kVA</td>
<td>17.9±10.4</td>
<td>17.8±8.4</td>
<td>19.1±9.7</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE 14: NETWORK VALIDATION METRICS FOR GOSFORTH AUDLEY LV FEEDER – MULTIPLE DAYS

<table>
<thead>
<tr>
<th></th>
<th>E Ø,A (MEAN)</th>
<th>E Ø,B (MEAN)</th>
<th>E Ø,C (MEAN)</th>
<th>E3Ø (MEAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Error (all day)</td>
<td>7.4±7.2</td>
<td>9.3±6.1</td>
<td>6.4±5.8</td>
<td>5.3±3.3</td>
</tr>
<tr>
<td>% Error (5-8pm)</td>
<td>13.7±9.3</td>
<td>8.3±5.5</td>
<td>8.7±9.5</td>
<td>6.4±3.3</td>
</tr>
<tr>
<td>% Error Peak kVA</td>
<td>15.6±10.7</td>
<td>15.4±7.4</td>
<td>19.2±8.9</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE 15: NETWORK VALIDATION METRICS FOR VALLEY LANE EAST LV FEEDER – MULTIPLE DAYS

<table>
<thead>
<tr>
<th></th>
<th>E Ø,A (MEAN)</th>
<th>E Ø,B (MEAN)</th>
<th>E Ø,C (MEAN)</th>
<th>E3Ø (MEAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Error (all day)</td>
<td>7.9±9.2</td>
<td>10.0±8.2</td>
<td>10.1±9.1</td>
<td>7.0±2.7</td>
</tr>
<tr>
<td>% Error (5-8pm)</td>
<td>11.5±5.1</td>
<td>10.5±5.5</td>
<td>9.2±5.7</td>
<td>9.6±7.6</td>
</tr>
<tr>
<td>% Error Peak kVA</td>
<td>17.5±3.5</td>
<td>9.9±10.7</td>
<td>7.4±11.9</td>
<td>-</td>
</tr>
</tbody>
</table>
TABLE 16: NETWORK VALIDATION METRICS FOR WYLAM DENE LV FEEDER – MULTIPLE DAYS

<table>
<thead>
<tr>
<th></th>
<th>E Ø,A (MEAN)</th>
<th>E Ø,B (MEAN)</th>
<th>E Ø,C (MEAN)</th>
<th>E3Ø (MEAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Error (all day)</td>
<td>7.9±8.9</td>
<td>10.5±4.0</td>
<td>9.9±8.9</td>
<td>7.1±4.1</td>
</tr>
<tr>
<td>% Error (5-8pm)</td>
<td>8.2±5.3</td>
<td>7.5±9.3</td>
<td>9.6±9.6</td>
<td>7.4±8.5</td>
</tr>
<tr>
<td>% Error Peak kVA</td>
<td>16.8±9.9</td>
<td>12.7±5.8</td>
<td>11.5±9.4</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE 17: NETWORK VALIDATION METRICS FOR CLYDESDALE ROAD LV FEEDER – MULTIPLE DAYS

<table>
<thead>
<tr>
<th></th>
<th>E Ø,A (MEAN)</th>
<th>E Ø,B (MEAN)</th>
<th>E Ø,C (MEAN)</th>
<th>E3Ø (MEAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Error (all day)</td>
<td>6.3±6.0</td>
<td>10.7±7.1</td>
<td>13.5±4.6</td>
<td>4.1±3.1</td>
</tr>
<tr>
<td>% Error (5-8pm)</td>
<td>10.3±3.4</td>
<td>12.6±5.0</td>
<td>9.1±7.8</td>
<td>9.6±5.2</td>
</tr>
<tr>
<td>% Error Peak kVA</td>
<td>17.0±10.2</td>
<td>16.9±9.0</td>
<td>16.1±9.1</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE 18: NETWORK VALIDATION METRICS FOR CORNEY ROAD LV FEEDER – MULTIPLE DAYS

<table>
<thead>
<tr>
<th></th>
<th>E Ø,A (MEAN)</th>
<th>E Ø,B (MEAN)</th>
<th>E Ø,C (MEAN)</th>
<th>E3Ø (MEAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Error (all day)</td>
<td>10.1±3.4</td>
<td>7.8±4.4</td>
<td>4.7±4.6</td>
<td>6.7±3.2</td>
</tr>
<tr>
<td>% Error (5-8pm)</td>
<td>14.4±13.9</td>
<td>12.9±9.5</td>
<td>11.8±7.2</td>
<td>7.6±5.7</td>
</tr>
<tr>
<td>% Error Peak kVA</td>
<td>14.2±5.6</td>
<td>12.6±7.1</td>
<td>10.8±10.0</td>
<td>-</td>
</tr>
</tbody>
</table>

APPENDIX B: EV IMPACT ASSESSMENT

This appendix presents in more details the EV impacts on the remaining residential LV feeders involved in the MEA project, i.e., MEA feeders. It also presents in details a simplified EV impact assessment on the commercial LV feeder also involved in the MEA project. The EV impacts on the representative LVNS feeders are finally presented.

B.1 MEA FEEDERS

This section is an extension of chapter 1.3. It details the impact analysis on the remaining LV feeders.

B.1.1 CLEADON MANOR LV FEEDER

— Figure 24 shows that this LV feeder does not present thermal issues at any penetration level.

FIGURE 24: IMPACTS OF DIFFERENT EV PENETRATIONS ON CLEADON MANOR LV FEEDER

(a) Weekday – Thermal Problems

(b) Weekend – Thermal Problems

(c) Weekday – Energy Losses

(d) Weekend – Energy Losses
B.1.2 GOSFORTH AUDLEY LV FEEDER
— Figure 25 shows that this LV feeder does not present thermal issues at any penetration level.

**FIGURE 25: IMPACTS OF DIFFERENT EV PENETRATIONS ON GOSFORTH AUDLEY LV FEEDER**

(a) Weekday – Thermal Problems

(b) Weekend – Thermal Problems

(c) Weekday – Energy Losses

(d) Weekend – Energy Losses

B.1.3 VALLEY LANE LV FEEDER
— Figure 26 shows that this LV feeder does not present thermal issues at any penetration level.

**FIGURE 26: IMPACTS OF DIFFERENT EV PENETRATIONS ON VALLEY LANE LV FEEDER**

(a) Weekday – Thermal Problems

(b) Weekend – Thermal Problems

(c) Weekday – Energy Losses

(d) Weekend – Energy Losses
B.1.4 WYLAM DENE LV FEEDER
— Figure 27 shows that this LV feeder does not present thermal issues at any penetration level.

FIGURE 27: IMPACTS OF DIFFERENT EV PENETRATIONS ON WYLAM DENE LV FEEDER

(a) Weekday – Thermal Problems
(b) Weekend – Thermal Problems
(c) Weekday – Energy Losses
(d) Weekend – Energy Losses

B.1.5 CLYDESDALE ROAD LV FEEDER
— Figure 28 shows that this LV feeder does not present thermal issues at any penetration level.

FIGURE 28: IMPACTS OF DIFFERENT EV PENETRATIONS ON CLYDESDALE ROAD LV FEEDER

(a) Weekday – Thermal Problems
(b) Weekend – Thermal Problems
(c) Weekday – Energy Losses
(d) Weekend – Energy Losses
B.1.6 CUFUADE VILLAGE LV FEEDER

— Figure 29 shows that this LV feeder does present thermal issues for EV penetration levels larger than 60% in winter and shoulder season. Thermal issues in summer only occur for penetration levels larger than 80%.

B.1.7 FOREST EDGE LV FEEDER

— Figure 30 shows that this LV feeder does not present thermal issues at any penetration level.
B.1.8 RYANS MOUNT LV FEEDER

— Figure 31 shows that this LV feeder does not present thermal issues at any penetration level.

FIGURE 31: IMPACTS OF DIFFERENT EV PENETRATIONS ON RYANS MOUNT LV FEEDER

(a) Weekday – Thermal Problems

(b) Weekend – Thermal Problems

(c) Weekday – Energy Losses

(d) Weekend – Energy Losses

B.1.9 YOUR HOMES

’Your Homes’ is the commercial LV feeder involved in the MEA project. This has not been analysed in previous reports given that it is out of the original list of tasks by The University of Manchester. However, it has been agreed to undertake a simplified EV impact assessment to try to understand the potential effects of EV uptake at commercial feeders.

To model this commercial feeder, information only of the first segment was available (i.e., main section of the cable). The main segment consist of a Waveform 185mm² cable (i.e., cable rating is 320 A). The three-phase connection point is therefore defined at the end of the first segment. In this way, the aggregate demand can be determined, and thus the feeder utilization factor quantified. However, voltage issues and energy losses cannot be quantified given that its topology is not provided.

To model the demand (per phase) of this place, phase currents measured at the substation are used. The net phase demand of the industry itself was found by subtracting the EV demand (13 EVs) available on the six intelligent control boxes (ICBs). To model the EV charging behaviour, CARWINGS data from this specific commercial place were used. Only weekdays are analysed for this commercial feeder, given that weekends are not working days. Although all seasons are investigated, it must be mentioned that summer data for the ICBs were not available. It is considered that EV’s demand is not significant, given that the EVs in this place were delivered around July.

The penetration level for the commercial feeder is defined in absolute numbers, given that the previous definition that uses the number of houses to define the penetration level cannot be used here. Thus, instead of using a penetration level relative to the number of houses, a penetration level of 10 indicates that 10 EVs can be connected. Thus, the existing penetration level in this feeder is 13. Up to 100 EVs is investigated in this report.

