Title: Work Activity 5 “ESPRIT-Enabled Deterministic Impact Studies” – Report for Deliverables 5.1 and 5.2

Synopsis: This document presents scenario-based deterministic impact studies on the validated and representative low voltage feeders (presented in previous deliverables) considering a control approach that manages (i.e., disconnects/ reconnects) electric vehicle charging points to avoid thermal problems. The performance of the ESPRIT Technology-based control approach is assessed for different penetration levels (from 0 to 150%), days and seasons. This report also quantifies the economic and environmental benefits from adopting such a control approach.

Document ID: UoM-EA-Technology_MEA_Deliverable5.1-5.2v04

Date: 30th September 2015

Prepared For: Daniel Hollingworth
EA Technology Ltd
Capenhurst Technology Park
Chester, CH1 6ES, UK

James Cross
EA Technology Ltd
Capenhurst Technology Park
Chester, CH1 6ES, UK

Prepared By: Dr Jairo Quiros-Tortos
The University of Manchester
Sackville Street, Manchester M13 9PL, UK

Revised By: Dr Luis(Nando) Ochoa
The University of Manchester
Sackville Street, Manchester M13 9PL, UK

Contacts: Dr Jairo Quiros-Tortos +44 (0)161 306 2687 jairo.quirostortos@manchester.ac.uk
Dr Luis(Nando) Ochoa +44 (0)161 306 4819 luis.ochoa@manchester.ac.uk
Executive Summary

This report corresponds to Deliverables 5.1 and 5.2 “ESPRIT-Enabled Deterministic Impact Studies” part of the Ofgem’s Low Carbon Network 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., disconnection of 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 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 highlights 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 the 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 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) 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.

- 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.
Table of Contents

Executive Summary .............................................................................................................. 2

1  Introduction .................................................................................................................. 5

2  ESPRIT-Enabled Deterministic Impact Studies ............................................................ 6
  2.1 ESPRIT-Based Control Algorithm ........................................................................... 6
  2.1.1 Disconnection ....................................................................................................... 7
  2.1.2 Reconnection ....................................................................................................... 7
  2.2 ESPRIT-Enabled Deterministic Impact Studies: Example LV Feeder .................... 7
  2.2.1 Thermal Problems ............................................................................................... 8
  2.2.2 Voltage Problems ............................................................................................... 10
  2.2.3 Energy Losses .................................................................................................... 10
  2.3 Effects of Control Settings ....................................................................................... 11
  2.3.1 Dynamic Settings .............................................................................................. 13
  2.4 Multi-Feeder Analysis and Dynamic Settings ........................................................... 13
  2.5 Your Homes (Commercial Trial) ............................................................................. 15
  2.6 Representative LVNS Feeders ............................................................................... 16
  2.7 Remarks .................................................................................................................. 19

3  Economic and Environmental Benefits of ESPRIT ...................................................... 21
  3.1 Economic Assessment .............................................................................................. 21
    3.1.1 Methodology ...................................................................................................... 21
    3.1.2 Results ............................................................................................................... 22
  3.2 Environmental Assessment ..................................................................................... 23
    3.2.1 Methodology ...................................................................................................... 23
    3.2.2 Results ............................................................................................................... 24
  3.3 Remarks .................................................................................................................. 26

4  Conclusions .................................................................................................................. 28

5  References ..................................................................................................................... 30
1 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 Energy Power Distribution (SSEPD), 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 to manage (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.

To address Deliverable 5.1, this report introduces a ESPRIT-based control algorithm (ESPRIT is a patent filed by EA Technology Limited [1]) that is adopted to carry out scenario-based deterministic impact studies on the validated and representative LVNS feeders 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 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 involved in the MEA project, as well as as the representative feeders without photovoltaic (PV) systems created in the industrial project “Low Voltage Network Solutions” (LVNS) [8-10]. Previous reports (i.e., Work Activity 2 [2], Work Activity 3 [3], and Work Activity 4 [4]) present full details of these LV feeders. This section uses the 1-min resolution residential and EV load profiles fully detailed in [3, 4] (see [11] for further analyses).

The impact assessment methodology introduced in [4] is adopted considering that the EV 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.