Considering a random selection of commercial demand, Figure 32 highlights that in winter this feeder can cope with approximately 52 EVs. The number of EVs that can be connected increases to approximately 65 in shoulder season (i.e., spring/autumn) and in summer no problems are experienced even if 100 employees have an EV.

If the highest demand in each season is considered, Figure 33 highlights that the maximum number of employees that can have an EV is reduced to approximately 45, given that thermal issues can occur during winter.

FIGURE 32: IMPACTS OF DIFFERENT EV PENETRATIONS ON YOUR HOMES FEEDER

(a) Winter

(b) Shoulder

(c) Summer

FIGURE 33: IMPACTS OF DIFFERENT EV PENETRATIONS ON YOUR HOMES FEEDER

(a) Winter

(b) Shoulder

(c) Summer
B.2 LUNS REPRESENTATIVE LV FEEDERS

FIGURE 33: IMPACTS OF DIFFERENT EV PENETRATIONS FOR THE HIGHEST DEMAND ON YOUR HOMES FEEDER

FIGURE 34: EU IMPACTS DURING WINTER – WEEKENDS ON REPRESENTATIVE LUNS FEEDER

(a) Winter

(b) Shoulder

(c) Summer

FIGURE 35: EU IMPACTS DURING WINTER – WEEKDAYS ON REPRESENTATIVE LUNS FEEDER

(a) Voltage Problems

(b) Thermal Problems

(c) Energy Losses

FIGURE 36: EU IMPACTS DURING SHOULDER – WEEKDAYS ON REPRESENTATIVE LUNS FEEDER

(a) Voltage Problems

(b) Thermal Problems

(c) Energy Losses
FIGURE 37: EU IMPACTS DURING SHOULDER – WEEKENDS ON REPRESENTATIVE LUNS FEEDER

(a) Voltage Problems

FIGURE 38: EU IMPACTS DURING SUMMER – WEEKDAYS ON REPRESENTATIVE LUNS FEEDER

(a) Voltage Problems

(b) Thermal Problems

(c) Energy Losses

FIGURE 39: EU IMPACTS DURING SUMMER – WEEKENDS ON REPRESENTATIVE LUNS FEEDER

(a) Voltage Problems

(b) Thermal Problems

(c) Energy Losses
2.0 WORK ACTIVITY 5 “ESPRIT-ENABLED DETERMINISTIC IMPACT STUDIES” – REPORT FOR DELIVERABLES 5.1 AND 5.2

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1. SECTION EXECUTIVE SUMMARY

This report corresponds to Deliverables 5.1 and 5.2 “ESPRIT-Enabled Deterministic Impact Studies” part of the GB Ofgem’s Low Carbon Networks Fund Tier 2 project “My Electric Avenue” (MEA) run by EA Technology Ltd.

The aim of the MEA project is to implement and evaluate the performance of an innovative, cost-effective operational approach to control the charging points at which electric vehicles (EVs) are connected to the low voltage (LV) distribution networks. This will allow more EVs to be connected to LV networks without the need of traditional reinforcement, thus deferring investment.

The following points have been thoroughly examined and discussed within this report:

— Scenario-based deterministic impact studies on validated and representative LV feeders considering the ESPRIT Technology; and,
— Economic and environmental assessment of the benefits of adopting the ESPRIT Technology to cope with high penetrations of EVs.

The main findings are summarised below.

DETERMINISTIC EV IMPACT STUDIES WITH THE ESPRIT TECHNOLOGY

— An ESPRIT-based control algorithm is presented to manage EV charging points to mitigate thermal problems (only) in LV feeders. Its effectiveness is demonstrated on nine residential MEA LV feeders, a commercial MEA LV feeder, and ten residential representative LV feeders. The assessment is carried out for different EV penetration levels (from 0 to 150% in the case of the residential LV feeders), seasons and type of days (i.e., weekdays and weekends).
— It is shown that there is an improvement in terms of voltages (due to the management of the demand). Moreover, the benefits in the energy losses (as a by-product of the thermal management) are on average 9%.
— It is demonstrated that short control cycles (e.g., 1 min) and lower disconnection thresholds (i.e., with EV charging points before assets reach their limits) can lead to the complete mitigation of thermal problems (never exceeding current limits). However, while very short control cycles have an impact on the battery life of EVs, very low disconnection thresholds may affect customer acceptability. Hence, a compromise must be achieved when adopting the ESPRIT-based control algorithm so these two factors are taken into account.
— In the particular case of the LVNS feeders, it is highlighted that a 10-min control cycle and lower disconnection thresholds result in the full mitigation of thermal problems (faced by only four feeders). This approach also results in fewer feeders with voltage problems. Nonetheless, it results in charging delays on the EVs.

ECONOMIC ASSESSMENT

— An economic assessment of the investment cost required to update the ESPRIT Technology in comparison to the ‘net present value’ is performed. This considers the DECC scenarios for EV uptake and the two MEA feeders that present thermal problems at some EV penetration level (i.e., Corney Road and Cufaude Village which have similar customer and length characteristics). These results are compared against the investment cost of adopting traditional network reinforcements (i.e., replacement of conductors).
— The following investment and operational costs were assumed: £2,000 per LV substation monitor and controller, £300 per Intelligent Control Box (ICB), £150 per ICB per 5 years, and £100 per metre of main underground cable. The calculations consider a discount rate of 3.5% per year.
— The assessment highlights that an ESPRIT Technology investment of circa £55,000 in Corney Road is needed to cope with EV penetrations up to 2050 (which corresponds to 150%). The second feeder with issues, Cufaude Village, would require an investment of £45,000. On the other hand, traditional reinforcements would cost circa £10,000 and £5,000 for Corney Road and Cufaude Village, respectively. It is important to mention that the adoption of the reinforcement methodology has resulted only in the replacement of the first 100m of cable.

With the traditional reinforcements are cheaper, it is important to highlight that the investment costs for the ESPRIT Technology are expected to decrease significantly with mass production and in time. Operational costs, which account for around half of the overall net present value, are also expected to decrease with the maturity of the technology as well as communication services. Additionally, the investment costs also assume the ‘ESPRIT Technology’ is deployed in the same manner as that trailed in the project, specifically that an additional unit requires installation at each charging point rather than being integrated directly within the charging point. Conversely, the cost adopted for the replacement of underground cables can also vary according to the local or regional characteristics. In addition, the costs used here are based on Ofgem’s allowable costs. As such, they may not be appropriate for all networks and other solutions are likely to have higher associated costs.

ENVIRONMENTAL ASSESSMENT

— An environmental assessment that quantifies the carbon emissions of adopting the ESPRIT Technology or reinforcing the network, at two EV penetration levels (i.e., assuming a cycle of the components of 35 years from 2015) is carried out considering the DECC scenarios for EV uptake and only the two MEA feeders that present thermal problems at some EV penetration level (i.e., Corney Road and Cufaude Village). These results are compared against the carbon emissions from traditional network reinforcements (i.e., replacement of conductors for new ones with smaller impedance).
— Given that the emission factors of the components used in the trials were not available, the values adopted in the analysis consider other electronic devices with similar manufacturing processes. The following emission factors are adopted: 73.5 kgCO2e per LV substation monitor and controller, 33 kgCO2e per ICB, 62.2 kgCO2e per PLC repeater, and 59 kgCO2e per metre of main underground cable.
— The environmental assessment highlights that the adoption of the network reinforcement results in lower CO2e emissions along the life cycle. This is mainly due to a significant reduction in energy losses due to the use of cables with lower impedances than the original ones which are used when adopting the ESPRIT Technology. The CO2e emissions adopting the ESPRIT Technology in Corney Road are as much as those from reinforcements (approximately 1% higher). For Cufaude Village LV feeder, ESPRIT results in approximately 20% more CO2e emissions than reinforcements.

Although the traditional reinforcements are cheaper, it is important to highlight that the investment costs for the ESPRIT Technology are expected to decrease significantly with mass production and in time. Operational costs, which account for around half of the overall net present value, are also expected to decrease with the maturity of the technology as well as communication services. Additionally, the investment costs also assume the ‘ESPRIT Technology’ is deployed in the same manner as that trailed in the project, specifically that an additional unit requires installation at each charging point rather than being integrated directly within the charging point. Conversely, the cost adopted for the replacement of underground cables can also vary according to the local or regional characteristics. In addition, the costs used here are based on Ofgem’s allowable costs. As such, they may not be appropriate for all networks and other solutions are likely to have higher associated costs.

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2.2 SECTION INTRODUCTION

In order to reduce greenhouse gas emissions by 2020 and beyond, the UK requires the decarbonisation of the entire energy system. Critical to this goal is the electrification of transport, particularly in the form of domestic-scale electric vehicles (EVs). The uncontrolled charging of EVs, however, might lead to technical impacts (low voltages and asset congestion/overload) on the very infrastructure they will be connected to: the residential low voltage (LV) networks.

In order to cope with these challenges, EA Technology, Scottish and Southern Electricity Networks (SSEN), and other Partners are involved in the “My Electric Avenue” (MEA) project (submitted and reported to Ofgem as “Innovation-Squared: Managing Unconstrained EV Connections”), which is funded through Ofgem’s Low Carbon Networks Fund Tier 2. The University of Manchester is also part of this project providing independent network modelling and analysis of the trial data. The MEA project aims to implement and evaluate the performance of an innovative, cost-effective operational approach (i.e., the ESPRIT Technology) to control the EV charging points in the LV distribution networks. This will allow more EVs to be connected to LV networks without the need of traditional reinforcements, thus deferring investment.

This report focuses on the following Deliverables:

— Deliverable 5.1: Scenario-based deterministic impact studies on validated MEA feeders and representative feeders from the “Low Voltage Network Solutions” (LVNS) project considering the ESPRIT Technology (i.e., disconnect/ reconnect) EV charging points; and,
— Deliverable 5.2: Economic and environmental assessment of the benefits of adopting the ESPRIT Technology to cope with high penetrations of EVs.

Considering only carbon emissions related to the assets, the largest CO2e contributor within the ESPRIT Technology is the ICB given that the number of units required is directly related to the EV penetration level. Consequently, any improvements in the corresponding manufacturing process, in terms of emissions, would significantly benefit the overall CO2e savings.

In general, the largest CO2e emissions, either using the ESPRIT Technology or reinforcing the network, corresponds to the energy losses along the life cycle rather than those embodied in the assets.
To address Deliverable 5.1, this report introduces an ESPRIT-based control algorithm (ESPRIT) is a patent filed by EA Technology Limited [11]) that is adopted to carry out scenario-based deterministic impact studies on the validated and representative LV networks that were introduced in [2-4] (i.e., Work Activity 2 “Low Voltage Networks”, Work Activity 3 “Model Validation and Data Analysis” and Work Activity 4 “Business as Usual Deterministic Impact Studies”). In order to extend the impact studies presented in [4], this report investigates EV penetration levels up to 150%. These studies are carried out considering the Business As Usual (BaU) operation of EVs, i.e., without management, as well as the scenario where the ESPRIT-based control algorithm is enabled.

To address Deliverable 5.2, this report presents an economic and environmental assessment of the adoption of the ESPRIT-based control (which uses the infrastructure adopted in the MEA project). This assessment considers the cost of adopting the technology (provided by EA Technology), EV uptake rates defined in [5] (report produced for the Department of Energy and Climate Change, DECC), and quantifies the investment as a net present value. The economic and environmental assessment is compared against the reinforcement results presented in [4] (i.e., Work Activity 4), and extended to EV penetration levels up to 150%, to quantify the benefits of adopting the ESPRIT Technology (or similar ones – e.g., [6, 7]) to manage the demand from EVs.

2.3 ESPRIT-ENABLED DETERMINISTIC IMPACT STUDIES

This chapter assesses in a deterministic approach the technical benefits of adopting a control strategy (i.e., an ESPRIT-based control algorithm) for managing EV charging points in residential LV networks.

This assessment uses the nine validated residential LV feeders involved in the MEA project (i.e., five belonging to SSE Power Distribution and four to Northern Powergrid), the non-validated commercial feeder belonging to SSE Power Distribution and four to Northern Powergrid (see [11]), to investigate more than one EV per household.

The impact assessment methodology introduced in [4] (i.e., adopting the ESPRIT control strategy) is enabled. This methodology is implemented in each LV feeder (a total of 20 LV feeders are assessed) for penetration levels ranging from 0 to 150% in steps of 10%. A penetration level indicates the number of houses with an EV. Penetration levels larger than 100% are assessed in this report to investigate more than one EV per household.

2.3.1 ESPRIT-BASED CONTROL ALGORITHM

This section details the ESPRIT-based control algorithm that is considered in this report to manage EV charging points to mitigate thermal problems at the head of the feeders (first segment). The mitigation of voltage problems and thermal problems at the transformer is not considered in this report. However, this is thoroughly investigated in [7].

Figure 40 shows the architecture of the control strategy as deployed in the MEA trial. The key infrastructure required includes: actuators at the charging points (i.e., an Intelligent Control Box, ICB), communication links (i.e., Power Line Carried, PLC), current sensors at the head of the LV feeders (i.e., monitor), and a control unit (i.e., controller) at the substation.

![Figure 40](image)

**FIGURE 40: ARCHITECTURE DEPLOYED IN THE MEA PROJECT FOR EV MANAGEMENT**

Similar to the control algorithm currently deployed in the trials [12], as well as others more advanced (e.g., [6, 7]), the control algorithm considered in this report checks for thermal issues at the head of the feeder (per phase) every control cycle. Every check, it collects the (average) phase currents at the head of the feeders and the status of each EV charging point (i.e., charging or not charging). The latter is used by an internal counter (e.g., at the control unit) that only takes into account the minutes from the start of a charging event until its un-controlled end (when the counter is reset). This internal counter is used to define the most suitable EVs to be managed, as detailed below.

### DISCONNECTION

To mitigate thermal problems, the controller calculates the number of EV charging points needed to lower the phase current below a corresponding threshold. If the phase current (in phase i), \( i_{t, i} \), at the head of the feeder (first segment) exceeds a threshold \( \alpha \) (e.g., \( \alpha = 1 \)), which corresponds to a 100% of the cable capacity \( i_{c, i} \), the control algorithm determines the number of EV charging points, \( X_i \), that must be disconnected in phase \( i \) to mitigate the thermal problem. The number \( X_i \) is determined as follows:

\[
X_i = \left\lfloor \frac{i_{t, i} - \beta i_{c, i}}{\delta i_{c, i}} \right\rfloor \quad (1)
\]

where the bracket \( \lfloor \cdot \rfloor \) represents the ceiling function (i.e., rounding up values), and \( IEV \) is the phase current lower than a corresponding threshold.

Once the number of EV charging points to be switched off is calculated, the next step is to decide which EV charging points are to be managed. The control algorithm considers as the most suitable ones those at the top of a ranking list (connected to the phase with problems) based on the corresponding charging times, i.e., adopting a first-in first-out approach. The charging time of each EV is computed by the internal counter. Once the number and selection of EV charging points to be disconnected are defined, the corresponding EV charging points are disconnected 1 min later.

In this practice, the delay would correspond to a 1 min delay. 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 are to be managed. The control algorithm considers as the most suitable ones those at the top of a ranking list (connected to the phase with problems) based on the corresponding charging times, i.e., adopting a first-in first-out approach. The charging time of each EV is computed by the internal counter. Once the number and selection of EV charging points to be disconnected are defined, the corresponding EV charging points are disconnected 1 min later.

In this practice, the delay would correspond to a 1 min delay. This process is repeated for each of the phases of the feeder.

### RECONNECTION

If at the start of the control cycle no thermal problems are detected, some previously managed EV charging points are reconnected adopting a security margin. To achieve this, the controller calculates the number of EVs that can be connected whilst leading to a total phase current lower than a corresponding threshold.

If the phase current, \( i_{t, i} \), in the feeder is below a security margin, \( \beta \), of its limits, a number of EV charging points, \( Y_i \), that can be reconnected in that particular phase is defined as follows:

\[
Y_i = \left\lfloor \frac{i_{t, i} - \beta i_{c, i}}{\delta i_{c, i}} \right\rfloor \quad (2)
\]

It is important to mention that the security margin, \( \beta \), allows catering for the unforeseen arrival of other EVs in that phase of the feeder. For simplicity, \( \beta \) is always set 10% below \( \alpha \) in this report.

When the number of EV charging points that can be reconnected is defined, the control algorithm determines the most suitable ones. For this, an inverse ranking to that of the disconnection is adopted, i.e., those EVs with the lowest charging time (as counted before the disconnection) are those to be reconnected first.

Once the number and selection of EV charging points to be reconnected are defined, the corresponding EV charging points are reconnected after 1 min.

2.3.2 ESPRIT-ENABLED DETERMINISTIC IMPACT STUDIES: EXAMPLE LV FEEDER

The phase current at the head of the feeder (first segment), voltage at customer connection points, and energy losses are investigated in this report to quantify the technical benefits of the ESPRIT-based control algorithm in managing EV charging points to avoid thermal problems. The assessment metrics adopted here are those defined in Work Activity 4 [4].

For completeness, the simulation results considering the ESPRIT-based control algorithm (introduced in section 2.3.1) are compared with those of the BaU case (i.e., without management). This section in particular compares the results on the Corney Road LV feeder (the most populated LV feeder in the MEA project) per penetration level (from 0 to 150%) and for different seasons and days. Section 1.3.5 summarises the EV impacts on the remaining residential LV feeders involved in the MEA project for every penetration level, every season, and both weekdays and weekends. Appendix B.1 presents all the results for each LV feeder involved in the MEA project.
It is important to mention that a line-to-line voltage of 424V (i.e., 1.06 p.u.) is considered at the secondary of the transformer, which is aligned with the Distribution Network Operators (DNOs) practice. The control cycle is defined to be 10 minutes (i.e., the average current used in the control algorithm corresponds to a 10-min window). This is done so as to meet the constraints imposed by EV battery manufacturers (i.e., connection/disconnection frequency should be higher than 6 minutes [12]). The disconnection threshold, $\alpha$, is set to 1 (i.e., 100% of the asset capacity) and the security margin for reconnections, $\beta$, is defined as 0.1 (i.e., 10% below the asset limit; in this report, $\beta$ is always set 10% below the limit imposed by $\alpha$). The effects of these control settings are investigated in section 1.2.

**THERMAL PROBLEMS**

To understand the technical benefits of adopting the ESPRIT-based control algorithm, the utilization factor at the head of the feeder is calculated. The utilization factor is quantified as the 10-minute maximum current divided by the ampacity (cable rating) of the first segment of the feeder [4].