2.1 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 1 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 1: Architecture deployed in the MEA project for EV management](image)

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.
2.1 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 $i$, $I_{\emptyset,i}$, at the head of the feeder (first segment) exceeds a threshold $\alpha$ (e.g., 1 which corresponds to a 100% of the cable capacity $I_{\emptyset,i}^{\text{max}}$), 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:

$$X_i = \left\lfloor \frac{I_{\emptyset,i} - \alpha I_{\emptyset,i}^{\text{max}}}{I_{\text{EV}}} \right\rfloor \quad (1)$$

where the bracket $\lfloor \cdot \rfloor$ represents the ceiling function (i.e., rounding up values), and $I_{\text{EV}}$ is the phase current of an EV (~16A in the case of a Nissan LEAF, 3.6 kW and 230 V). This process is repeated for each of the phases of the feeder.

Once the number of EV charging points to be switched off is calculated, the next step is to decide which EV charging points 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 practice, this delay would correspond to communications and switching actions.

2.1.2 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, $I_{\emptyset,i}$, 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:

$$Y_i = \left\lfloor \frac{(1 - \beta) I_{\emptyset,i}^{\text{max}} - I_{\emptyset,i}}{I_{\text{EV}}} \right\rfloor \quad (2)$$

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 times (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.

2.2 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 2.1) are compared with those of the BaU case (i.e., without management). This section in particular compares the results on the Cornley 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 2.3 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 A.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 by 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 2.3.

### 2.2.1 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].

**Figure 2: Thermal analysis for winter weekdays – Corney Road, 100% EV penetration**

For a typical weekday during winter (i.e., January), Figure 2 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 2 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 2.3, 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 2 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 3 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 3 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 2.3 for details).

2.2.2 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 A.1 for details). Considering a typical weekday during winter (same simulation as in Figure 2), Figure 4 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.

![Figure 4: Minimum voltage for winter weekdays – Corney Road, 100% EV penetration](image-url)

2.2.3 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 5 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).

![Graphs showing daily energy losses analysis per penetration and season](image)

**Figure 5: Daily energy losses analysis per penetration and season**

### 2.3 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 6 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 2.2); 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 2.2.1).

![Thermal analysis for winter weekdays – 100% EV penetration different control cycles](image)

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 7 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. To explore the latter, section 2.6 presents a charging delay metric that quantifies the typical delay that can be experienced by EV users for different EV penetration levels.
2.3.1 Dynamic Settings

A simple way of selecting the values for the threshold ($\alpha$) and the security margin ($\beta$) is to carry out a trial and error analysis for the highest EV penetration to be expected in a given feeder. This worst-case approach, however, would result in more EV disconnections during lower penetrations.

To ensure an adequate number of EV disconnections at each penetration level, the settings can be tuned accordingly. These ‘dynamic’ settings can be produced also by trial and error analyses for each penetration or adopting rules that modify the values according to the penetration. The latter is investigated in section 2.4.

2.4 Multi-Feeder Analysis and Dynamic Settings

The analysis of the benefits of using the ESPRIT-based control algorithm 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.

This section summarises the benefits of adopting the ESPRIT-based control algorithm in all the feeders involved in the MEA project (Appendix A.1 details this analysis) considering up to 150% EV penetrations. This is carried out for each season (winter, shoulder and summer) and for typical weekdays and weekends.

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.

Figure 7: Thermal analysis for winter weekdays – 100% EV penetration different thresholds
below the limit imposed by $\alpha$). This approach defines the penetration at which no thermal problems are experienced, $E_{V_{no\ problems}}$. Then, it checks (in a trial and error basis) for the disconnection threshold that will completely mitigate thermal problems for the highest EV penetration, $\alpha_{150\%}$. Then, considering a linear behaviour of the disconnection threshold $\alpha$ (given that in general the utilization factor of the feeder increases linearly with the penetration level, see [4] for more details), this approach defines the disconnection threshold as a function of the penetration level as follows:

$$\alpha = \frac{1 - \alpha_{150\%}}{E_{V_{no\ problems}} - 150(E_{V_{penetration}} - E_{V_{no\ problems}})} + 1 \quad (3)$$

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 3), i.e., $E_{V_{no\ problems}} = 40\%$. 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:

$$\alpha = \frac{1 - 0.7}{40 - 150(E_{V_{penetration}} - 40)} + 1 \quad (4)$$

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 8: Multi-Feeder analysis of MEA feeders per penetration and season

Figure 8 illustrates the number of MEA feeders that presents 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 2.6.

2.5 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 2.2). 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 9 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.
2.6 Representative LVNS Feeders

This section summarises the technical benefits of adopting the ESPRIT-based control algorithm (section 2.1) 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 A.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 2.4 (the corresponding equations are detailed in Appendix A.2).

Table 1 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>
<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>Weekday</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 10 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.
Figure 10: Representative LVNS Feeders with technical problems per penetration level

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 11 to Figure 14).