For a typical weekday during winter (i.e., January), Figure 11 shows the phase current for a 24-hour period (10-min average) for a 100% EV penetration level considering both scenarios: the BaU and the ESPRIT-Enabled (i.e., adopting the ESPRIT-based control algorithm). As expected (see section 2.4 of [4]) if every house on the Corney Road LV feeder has an EV, the phase current exceeds the capacity of the cable (374 A), thus resulting in an utilization factor on the Corney Road LV feeder for a 100% EV penetration of 134% (i.e., 34% over the cable capacity).

Crucially, Figure 11 highlights that the use of the ESPRIT-based control algorithm (adopting the control settings defined above, i.e., 10-min control cycle, $\alpha = 1$ and $\beta = 0.1$) can considerably reduce the utilization factor of the feeder to 114% (i.e., a reduction of 20% for a very high EV penetration). Indeed and as further discussed in section 1.2, the ESPRIT-based control algorithm can completely mitigate thermal problems by adopting shorter control cycles or a more conservative approach to disconnect EV charging points (e.g., by disconnecting EV charging points for lower values of $\alpha$).

Finally, it is important to note in Figure 11 the autonomy across phases of the ESPRIT-based control algorithm. A phase without thermal problems (e.g., Phase A) will not be affected by the strategy. This is beneficial as it guarantees that EV users connected on a phase without problems will not be disconnected.

The above analysis has also been done for every EV penetration level (from 0 to 150% in steps of 10%) and for typical weekdays and weekends across seasons (i.e., winter, shoulder, and summer). The shoulder season refers to spring and autumn seasons (see [4] for more details). Considering the control settings mentioned above, Figure 14 highlights that the ESPRIT-based control algorithm reduces in approximately 20% (on average) the utilization factor of the feeder for high penetration levels. Crucially, Figure 14 shows that the control algorithm increases the hosting capacity (defined as the previous penetration level at which the feeder presents problems) of the Corney Road LV feeder. Indeed, if shorter control cycles or a more conservative approach is adopted, it can allow high EV penetration levels without violating the thermal limits of the cables (see section 1.2 for details).

**FIGURE 41: THERMAL ANALYSIS FOR WINTER WEEKDAYS – CORNEY ROAD, 100% EV PENETRATION**

(a) Phase A

(b) Phase B

(c) Phase C
VOLTAGE PROBLEMS
This section quantifies the benefits of the ESPRIT-based control algorithm in terms of voltages (according to the British Standard BS EN 50160 [13], adapted to the UK statutory limits). Similar to the analysis presented in [4], the number of customers with voltage problems is calculated in each simulation. To calculate this, the daily voltage profiles (1-min resolution) for each customer in the feeder are averaged in 10 minutes to make the calculation according to BS EN 50160.

The Corney Road LV feeder does not present any customer with voltage problems for any of the penetrations and seasons analysed (see the Appendix B.1 for details). Considering a typical weekday during winter (same simulation as in Figure 11), Figure 43 shows for a 100% penetration the minimum voltage per phase across all houses at every 10 min for a 24 hours period both without (BaU) and with (ESPRIT-Enabled) management. The effect of managing some EV charging points can be seen in the voltage profile in this feeder. In general, the voltages are improved during peak time by using the ESPRIT-based control algorithm given that the demand is managed.

ENERGY LOSSES
The objective of the ESPRIT-based control algorithm is to avoid thermal problems. To achieve this, it manages the demand. Although the control algorithm effectively moves demand from one moment to another, it is still important to understand the extent to which daily energy losses might be affected. This section calculates the corresponding losses. To present the results as the percentage of the total energy demanded, the energy losses are divided by the total energy consumption in the feeder.

Figure 15 shows the results for each penetration, season and both typical weekdays and weekends. It can be concluded that the energy losses are not significantly reduced by the use of the ESPRIT-based control algorithm (on average, the energy losses are reduced in 9% for high EV penetration levels).
1.2 EFFECTS OF CONTROL SETTINGS

As previously mentioned, shorter control cycles (e.g., 1 min) and a lower disconnection threshold, $\alpha$, (and consequently a higher security margin $\beta$, see equations (1)-(2) for more details) can improve the utilization factor of the feeder, as also discussed in [7]. This section investigates the effects, particularly on the utilization factor of the feeder, of changing these control settings.

Figure 45 shows the phase current at the head of the Corney Road LV feeder considering three cases: (a) BaU; (b) ESPRIT-Enabled with 10-min control cycle (as in section 2.3.2); and (c) ESPRIT-Enabled with 1-min control cycle. These results consider $\alpha = 1$ and $\beta = 0.1$. It can be seen that a control cycle of 1 min considerably reduces the utilization factor of the feeder from 134% (without management) to 99% (i.e., it mitigates thermal problems). This very frequent control cycle is capable of reacting quickly to the unexpected arrival of EVs (i.e., new EV connections). Conversely, the slower response of the 10-min control cycle results in a reduction of the utilization factor from 134% to only 114%, i.e., problems still exist (see section 0).
The ESPRIT-based control algorithm can also be adjusted to carry out disconnections for a lower disconnection threshold \( \alpha \) (e.g., 85% of the asset capacity). This preventive disconnection approach can be used to further reduce the utilization factor of the feeder [7]. Indeed, Figure 46 highlights that a disconnection threshold \( \alpha = 0.85 \) completely mitigates the thermal problems for a 100% EV penetration level (from a 134% utilization factor to 100%) on the Corney Road LV feeder (the most loaded feeder in the MEA project) even with a control cycle of 10 min.

In conclusion, the ESPRIT-based control algorithm is a very effective strategy that can be adapted to completely mitigate thermal problems in LV feeders. Shorter control cycles can reduce the impacts of EVs; nonetheless, this may not be practical due to the limitations imposed by EV battery manufacturers [12]. On the other hand, the disconnection threshold, \( \alpha \), can be reduced to mitigate thermal problems for high EV penetration levels (up to 150%); however, this practice may affect customer acceptability.

Therefore, a compromise must be achieved in practical implementations to mitigate thermal problems, while ensuring that EV charging needs are kept within acceptable limits. The results presented here adopt a 10-min control cycle given that this is more likely to be used in practice to satisfy battery constraints. The concept of dynamic settings is investigated here by which the values of \( \alpha \) are produced using a rule and the EV penetration level (\( \beta \) is always defined as 0.1 below the limit imposed by \( \alpha \)). This approach defines the disconnection threshold at which no thermal problems are experienced, \( \alpha_{\text{no-problems}} \).

To illustrate this approach, the Corney Road LV feeder is now used considering winter weekdays. In this LV feeder, the highest EV penetration for which no thermal problems are experienced is 40% (see Figure 14), i.e., \( \alpha_{\text{no-problems}} = 40\% \). In addition, it was found that a disconnection threshold of 0.7 solves the thermal problems at 150% EV penetration, i.e., \( \alpha_{150\%} = 0.7 \). Therefore, the disconnection threshold \( \alpha \) as a function of the penetration for the Corney Road LV feeder during winter weekdays is:

\[
\alpha = \frac{1 - \alpha_{\text{no-problems}}}{\frac{150}{EV_{\text{penetration}}}} + 1
\]

To illustrate this approach, the Corney Road LV feeder is now used considering winter weekdays. In this LV feeder, the highest EV penetration for which no thermal problems are experienced is 40% (see Figure 14), i.e., \( EV_{\text{penetration}} = 40\% \). In addition, it was found that a disconnection threshold of 0.7 solves the thermal problems at 150% EV penetration, i.e., \( \alpha_{150\%} = 0.7 \). Therefore, the disconnection threshold \( \alpha \) as a function of the penetration for the Corney Road LV feeder during winter weekdays is:

\[
\alpha = \frac{1 - 0.7}{\frac{150}{EV_{\text{penetration}}} - 40} + 1
\]

Similar equations have been defined per season per feeder for those feeders with thermal problems at some penetration level (see Appendix A.1). In this report, it is considered that weekdays and weekends of the same season will have the same threshold.
Figure 47 illustrates the number of MEA feeders that present technical problems (i.e., thermal and/or voltage) for each EV penetration level considering the BaU and the ESPRIT-Enabled scenarios. Without management, it can be seen that thermal problems start at 50% in one feeder. Crucially, it is clear that the use of the ESPRIT-based control algorithm with dynamic settings completely mitigates the thermal problems, thus increasing the hosting capacity of all the feeders (up to the highest investigated penetration level of 150%).

It is important to mention that the control settings considered here (10-min control cycle and the dynamic $\alpha$) may need to be assessed in terms of customer acceptability, given that these may result in significant number of disconnection and charging delays. The latter is quantified in this report for the LVNS feeder in section 2.3.4.

### 2.3.3 Your Homes (Commercial Trial)

The ESPRIT-based control algorithm has also been used to control EV charging points in the commercial LV feeder involved in the MEA project (Your Homes). The demand (per phase) and the EV charging behaviour have been produced using the data for this LV feeder (see [4] for more details). Only weekdays are considered for this LV feeder given its commercial use.

Two scenarios are investigated. First, the disconnection threshold and security margin are defined as $\alpha = 1$ and $\beta = 0.1$ (similar to the control settings investigated in section 2.3.2). Then, 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 48 demonstrates that the ESPRIT-based control algorithm presented here (and similar ones) can also be adopted to effectively manage EV charging points in commercial LV feeders.
2.3.4 REPRESENTATIVE LVNS FEEDERS

This section summarises the technical benefits of adopting the ESPRIT-based control algorithm (section 2.3.1) on the eight LVNS feeders and the two rural feeders (see [4]). The assessment has been carried out for each season as well as weekdays and weekends, and considering EV penetration levels up to 150%. The Appendix B.2 details the results for all these representative LV feeders. It should be mentioned that these results consider a 10-min control cycle. This longer 10-min control cycle is adopted to reflect the potential practical limitations imposed by EV battery manufacturers [12]. For those feeders with thermal problems, a dynamic disconnection threshold \( \alpha \) has been defined as explained in section 1.3 (the corresponding equations are detailed in Appendix B.2).