Figure 11 to Figure 14 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.

![Image 1: Charging delay per penetration – LVNS Feeder 2, winter, weekday](image1.png)

![Image 2: Charging delay per penetration – LVNS Feeder 4, winter, weekday](image2.png)
2.7 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 penetration levels (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).
3 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 2), 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 2.1 (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.

3.1 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 (investment plus installation) required to manage EV charging points. Therefore, it is possible to determine the investment cost for each simulation presented in section 2 (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 EV uptake rates defined in [5] (report produced for the Department of Energy and Climate Change, DECC) are utilised to determine the year 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 value provided by EA Technology. The CAPEX today (2015) considers two aspects: (i) the ICB plus the corresponding communications which has a cost of approximately £300 per household; and (ii) the installation of the monitor and controller at the substation to host the control which has a cost of £2000 per substation. It is assumed that the latter cost considers the repeaters needed. The OPEX today corresponds to £150 per customer per five years. It is important to mention that these costs are average. As such, they may depend on the LV feeder characteristics (rural/urban).

3.1.1 Methodology

The simplified investment cost calculation methodology presented here to quantify the economic benefits of adopting the ESPRIT Technology is summarised below. Given that CAPEX and OPEX costs are involved, it consists of two calculations.

3.1.1.1 Capital Expenditure: CAPEX

Investments related to CAPEX are determined as follows:

1. The first CAPEX is defined for the penetration level at which the LV feeder presents the first (thermal) problem. The cost is defined for the given number of EV customers. This first cost also includes the corresponding cost of installing the monitor controller at that substation.
2. For every subsequent penetration level, the CAPEX considers the cost of installing the corresponding (10%) of new ICBs plus the corresponding communications.

3.1.1.2 Operational Expenditure: OPEX

Investments related to OPEX are determined as follows:

1. The first OPEX is also defined for the penetration level at which the LV feeder presents the first (thermal) problem. The cost is defined for the corresponding number of EV customers.
2. The corresponding OPEX every five years is then calculated considering the number of customer that adopted the technology up to that point in time.
3.1.2 Results

This section presents the economic assessment results required to adopt the ESPRIT Technology in the MEA feeders (presented only for those with problems). The EV uptake rates used in this report correspond to the EV uptake scenarios 2-3 (highest uptake) as defined in [5] and shown in Figure 15. 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 [14]. It should be noted that the analyses 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 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 2 and Table 3 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 4. 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 2. Investment cost (ESPRIT Technology) Corney Road LV feeder

<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.

<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>2038 (70%)</td>
<td>12520</td>
<td>2038 (70%)</td>
<td>5807</td>
</tr>
<tr>
<td>2040 (80%)</td>
<td>1549</td>
<td>2043 (100%)</td>
<td>6984</td>
</tr>
<tr>
<td>2041 (90%)</td>
<td>1496</td>
<td>2048 (130%)</td>
<td>8969</td>
</tr>
<tr>
<td>2043 (100%)</td>
<td>1397</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2044 (110%)</td>
<td>1553</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2046 (120%)</td>
<td>1464</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2048 (130%)</td>
<td>1380</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2049 (140%)</td>
<td>1340</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2050 (150%)</td>
<td>1301</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Investment</td>
<td>24000</td>
<td>Total Investment</td>
<td>21761</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year of 1st problem</th>
<th>Corney Road LV feeder</th>
<th>Cufaude Village LV feeder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Present Cost (1st investment)</td>
<td>2034 (50% EV penetration)</td>
<td>£5,600</td>
</tr>
<tr>
<td>Year of 2nd problem</td>
<td>2043 (100% EV penetration)</td>
<td>£4,100</td>
</tr>
<tr>
<td>Net Present Cost (2nd investment)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total Investment</td>
<td>£9,700</td>
<td>£4,800</td>
</tr>
</tbody>
</table>

### 3.2 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 15 [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.

### 3.2.1 Methodology

The carbon emissions associated with the ESPRIT Technology consist of two aspects: (i) the manufacture and deployment of the devices required onto 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 emission given the operation of the ESPRIT Technology over time (technical crew visiting the place when providing maintenance), and the savings in energy.
### 3.2.1.1 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 increases, 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. In 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 5 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 5. Carbon content of the (equivalent) assets for adopting ESPRIT](image)

#### 3.2.1.2 Carbon Impacts of Operations

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 5 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].

#### 3.2.2 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 15 (i.e., scenarios 2-3, highest uptake [5]) is also used here.

Table 6 and Table 7 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 8 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.

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.
Table 6. Environmental Assessment (ESPRIT Technology) Corney Road LV feeder

<table>
<thead>
<tr>
<th>Year (EV Penetration)</th>
<th>Asset Emissions (tCO2e)</th>
<th>Energy Losses Emissions (tCO2e)</th>
<th>Travel Emissions (tCO2e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2034 (50%)</td>
<td>2.719</td>
<td>22.611</td>
<td>0.001</td>
</tr>
<tr>
<td>2037 (60%)</td>
<td>0.492</td>
<td>8.792</td>
<td>0.000</td>
</tr>
<tr>
<td>2038 (70%)</td>
<td>0.492</td>
<td>20.002</td>
<td>0.000</td>
</tr>
<tr>
<td>2040 (80%)</td>
<td>0.492</td>
<td>11.280</td>
<td>0.001</td>
</tr>
<tr>
<td>2041 (90%)</td>
<td>0.492</td>
<td>23.567</td>
<td>0.000</td>
</tr>
<tr>
<td>2043 (100%)</td>
<td>0.492</td>
<td>12.673</td>
<td>0.000</td>
</tr>
<tr>
<td>2044 (110%)</td>
<td>0.492</td>
<td>25.533</td>
<td>0.001</td>
</tr>
<tr>
<td>2046 (120%)</td>
<td>0.492</td>
<td>24.963</td>
<td>0.000</td>
</tr>
<tr>
<td>2048 (130%)</td>
<td>0.492</td>
<td>12.200</td>
<td>0.000</td>
</tr>
<tr>
<td>2049 (140%)</td>
<td>0.492</td>
<td>11.875</td>
<td>0.001</td>
</tr>
<tr>
<td>2050 (150%)</td>
<td>0.492</td>
<td>11.644</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7.639</strong></td>
<td><strong>185.140</strong></td>
<td><strong>0.004</strong></td>
</tr>
</tbody>
</table>

Table 7. Environmental Assessment (ESPRIT Technology) Cufaude Village LV feeder

<table>
<thead>
<tr>
<th>Year (EV Penetration)</th>
<th>Asset Emissions (tCO2e)</th>
<th>Energy Losses Emissions (tCO2e)</th>
<th>Travel Emissions (tCO2e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2038 (70%)</td>
<td>3.078</td>
<td>11.734</td>
<td>0.001</td>
</tr>
<tr>
<td>2040 (80%)</td>
<td>0.403</td>
<td>6.442</td>
<td>0.000</td>
</tr>
<tr>
<td>2041 (90%)</td>
<td>0.403</td>
<td>13.998</td>
<td>0.000</td>
</tr>
<tr>
<td>2043 (100%)</td>
<td>0.403</td>
<td>7.858</td>
<td>0.001</td>
</tr>
<tr>
<td>2044 (110%)</td>
<td>0.403</td>
<td>15.090</td>
<td>0.000</td>
</tr>
<tr>
<td>2046 (120%)</td>
<td>0.403</td>
<td>14.742</td>
<td>0.000</td>
</tr>
<tr>
<td>2048 (130%)</td>
<td>0.403</td>
<td>7.354</td>
<td>0.001</td>
</tr>
<tr>
<td>2049 (140%)</td>
<td>0.403</td>
<td>7.458</td>
<td>0.000</td>
</tr>
<tr>
<td>2050 (150%)</td>
<td>0.403</td>
<td>7.281</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6.302</strong></td>
<td><strong>91.96</strong></td>
<td><strong>0.003</strong></td>
</tr>
</tbody>
</table>

Table 8. Environmental benefits of reinforcing the LV network

<table>
<thead>
<tr>
<th>Year (EV Penetration)</th>
<th>Corney Road Emissions (tCO2e)</th>
<th>Cufaude Village Emissions (tCO2e)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Asset Operation</td>
<td>Asset Operation</td>
</tr>
<tr>
<td>2034 (50%)</td>
<td>5.900</td>
<td>22.014</td>
</tr>
<tr>
<td>2037 (60%)</td>
<td>-</td>
<td>8.195</td>
</tr>
<tr>
<td>2038 (70%)</td>
<td>-</td>
<td>18.410</td>
</tr>
<tr>
<td>2040 (80%)</td>
<td>-</td>
<td>10.683</td>
</tr>
<tr>
<td>2041 (90%)</td>
<td>-</td>
<td>22.373</td>
</tr>
<tr>
<td>2043 (100%)</td>
<td>5.900</td>
<td>11.877</td>
</tr>
<tr>
<td>2044 (110%)</td>
<td>-</td>
<td>10.683</td>
</tr>
<tr>
<td>2046 (120%)</td>
<td>-</td>
<td>24.339</td>
</tr>
<tr>
<td>2048 (130%)</td>
<td>-</td>
<td>12.330</td>
</tr>
<tr>
<td>2049 (140%)</td>
<td>-</td>
<td>12.440</td>
</tr>
<tr>
<td>2050 (150%)</td>
<td>-</td>
<td>12.440</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>11.800</strong></td>
<td><strong>179.525</strong></td>
</tr>
</tbody>
</table>