Table 4 shows the penetration level for which each LVNS feeder (and the two rural) presents the first technical problem (thermal or voltage) without the ESPRIT-based control algorithm. The hosting capacity for a given feeder corresponds to the previous penetration level (i.e., minus 10%). Note that a “--” indicates that no problems occur on the feeder as it can cope with the highest EV penetration studied (150%). As noticed, only four LVNS feeders present a technical problem for a given EV penetration. Moreover, weekdays in winter are in general the bottleneck. This is expected given the coincidence between the residential demand (highest during the year) and the demand from EVs.

**TABLE 19: EV PENETRATION LEVEL (%) FOR FIRST PROBLEM IN LVNS AND RURAL FEEDERS**

<table>
<thead>
<tr>
<th>LV FEEDER NAME</th>
<th>WINTER</th>
<th>SPRING/AUTUMN</th>
<th>SUMMER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WEEKDAY</td>
<td>WEEKEND</td>
<td>WEEKDAY</td>
</tr>
<tr>
<td>Feeder 1</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Feeder 2</td>
<td>70</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Feeder 3</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Feeder 4</td>
<td>40</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Feeder 5</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Feeder 6</td>
<td>50</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>Feeder 7</td>
<td>70</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>Feeder 8</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Rural 1</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Rural 2</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Figure 17 shows the number of feeders without (i.e., BaU) and with management (i.e., ESPRIT-Enabled) that presents technical problems for each day and season. It can be seen that adopting a 10-min control cycle with a dynamic disconnection threshold \( \alpha \) completely mitigates thermal problems, thus allowing the adoption of more EVs (up to 150% has been investigated in this report). Moreover, the use of the control algorithm reduces the number of feeders with voltage problems, although the ESPRIT-based control algorithm only aims to solve thermal issues.
Any control action, however, may affect customer acceptability (i.e., EVs may remain disconnected for long periods). Therefore, the EV charging delays must be quantified. Assessing this is critical to determine if the expectations of comfort are met and to promote customer acceptance [7]. The charging delays are quantified in this report for each of the LVNS feeders with thermal problems and winter weekdays (the worst case scenario). This charging delay quantifies the time (in a 15-min resolution) that the EV remained disconnected due to the control. Given the typical duration of the domestic peak demand (17:30h – 20:30h [4]), a maximum time delay of 180 min is considered here. If there is a delay longer than 180 min, this will be grouped in 180+ (see Figure 50 to Figure 53).

Figure 50 to Figure 53 show for each LVNS feeder the number of EVs (in percentage of the total number of EVs for the given penetration) that had a delay in the charging process (up to 180min or more). It can be seen that as the EV penetration level increases, the number of EVs that are never managed (i.e., those with delay = 0) decreases. Crucially, it can be seen that the number of EVs with significant charging delays significantly increases for high penetration levels. Indeed, it can be observed for Feeder 4 that penetration levels higher than 100% result in more than 40% of the EVs with a charging delay higher or equal to 180min+ (i.e., 3 hours or more).

It is important to note that the number of EV users with significant time delays can be reduced by adapting the control algorithm to prioritise EV charging points that have remained managed for long periods. This prioritisation, however, is not detailed in this report as it is out of its scope. The analyses considering this approach, nonetheless, have been carried out by The University of Manchester and they highlight that the number of EV users with long delays is commonly spread across shorter ones. In general, this approach has been found to reduce in approximately 4% the number of EV users with time delays of 180 min or more.

In conclusion, the ESPRIT-based control algorithm with dynamic settings can mitigate thermal problems in the LVNS feeders. This can be achieved by disconnecting EV charging points before the rating capacity of the cable is reached. This, however, may result in charging delays that may considerably affect customer acceptability.
2.3.5 REMARKS
— An ESPRIT-based control algorithm has been presented to manage EV charging points to mitigate thermal problems (only) in LV feeders.
— The ESPRIT-based control algorithm checks the occurrence of problems per phase, thus enabling EV users in a phase without thermal problems to charge with no effects.
— Its effectiveness has been demonstrated on nine residential LV feeders involved in the MEA project, a commercial LV feeder also involved in the MEA project, and ten residential representative LV feeders. The assessment was carried out for different EV penetrations (from 0 to 150% in the case of the residential LV feeders), seasons and type of days.
— It has been shown that the management of the EV demand improves the voltages in the network (reducing the demand decreases the voltage drop along the feeder).
— It has also been presented that the improvement in terms of energy losses (as a by-product of the thermal management) is approximately 9% for high EV penetrations.
— It has been demonstrated that shorter control cycles (e.g., 1 min) can considerably improve the performance of the control. This, however, may not satisfy the constraints imposed by EV battery manufacturers (i.e., control action frequency should be lower than once every six minutes).
— Crucially, it has been shown that a 10-min control cycle along with a lower disconnection thresholds (i.e., disconnection of EV charging points before the asset reaches its limit) can lead to the complete mitigation of thermal problems even for the highest EV penetration level (i.e., 150% here).
— The use of dynamic settings, i.e., disconnection thresholds in function of the penetration level, has been proposed. The effectiveness of this approach has been demonstrated in all the residential LV feeders with thermal problems (two MEA feeders and four LVNS feeders).
— In the particular case of the LVNS feeders, it has been highlighted that a 10-min control cycle with a dynamic disconnection threshold leads to the full mitigation of thermal problems. Moreover, the number of feeders with voltage problems has been reduced. Nonetheless, this approach results in charging delays on the EVs that require to be compared against customer satisfaction levels (i.e., customer acceptance, which is out of the scope of this report).

2.4 ECONOMIC AND ENVIRONMENTAL BENEFITS OF ESPRIT
To understand the economic and environmental benefits of adopting the ESPRIT-based control algorithm (or eventually the ESPRIT Technology), this section investigates the potential cost and carbon emissions of adopting this practical solution in residential LV feeders.

For completeness, the results are compared with those of adopting the traditional network reinforcement approach (which do not consider the replacement of the transformer) see [4] for more details). This chapter focuses on the two MEA LV feeders that have thermal overloads (section 1.3), i.e., Corney Road and Cufaude Village. The scenarios produced by DECC for EV uptake in the UK [5] are adopted. In addition to the infrastructure detailed in section 2.3.1 (i.e., ICBS, communication links, as well as a monitor and controller at the substation), signal repeaters are considered as they are likely to be required if Power Line Carrier-based communications are adopted.

2.4.1 ECONOMIC ASSESSMENT
To assess the cost of this practical solution (i.e., ESPRIT Technology), this section presents a simplified methodology that calculates the investment cost (CAPEX) plus the corresponding (10%) of new ICBs plus the operational expenditure (OPEX). When the investment cost is defined, the cost is determined for each simulation presented in section 1.3 (each penetration level is independently assessed).

This investment cost considers both the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). When the investment cost is defined, the OPEX for each simulation presented in section 1.3 (each penetration level is independently assessed). This investment cost considers both the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). When the investment cost is defined, the OPEX for each simulation presented in section 1.3 (each penetration level is independently assessed).

The installation plus investment cost used in this analysis is calculated considering the number of customer that adopt the technology up to that point in time.
The investment methodology to adopt the ESPRIT Technology is applied considering the winter-weekday scenario (worst-case scenario in all the MEA feeders). It is important to highlight that, considering the initial year as 2015, the total net present cost considers the sum of all the reinforcements needed along the years up to 2050 (150% EV penetration).

Table 5 and Table 21 present the net present cost of adopting the technology on both the Corney Road and Cufaude Village LV feeders. Updated reinforcement costs required on these LV feeders (see [4] for the reinforcement methodology) can be observed in Table 22. It is important to mention that the adoption of the reinforcement methodology [4] has resulted only in the replacement of the first 100m of cable. This is likely to be due to the characteristics of these two LV feeders. It can be seen that the cost of adopting the ESPRIT Technology is higher than that of replacing the cable.

<table>
<thead>
<tr>
<th>Year of Investment (EV Penetration)</th>
<th>Net Present Cost (£)</th>
<th>Year of Investment (EV Penetration)</th>
<th>Net Present Cost (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2034 (50%)</td>
<td>12666</td>
<td>2034 (50%)</td>
<td>5813</td>
</tr>
<tr>
<td>2037 (60%)</td>
<td>2097</td>
<td>2039 (80%)</td>
<td>7831</td>
</tr>
<tr>
<td>2038 (70%)</td>
<td>2026</td>
<td>2044 (110%)</td>
<td>9066</td>
</tr>
<tr>
<td>2040 (80%)</td>
<td>1891</td>
<td>2049 (140%)</td>
<td>11454</td>
</tr>
<tr>
<td>2041 (90%)</td>
<td>1828</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2043 (100%)</td>
<td>1706</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2044 (110%)</td>
<td>1897</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2046 (120%)</td>
<td>1788</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2048 (130%)</td>
<td>1685</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2049 (140%)</td>
<td>1636</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2050 (150%)</td>
<td>1589</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Investment</strong></td>
<td><strong>30809</strong></td>
<td><strong>Total Investment</strong></td>
<td><strong>34163</strong></td>
</tr>
</tbody>
</table>

The reinforcement costs in these LV feeders are lower because of the length of cable needed to be replaced to solve the thermal problem in these LV feeders (>100m). Moreover, the replacement costs that have been used in this report are based on Ofgem’s allowable costs. As such, they may not be appropriate for all networks and other solutions are likely to have higher associated costs.