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).

3.3 Remarks

Economic Assessment

- An economic assessment that quantifies as net present value the investment cost needed to adopt the ESPRIT Technology 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].

- The following investment and operational costs 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 have considered a discount rate of 3.5% per year [14].

- The 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 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). These results have been 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 have considered other electronic devices with similar manufacturing processes. The following emission factors have been 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 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.

- 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.
4 Conclusions

This report corresponds to Deliverables 5.1 and 5.2 “ESPRIT-Enabled Deterministic Impact Studies” part of the GB Ofgem’s Low Carbon Network 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 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 to manage (i.e., disconnect/reconnect) EV charging points”

- An ESPRIT-based control algorithm has been presented to manage EV charging points to mitigate thermal problems (only) in LV feeders. Its effectiveness has been demonstrated on nine residential MEA LV feeders, a commercial MEA LV feeder, and ten residential representative LV feeders. The assessment has been carried out for different EV penetration levels (from 0 to 150% in the case of the residential LV feeders), seasons and type of days.
- It has been shown that the improvement in terms of voltages can be considerable (due to the management of the demand). Moreover, the benefits in the energy losses (as a by-product of the thermal management) have been found to be 9% on average for high EV penetration.
- It has been demonstrated that short control cycles (e.g., 1 min) and 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 (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, it has been concluded that 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 has been found 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 has also resulted in fewer feeders with voltage problems. Nonetheless, it has led to charging delays on the EVs.

Deliverable 5.2 “Economic and environmental assessment of the benefits of adopting the ESPRIT Technology to cope with high penetrations of EVs”

- An economic assessment of the investment cost required to update the ESPRIT technology in comparison to the ‘net present value’ has been performed. This has considered 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 have been compared against the investment cost of adopting traditional network reinforcements (i.e., replacement of conductors).
- The following investment and operational costs 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 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 the 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). These results have been 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 have considered other electronic devices with similar manufacturing processes. The following emission factors have been 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 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.

- 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.
5 References


[13] British Standards Institution, BS EN 50160: Voltage characteristics of electricity supplied by public distribution systems,


Appendix A ESPRIT-Enabled EV Impact Assessment

This appendix is an extension of chapter 2. It presents in more details the benefits of adopting the ESPRIT-based control algorithm (section 2.1) 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 2.3.1) 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 16 shows that this LV feeder does not present thermal issues at any penetration level.

![Graphs showing ESPRIT benefits for EV penetrations on Cleadon Manor LV feeder](image-url)
A.1.2 Gosforth Audley LV Feeder

Figure 17 shows that this LV feeder does not present thermal issues at any penetration level.

Figure 17: ESPRIT benefits for EV penetrations on Gosforth Audley LV feeder
A.1.3 Valley Lane LV Feeder

Figure 18 shows that this LV feeder does not present thermal issues at any penetration level.

Figure 18: ESPRIT benefits for different EV penetrations on Valley Lane LV feeder
A.1.4 Wylam Dene LV Feeder

Figure 19 shows that this LV feeder does not present thermal issues at any penetration level.

Figure 19: ESPRIT benefits for different EV penetrations on Wylam Dene LV feeder
A.1.5 Clydesdale Road LV feeder

Figure 20 shows that this LV feeder does not present thermal issues at any penetration level.