However, it is possible that reinforcement costs significantly increase in other types of LV feeders (e.g., the LVNS feeders). Therefore, it is important to also investigate the reinforcement methodology in the LVNS feeders to quantify the economic benefits of adopting the ESPRIT Technology in a more diverse set of residential LV feeders.

2.4.4 ENVIRONMENTAL ASSESSMENT

This section presents a simplified methodology to quantify the environmental benefits of adopting the ESPRIT Technology. For completeness, this is compared against the traditional network reinforcement approach. This quantification is undertaken until 2050 considering the EV uptake rates shown in Figure 19 [5] and assuming a life cycle of the components of 35 years (i.e., from 2015).

The carbon quantification considering the traditional network reinforcement only quantifies the carbon impact of replacing the cable and the benefits in terms of energy losses [15-17]. However, the replacement of the transformer may need to be considered in further studies. It is also important to note that network reinforcement (i.e., replacing of cables for bigger one) results in smaller impedances, which in turn leads to less energy losses. The emissions factor of replacing the cable considered in this report is based on the industrial project “Capacity to Customers” [18]. It corresponds to 59 kgCO2e/m [16]; however, it can increase up to 75 kgCO2e/m depending on several factors such as the precedence of the copper [16]. This figure includes cables, joints and installation [16], and it considers a detailed assessment of civil engineering works.
METHODOLOGY

The carbon emissions associated with the ESPRIT Technology consist of two aspects: (i) the manufacture and deployment of the devices required on the network, i.e., carbon impacts of assets; and (ii) the operation of the electricity LV network once the technology is adopted, i.e., carbon impacts of operations. While the former is associated with the infrastructure required to implement the technology, the latter considers both carbon emissions given the operation of the ESPRIT Technology over time (technical crew visiting the place when providing maintenance), and the savings in energy.

CARBON IMPACTS OF ASSETS

The emissions caused by this infrastructure depend on the initial installation (monitor, controller, and initial number of ICBs which is considered to include the corresponding communications). Moreover, as the penetration levels increase, the carbon impact of adopting the technology increases (more ICBs are needed). To determine the carbon emissions, the estimated carbon content of the assets is required. However, these values have not been provided by EA Technology. An attempt to illustrate the methodology, electronic components available in the market that are similar (the manufacture line follows a comparable process) are considered in this report (and agreed with EA Technology).

Table 23 shows the original asset that is used in the trial and the equivalent asset considered in this report along with its corresponding emissions factor. Given that similar component could not be found for the monitor at the substation this is not considered. It is important to mention that life cycle assessment studies are highly sensitive to internal study assumptions, data sources, variations in processes and products under study, emissions of unknown but high-impact materials, etc. As such, the figures presented below may change if more accurate emission factors become available.

TABLE 23: CARBON CONTENT OF THE (EQUIVALENT) ASSETS FOR ADOPTING ESPRIT

<table>
<thead>
<tr>
<th>ASSET CARBON CONTENT (OF THE EQUIVALENT) ASSETS FOR ADOPTING ESPRIT</th>
<th>ASSET</th>
<th>EMISSIONS FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Asset</td>
<td>Replaced Asset</td>
<td>Emissions Factor</td>
</tr>
<tr>
<td>ICB + Communications [19]</td>
<td>Dell FX-100 Zero Client</td>
<td>33.6 kg CO2e/device</td>
</tr>
<tr>
<td>Monitor and Controller [19]</td>
<td>Dell Optiplex 780 ultra-small</td>
<td>73.5 kg CO2e/device</td>
</tr>
<tr>
<td>Repeater [19]</td>
<td>HP Mini 110 CA Netbook, 10&quot;</td>
<td>62.2 kg CO2e/device</td>
</tr>
</tbody>
</table>

OPERATIONS CARBON IMPACTS

The operation of the LV network once the technology is adopted will also have an impact on the carbon emissions. In terms of energy losses, these will have to be compared against the energy losses of network reinforcement. Previous studies have found that energy losses can be significant in the carbon assessment of a technology [15]. Moreover, technical personnel (e.g., crew from the DNO) will travel to provide the corresponding maintenance of the technology, thus increasing carbon emissions. It is considered that this travel occurs every five years, as for the OPEX. Table 23 also shows the emissions factor for these two aspects. An average new car fuel consumption of 4.87 Litres per 100 km is considered according to the Department for Transport [21].

TABLE 24: ENVIRONMENTAL ASSESSMENT (ESPRIT TECHNOLOGY) CORNEY ROAD LV FEEDER

| RESULTS | This section presents the environmental assessment results caused by the adoption of the ESPRIT Technology in the MEA feeders (presented only for those with problems). The EV uptake scenario presented in Figure 19 (i.e., scenarios 2-3, highest uptake [5]) is also used here.

Table 24 and Table 25 show the carbon emissions of adopting the ESPRIT Technology on the two LV feeders involved in the MEA project that presented thermal problems (i.e., Corney Road and Cufaude Village).

Table 26 presents the environmental assessment of reinforcement. It is important to mention that this study is divided into the carbon emissions resulting from the deployment/replacement of assets and those from the operation of the network in the next 35 years. Moreover, it should be noted that losses produce a significant amount of CO2e given the operation of the LV network in the years.

| ASSET | OPERATION |
|---|---|---|
| Year (EV Penetration) | Emissions (tCO2e) | Energy Losses Emissions (tCO2e) | Travel Emissions (tCO2e) |
| 2034 (50%) | 2.719 | 22.611 | 0.001 |
| 2037 (60%) | 0.492 | 8.792 | 0.000 |
| 2038 (70%) | 0.492 | 20.002 | 0.000 |
| 2040 (80%) | 0.492 | 11.280 | 0.000 |
| 2041 (90%) | 0.492 | 23.567 | 0.000 |
| 2044 (110%) | 0.492 | 25.533 | 0.001 |
| 2046 (120%) | 0.492 | 24.963 | 0.000 |
| 2048 (130%) | 0.492 | 12.200 | 0.000 |
| 2049 (140%) | 0.492 | 11.875 | 0.001 |
| 2050 (150%) | 0.492 | 11.644 | 0.000 |
| Total | 7.639 | 185.140 | 0.004 |

For the assumed data and from an asset point of view, it can be observed that adopting the ESPRIT Technology in Corney Road LV feeder is environmentally more beneficial (7.639 tCO2) than network reinforcement (11.800 tCO2). This occurs as Corney Road LV feeder requires two reinforcements (at 50% and at 100%). On the other hand, network reinforcement on Cufaude Village LV feeder (5.900 tCO2) has been found to be more environmentally friendly than adopting the ESPRIT Technology (6.302 tCO2), although the difference is not so significant (<10%). Finally, it has been identified that the component that results in the highest carbon emission is the ICB + communications. This is particularly important given that the number of ICBs increases with the number of EV users.
From the operation point of view, it can be noted that the largest CO2e emissions, either using the ESPRIT Technology or reinforcing the network, corresponds to the energy losses along the life cycle rather than those embodied in the assets.

From an environmental point of view, and particularly due to CO2e emissions resulting from the operation of the LV network, it can be concluded that the ESPRIT Technology is slightly less environmentally friendly. Although the resulting CO2e emissions in Corney Road LV feeder are as much as those from network reinforcement (~1% difference), this is not the case for Cufaude Village LV feeder (the CO2e emissions are approximately 20% higher than reinforcement).

### 2.4.3 REMARKS

#### ECONOMIC ASSESSMENT

— The environmental assessment has highlighted that an ESPRIT Technology investment of circa £65,000 in Corney Road is needed to cope with EV penetrations up to 2050 (which corresponds to 150%). The second feeder with issues, Cufaude Village, would require an investment of £45,000. On the other hand, traditional reinforcements would cost circa £10,000 and 5,000 for Corney Road and Cufaude Village, respectively. It is important to mention that the adoption of the reinforcement methodology has resulted only in the replacement of the first 100m of cable.

— Although the traditional reinforcements are cheaper, it is important to highlight that the investment costs for the ESPRIT Technology are expected to decrease significantly with mass production and in time. Operational costs, which account for around half of the overall net present value, are also expected to decrease with the maturity of the technology as well as communication services. Additionally, the investment costs also assume the ‘ESPRIT Technology’ will be deployed in the same manner as that trialled in the project, specifically that an additional unit requires installation at each charging point rather than being integrated directly within the charging point. Conversely, the cost adopted for the replacement of underground cables can also vary according to the local or regional characteristics. In addition, the costs used here are based on Ofgem’s allowable costs. As such, they may not be appropriate for all networks and other solutions are likely to have higher associated costs.

### ENVIRONMENTAL ASSESSMENT

— An economic assessment that quantifies the carbon emissions of adopting the ESPRIT Technology until 2050 (i.e., assuming a life cycle of the components of 35 years from 2015) has been carried out considering the DECC scenarios for EV uptake [5] and only the two MEA feeders that present thermal problems at some EV penetration level (i.e., Corney Road and Cufaude Village – which have similar customer and length characteristics). These results have been compared against the investment cost of adopting traditional network reinforcements (i.e., replacement of conductors), which has been previously presented in Work Activity 4 [4].

<table>
<thead>
<tr>
<th>YEAR (EV PENETRATION)</th>
<th>CORNEY ROAD EMISSIONS (tCO2e)</th>
<th>CUFARDE VILLAGE EMISSIONS (tCO2e)</th>
<th>ASSET</th>
<th>OPERATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>2035 (50%)</td>
<td>5,900</td>
<td>22,014</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2037 (60%)</td>
<td>–</td>
<td>8,195</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2038 (70%)</td>
<td>–</td>
<td>18,410</td>
<td>5,900</td>
<td>9,744</td>
</tr>
<tr>
<td>2040 (80%)</td>
<td>–</td>
<td>10,683</td>
<td>–</td>
<td>5,248</td>
</tr>
<tr>
<td>2041 (90%)</td>
<td>–</td>
<td>22,373</td>
<td>–</td>
<td>10,814</td>
</tr>
<tr>
<td>2043 (100%)</td>
<td>5,900</td>
<td>11,877</td>
<td>–</td>
<td>5,868</td>
</tr>
<tr>
<td>2044 (110%)</td>
<td>–</td>
<td>24,339</td>
<td>–</td>
<td>12,304</td>
</tr>
<tr>
<td>2046 (120%)</td>
<td>–</td>
<td>24,565</td>
<td>–</td>
<td>12,354</td>
</tr>
<tr>
<td>2048 (130%)</td>
<td>–</td>
<td>12,300</td>
<td>–</td>
<td>6,757</td>
</tr>
<tr>
<td>2049 (140%)</td>
<td>–</td>
<td>12,330</td>
<td>–</td>
<td>7,060</td>
</tr>
<tr>
<td>2050 (150%)</td>
<td>–</td>
<td>12,440</td>
<td>–</td>
<td>7,480</td>
</tr>
<tr>
<td>Total</td>
<td>11,800</td>
<td>179,525</td>
<td>5,900</td>
<td>77,628</td>
</tr>
</tbody>
</table>

From an environmental point of view, and particularly due to CO2e emissions resulting from the operation of the LV network, it can be concluded that the ESPRIT Technology is slightly less environmentally friendly. Although the resulting CO2e emissions in Corney Road LV feeder are as much as those from network reinforcement (~1% difference), this is not the case for Cufaude Village LV feeder (the CO2e emissions are approximately 20% higher than reinforcement).

### ENVIRONMENTAL BENEFITS OF REINFORCING THE LV NETWORK

<table>
<thead>
<tr>
<th>YEAR (EV PENETRATION)</th>
<th>CORNEY ROAD EMISSIONS (tCO2e)</th>
<th>CUFARDE VILLAGE EMISSIONS (tCO2e)</th>
<th>ASSET</th>
<th>OPERATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>2034 (50%)</td>
<td>5,900</td>
<td>22,014</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2033 (60%)</td>
<td>–</td>
<td>8,195</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2038 (70%)</td>
<td>–</td>
<td>18,410</td>
<td>5,900</td>
<td>9,744</td>
</tr>
<tr>
<td>2040 (80%)</td>
<td>–</td>
<td>10,683</td>
<td>–</td>
<td>5,248</td>
</tr>
<tr>
<td>2041 (90%)</td>
<td>–</td>
<td>22,373</td>
<td>–</td>
<td>10,814</td>
</tr>
<tr>
<td>2043 (100%)</td>
<td>5,900</td>
<td>11,877</td>
<td>–</td>
<td>5,868</td>
</tr>
<tr>
<td>2044 (110%)</td>
<td>–</td>
<td>24,339</td>
<td>–</td>
<td>12,304</td>
</tr>
<tr>
<td>2046 (120%)</td>
<td>–</td>
<td>24,565</td>
<td>–</td>
<td>12,354</td>
</tr>
<tr>
<td>2048 (130%)</td>
<td>–</td>
<td>12,300</td>
<td>–</td>
<td>6,757</td>
</tr>
<tr>
<td>2049 (140%)</td>
<td>–</td>
<td>12,330</td>
<td>–</td>
<td>7,060</td>
</tr>
<tr>
<td>2050 (150%)</td>
<td>–</td>
<td>12,440</td>
<td>–</td>
<td>7,480</td>
</tr>
<tr>
<td>Total</td>
<td>11,800</td>
<td>179,525</td>
<td>5,900</td>
<td>77,628</td>
</tr>
</tbody>
</table>
The following Deliverables are discussed within EVs to be connected to LV networks without the need of voltage (LV) distribution networks. This will allow more operational approach to control the charging points at the LV feeder, and ten residential representative LV feeders have been adopted: £2,000 per LV substation monitor and controller, £300 per Intelligent Control Box (ICB), £150 per ICB per 5 years, and £106 per metre of main underground cable. The calculations consider a discount rate of 3.5% per year.

The assessment has highlighted that an ESPRIT Technology investment of circa £65,000 in Corney Road is needed to cope with LV penetrations up to 2050 (which corresponds to 150%). The second feeder with issues, Cufaude Village, would require an investment of £45,000. On the other hand, traditional reinforcements would cost circa £10,000 and £5,000 for Corney Road and Cufaude Village, respectively. It is important to mention that the adoption of the reinforcement methodology has resulted only in the replacement of the first 100m.

Although the traditional reinforcements have been found to be cheaper, it is important to highlight that the investment costs for the ESPRIT Technology are expected to decrease significantly with mass production and in time. Operational costs, which account for around half of the overall net present value, are also expected to decrease with the maturity of the technology as well as communication services. Additionally, the investment costs have also assumed that the ‘ESPRIT Technology’ will be deployed in the same manner as that trialled in the project, specifically that an additional unit requires installation at each charging point rather than being integrated directly within the charging point. Conversely, the cost adopted for the replacement of underground cables can also vary according to the local or regional characteristics. In addition, the costs used here are based on Ofgem’s allowable costs. As such, they may not be appropriate for all networks and other solutions are likely to have higher associated costs.

An environmental assessment that quantifies the carbon emissions of adopting the ESPRIT Technology until 2050 (i.e., assuming a life cycle of the components of 35 years from 2015) has been carried out considering the DECC scenarios for EV uptake and only the two MEA feeders that present thermal problems at some EV penetration level (i.e., Corney Road and Cufaude Village which have clear customer and length characteristics). These results have been compared against the investment cost of adopting traditional network reinforcements (i.e., replacement of conductors).

Given that the emission factors of the components used in the trials were not available, the values adopted in the analysis have considered other electronic devices with similar manufacturing processes. The following emission factors have been adopted: T35.5 kCO2e per LV substation monitor and controller, 33 kgCO2e per ICB, 62.2 kgCO2e per PLC repeater, and 59 kgCO2e per metre of main underground cable.

The environmental assessment has highlighted that the adoption of the network reinforcement results in lower CO2e emissions along the life cycle. This is mainly due to a significant reduction in energy losses due to the use of cables with lower impedances than the original ones which are used when adopting the ESPRIT Technology. The CO2e emissions adopting the ESPRIT Technology in Corney Road are as much as those from reinforcements (approximately 1% higher). For Cufaude Village LV feeder, ESPRIT results in approximately 20% more CO2e emissions than reinforcements.

2.6 REFERENCES


APPENDIX A: ESPRIT-ENABLED EV IMPACT ASSESSMENT

This appendix is an extension of chapter 1.3. It presents in more details the benefits of adopting the ESPRIT-based control algorithm (section 2.3.1) on the residential LV feeders involved in the MEA project, i.e., MEA feeders as well as on the representative LVNS feeders, i.e., representative LVNS feeders. Specifically, the utilization factor of the feeder, the number of customers with voltage problems (for the LVNS feeders given that the MEA feeders do not present voltage issues) and the energy losses, in percentage of the energy consumed, is given per penetration level. These results are provided for different penetration levels (from 0 to 150%) and per season. It is considered that in practice these settings may not be changeable from weekdays to weekends. In all the simulations, the control cycle is 10 min, given that this value is more likely to be adopted in practice. For the feeders that do not present thermal problems the following control settings are defined: $\alpha = 100\%$ and $\beta = 10\%$. However, these settings are adjusted (i.e., dynamic settings as in section 1.2.1) for the feeders that present thermal problems (two MEA feeders, Corney Road and Cufaude Village and four LVNS feeders, Feeders 2, 4, 6 and 7). The equation for $\alpha$, per season, is presented.

A.1 MEA FEEDERS

A.1.1 CLEADON MANOR LV FEEDER

Figure 24 shows that this LV feeder does not present thermal issues at any penetration level.

FIGURE 55: ESPRIT BENEFITS FOR EV PENETRATIONS ON CLEADON MANOR LV FEEDER

(a) Weekday – Thermal Problems

(b) Weekend – Thermal Problems

(c) Weekday – Energy Losses

(d) Weekend – Energy Losses
A.1.2 GOSFORTH AUDLEY LV FEEDER

Figure 25 shows that this LV feeder does not present thermal issues at any penetration level.

FIGURE 56: ESPRIT BENEFITS FOR EU PENETRATIONS ON GOSFORTH AUDLEY LV FEEDER

(a) Weekday – Thermal Problems

(b) Weekend – Thermal Problems

(c) Weekday – Energy Losses

(d) Weekend – Energy Losses

FIGURE 57: ESPRIT BENEFITS FOR DIFFERENT EU PENETRATIONS ON VALLEY LANE LV FEEDER

A.1.3 VALLEY LANE LV FEEDER

Figure 26 shows that this LV feeder does not present thermal issues at any penetration level.