Figure 20: ESPRIT benefits for different EV penetrations on Clydesdale Road LV feeder
A.1.6 Corney Road LV feeder

Figure 21 shows the simulation results for the Corney Road LV feeder considering the adoption of the dynamic disconnection threshold (Table 9). 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 9. Characterization of $\alpha$ per season for each EV penetration – Corney Road LV feeder

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

![Graphs showing ESPRIT benefits](image)

Figure 21: ESPRIT benefits for different EV penetrations on Corney Road LV feeder
A.1.7 Cufaude Village LV Feeder

Figure 22 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 10) 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 10. 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>$\frac{1 - 0.8}{60 - 150} (EV_{penetration} - 60) + 1$</td>
<td>$\frac{1 - 0.85}{70 - 150} (EV_{penetration} - 70) + 1$</td>
<td>$\frac{1 - 0.85}{70 - 150} (EV_{penetration} - 70) + 1$</td>
</tr>
</tbody>
</table>

![Graph](image1)

![Graph](image2)

![Graph](image3)

![Graph](image4)

**Figure 22: ESPRIT benefits for different EV penetrations on Cufaude Village LV feeder**
A.1.8 Forest Edge LV Feeder

Figure 23 shows that this LV feeder does not present thermal issues at any penetration level.

Figure 23: ESPRIT benefits for different EV penetrations on Forest Edge LV feeder
A.1.9 Ryans Mount LV Feeder

Figure 24 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 experience if atypical situations occur (e.g., a very cold day).

Figure 24: ESPRIT benefits for different EV penetrations on Ryans Mount LV feeder
A.2 LVNS 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.

![Thermal Problems Graph](image1)

![Voltage Problems Graph](image2)

![Energy Losses Graph](image3)

Figure 25: ESPRIT benefits during winter – weekdays on Representative LVNS feeder 1
Table 11. Characterization of $\alpha$ per season for each EV penetration – LVNS Feeder 2

<table>
<thead>
<tr>
<th>Season</th>
<th>Winter $\alpha = 1 - 0.7 \left( EV_{penetration} - 60 \right) + 1$</th>
<th>Shoulder $\alpha = 1 - 0.75 \left( EV_{penetration} - 80 \right) + 1$</th>
<th>Summer $\alpha = 1 - 0.75 \left( EV_{penetration} - 80 \right) + 1$</th>
</tr>
</thead>
</table>

Figure 26: ESPRIT benefits during winter – weekdays on Representative LVNS feeder 2
Work Activity 5 “ESPRIT-Enabled Deterministic Impact Studies”
Report for Deliverables 5.1 and 5.2
UoM-EA-Technology_MEA_Deliverable5.1-5.2v0; 30th September 2015

Figure 27: ESPRIT benefits during winter – weekdays on Representative LVNS feeder 3
Table 12. Characterization of $\alpha$ per season for each EV penetration – LVNS Feeder 4

<table>
<thead>
<tr>
<th>Season</th>
<th>Formula 1</th>
<th>Formula 2</th>
<th>Formula 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>$\alpha = \frac{1 - 0.7}{30 - 150} (EV_{\text{penetration}} - 30) + 1$</td>
<td>$\alpha = \frac{1 - 0.75}{50 - 150} (EV_{\text{penetration}} - 50) + 1$</td>
<td>$\alpha = \frac{1 - 0.75}{40 - 150} (EV_{\text{penetration}} - 40) + 1$</td>
</tr>
</tbody>
</table>

Figure 28: ESPRIT benefits during winter – weekdays on Representative LVNS feeder 4
Figure 29: ESPRIT benefits during winter – weekdays on Representative LVNS feeder 5
Table 13. Characterization of $\alpha$ per season for each EV penetration – LVNS Feeder 6

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

Figure 30: ESPRIT benefits during winter – weekdays on Representative LVNS feeder 6
Table 14. Characterization of $\alpha$ per season for each EV penetration – LVNS Feeder 7

<table>
<thead>
<tr>
<th>Season</th>
<th>Winter</th>
<th>Shoulder</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$1 - 0.7\frac{(EV_{penetration} - 60)}{60 - 150} + 1$</td>
<td>$1 - 0.75\frac{(EV_{penetration} - 50)}{50 - 150} + 1$</td>
<td>$1 - 0.75\frac{(EV_{penetration} - 80)}{80 - 150} + 1$</td>
</tr>
</tbody>
</table>

![Diagram a] Weekday – Thermal Problems

![Diagram b] Weekend – Thermal Problems

![Diagram c] Weekday – Voltage Problems

![Diagram d] Weekend – Voltage Problems

![Diagram e] Weekday – Energy Losses

![Diagram f] Weekend – Energy Losses

Figure 31: ESPRIT benefits during winter – weekdays on Representative LVNS feeder 7
Figure 32: ESPRIT benefits during winter – weekdays on Representative LVNS feeder 8
Figure 33: ESPRIT benefits during winter – weekdays on Representative LVNS feeder 9
Figure 34: ESPRIT benefits during winter – weekdays on Representative LVNS feeder 10