FIGURE 57: ESPRIT BENEFITS FOR DIFFERENT EU PENETRATIONS ON VALLEY LANE LV FEEDER

(a) Weekday – Thermal Problems

(b) Weekend – Thermal Problems

(c) Weekday – Energy Losses

(d) Weekend – Energy Losses
Figure 58: ESPRIT Benefits for Different EU Penetrations on WyLam Dene LV Feeder

(a) Weekday – Thermal Problems

(b) Weekend – Thermal Problems

Figure 59: ESPRIT Benefits for Different EU Penetrations on Clydesdale Road LV Feeder

(a) Weekday – Thermal Problems

(b) Weekend – Thermal Problems

A.1.4 WyLam Dene LV Feeder

Figure 27 shows that this LV feeder does not present thermal issues at any penetration level.

A.1.5 Clydesdale Road LV Feeder

Figure 28 shows that this LV feeder does not present thermal issues at any penetration level.
A.1.6 CORNEY ROAD LV FEEDER

Figure 60 shows the simulation results for the Corney Road LV feeder considering the adoption of the dynamic disconnection threshold (Table 27). As it can be seen, the utilization factor of the feeder is significantly reduced by the use of the ESPRIT-based control algorithm. Indeed, the adoption of lower values of $\alpha$ has completely mitigated the thermal problems that would otherwise occur.

TABLE 27: CHARACTERIZATION OF $\alpha$ PER SEASON FOR EACH EV PENETRATION – CORNEY ROAD LV FEEDER

<table>
<thead>
<tr>
<th>Season</th>
<th>Winter</th>
<th>Shoulder</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$1 - 0.7 \frac{(EV_{\text{Winter}} - 40)}{40 - 150}$</td>
<td>$1 - 0.75 \frac{(EV_{\text{Shoulder}} - 50)}{50 - 150}$</td>
<td>$1 - 0.75 \frac{(EV_{\text{Summer}} - 60)}{60 - 150}$</td>
</tr>
</tbody>
</table>

A.1.7 CUFAUDE VILLAGE LV FEEDER

Figure 29 shows that the Cufaude Village LV feeder does present thermal issues for EV penetration levels larger than 60, 70 and 70% in winter, shoulder and summer season, respectively. Crucially, it shows that the ESPRIT-based control algorithm (adopting the dynamic $\alpha$ shown in Table 28) fully mitigates thermal problems on this LV feeder. This in turn increases the hosting capacity of this LV feeder to the maximum penetration level investigated in this report (i.e., 150%).

TABLE 28: CHARACTERIZATION OF $\alpha$ PER SEASON FOR EACH EV PENETRATION – CUFAUDE VILLAGE LV FEEDER

<table>
<thead>
<tr>
<th>Season</th>
<th>Winter</th>
<th>Shoulder</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$1 - 0.8 \frac{(EV_{\text{Winter}} - 60)}{60 - 150}$</td>
<td>$1 - 0.85 \frac{(EV_{\text{Shoulder}} - 70)}{70 - 150}$</td>
<td>$1 - 0.85 \frac{(EV_{\text{Summer}} - 70)}{70 - 150}$</td>
</tr>
</tbody>
</table>
**A.1.8 FOREST EDGE LV FEEDER**

Figure 30 shows that this LV feeder does not present thermal issues at any penetration level.

**A.1.9 RYANS MOUNT LV FEEDER**

Figure 31 shows that this LV feeder does not present thermal issues at any penetration level. However, for high penetration levels during winter weekdays, it shows that the utilization factor of the feeder can be higher than 90%. Thus, potential thermal overloads may be experienced if atypical situations occur (e.g., a very cold day).
A.2 LUNNS REPRESENTATIVE LV FEEDERS

This section presents the results of adopting the ESPRIT-based control algorithm on the representative LVNS feeders. It is shown that only four representative LVNS feeders (Feeder 2, 4, 6 and 7) present thermal issues at some penetration levels. More importantly, it is shown that the adoption of the ESPRIT-based control algorithm (along with the dynamic disconnection threshold) completely mitigates the thermal problems.

FIGURE 64: ESPRIT BENEFITS DURING WINTER – WEEKDAYS ON REPRESENTATIVE LVNS FEEDER 1

(a) Weekday – Thermal Problems
(b) Weekend – Thermal Problems
(c) Weekday – Voltage Problems
(d) Weekend – Voltage Problems
(c) Weekday – Energy Losses
(d) Weekend – Energy Losses

FIGURE 65: ESPRIT BENEFITS DURING WINTER – WEEKDAYS ON REPRESENTATIVE LVNS FEEDER 2

(a) Weekday – Thermal Problems
(b) Weekend – Thermal Problems
(c) Weekday – Voltage Problems
(d) Weekend – Voltage Problems
(c) Weekday – Energy Losses
(d) Weekend – Energy Losses

TABLE 29: CHARACTERIZATION OF $\alpha$ PER SEASON FOR EACH EV PENETRATION – LVNS FEEDER 2

<table>
<thead>
<tr>
<th>Season</th>
<th>Winter</th>
<th>Shoulder</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$1 - 0.7 \cdot (E_{\text{EV PENETRATION}} - 60) + 1$</td>
<td>$1 - 0.75 \cdot (E_{\text{EV PENETRATION}} - 80) + 1$</td>
<td>$1 - 0.75 \cdot (E_{\text{EV PENETRATION}} - 80) + 1$</td>
</tr>
<tr>
<td>Range</td>
<td>60 – 150</td>
<td>80 – 150</td>
<td>80 – 150</td>
</tr>
</tbody>
</table>
FIGURE 66: ESPRIT BENEFITS DURING WINTER – WEEKDAYS ON REPRESENTATIVE LVNS FEEDER 3

(a) Weekday – Thermal Problems
(b) Weekend – Thermal Problems
(c) Weekday – Voltage Problems
(d) Weekday – Energy Losses

FIGURE 67: ESPRIT BENEFITS DURING WINTER – WEEKDAYS ON REPRESENTATIVE LVNS FEEDER 4

(a) Weekday – Thermal Problems
(b) Weekend – Thermal Problems
(c) Weekday – Voltage Problems
(d) Weekend – Voltage Problems

TABLE 30: CHARACTERIZATION OF $\alpha$ PER SEASON FOR EACH EU PENETRATION – LVNS FEEDER 4

<table>
<thead>
<tr>
<th>Season</th>
<th>Winter Formula</th>
<th>Shoulder Formula</th>
<th>Summer Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha = \frac{1}{9} (EV_{\text{winter}} - 30 + 1)$</td>
<td>$\alpha = \frac{1}{9} (EV_{\text{shoulder}} - 50 + 1)$</td>
<td>$\alpha = \frac{1}{9} (EV_{\text{summer}} - 40 + 1)$</td>
</tr>
<tr>
<td></td>
<td>30 – 150</td>
<td>50 – 150</td>
<td>40 – 150</td>
</tr>
</tbody>
</table>
TABLE 31: CHARACTERIZATION OF α PER SEASON FOR EACH EV PENETRATION – LVNS FEEDER 6

<table>
<thead>
<tr>
<th>Season</th>
<th>Winter</th>
<th>Shoulder</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>$1 - 0.7 \left( EV_{\text{penetration}} - 40 \right) + 1$</td>
<td>$1 - 0.75 \left( EV_{\text{penetration}} - 40 \right) + 1$</td>
<td>$1 - 0.75 \left( EV_{\text{penetration}} - 50 \right) + 1$</td>
</tr>
</tbody>
</table>

$$40 - 150$$  $$40 - 150$$  $$50 - 150$$
TABLE 32: CHARACTERIZATION OF $\alpha$ PER SEASON FOR EACH EV PENETRATION – LVNS FEEDER 7

<table>
<thead>
<tr>
<th>Season</th>
<th>$\alpha$ = 1 - 0.75 ($EV_{winter}$ - 50) + 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>WINTER</td>
<td>$60 - 150$</td>
</tr>
<tr>
<td>SHOULDER</td>
<td>$50 - 150$</td>
</tr>
<tr>
<td>SUMMER</td>
<td>$80 - 150$</td>
</tr>
</tbody>
</table>

FIGURE 70: ESPRIT BENEFITS DURING WINTER – WEEKDAYS ON REPRESENTATIVE LVNS FEEDER 7

(a) Weekday – Thermal Problems

(b) Weekday – Voltage Problems

(c) Weekday – Energy Losses

FIGURE 71: ESPRIT BENEFITS DURING WINTER – WEEKENDS ON REPRESENTATIVE LVNS FEEDER 8

(a) Weekend – Thermal Problems

(b) Weekend – Voltage Problems

(c) Weekend – Energy Losses
FIGURE 72: ESPRIT BENEFITS DURING WINTER – WEEKDAYS ON REPRESENTATIVE LVNS FEEDER 9

(a) Weekday – Thermal Problems

(b) Weekend – Thermal Problems

(c) Weekday – Voltage Problems

(d) Weekend – Voltage Problems

(e) Weekday – Energy Losses

(f) Weekend – Energy Losses

FIGURE 73: ESPRIT BENEFITS DURING WINTER – WEEKDAYS ON REPRESENTATIVE LVNS FEEDER 10

(a) Weekday – Thermal Problems

(b) Weekend – Thermal Problems

(c) Weekday – Voltage Problems

(d) Weekend – Voltage Problems

(e) Weekday – Energy Losses

(f) Weekend – Energy Losses
My Electric Avenue has received support from Ofgem through the Low Carbon Networks (LCN) Fund.