WESTERN POWER DISTRIBUTION

INNOVATION

NEXT GENERATION NETWORKS

LOSSES INVESTIGATION

WPD_NIA_005

NIA MAJOR PROJECT PROGRESS REPORT

REPORTING PERIOD: APR 2015 – MAR 2017

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Contents

Glossary

Term	Definition
BAU	Business as usual
DG	Distributed Generation
DNO	Distribution Network Operator
DUKES	Digest of UK Energy Statistics
EDMI	Meter design and manufacturing company.
GB	Great Britain
GIS	Geographic information system
GPRS	General Packet Radio Service, the mobile data service on 2G and 3G cellular communications systems.
HH	Half Hourly
HV	High Voltage
IPR	Intellectual Property Register
LCT	Low Carbon Technologies
LLF	Line Loss Factor: means the multiplier which, when applied to generation or demand on the distribution system, converts the data to an equivalent value at the transmission system boundary inclusive of distribution system losses
LV	Low Voltage
NHH	Non Half Hourly
NIA	Network Innovation Allowance
PICAS	Paper insulated corrugated aluminium sheath cable
PILCSWA	Paper insulated lead covered steel wire armoured cable
MUA	Manx Utilities (Manx Utilities Authority)
RMS	Root mean square
SCADA	Supervisor Control and Data Acquisition
WPD	Western Power Distribution
XLPE	Cross-linked polyethylene cable

1 Executive Summary

Losses Investigation is funded through Ofgem's Network Innovation Allowance (NIA). Losses Investigation was registered in April 2015 and will be complete by July 2018[1].

Losses Investigation aims to quantify technical losses on the LV and HV network, and determine the minimum information required to accurately predict network losses.

This report details progress of the project, from initial registration in April 2015 to the end of March 2017.

1.1 Business Case

This project will provide information that should allow us in subsequent work to accurately target the most economically viable mitigation techniques, allowing us to reduce losses where action presents a net benefit.

From the Digest of UK Energy Statistics 2014 (DUKES) the final electricity consumption across the UK was 317TWh in 2013. Of this approximately 25.2% or 83.7TWh is consumed within WPDs network. With the conservative figure of 5.8% losses in the distribution network this means that 4.64TWh is lost on WPDs network, of this approximately 3.34TWh (72%) is lost after transformation down to HV. Using the Ofgem value of £48.42/MWh this is worth £161.9 million directly with a further contribution of £103 million from the value of the carbon emitted generating it (figures of 524.62 TCO2/GWh and £59/TCO2 was used from the NIA benefits guide).

Estimated cost of HV and LV losses on WPD network = £161.9m + £103.5m = £265m per year.

If we can target losses and reduce 10% of the technical losses on the LV and HV networks by 10% then the method cost would be £2.65 million a year.

[1] This completion date is the subject of Project Change Request 001, changing the end date from Dec 2017 to July 2018.

1.2 Project Progress

This is the first six monthly progress report. It covers progress from initial registration in April 2015 to the end of March 2017. To date, the project:

- Has selected Loughborough University as its academic and analytical partner, and has confirmed Manx Utilities (Isle of Man) as its partner for investigating losses on LV networks. Collaboration Agreements have been established with both.
- Has successfully completed initial lab testing of the proposed monitoring and measurement arrangements.
- Has successfully completed monitoring for losses on a pilot HV feeder in Milton Keynes, and a pilot domestic LV feeder in the Isle of Man. These pilots established in detail the measurement arrangements plus modelling and calculation algorithms necessary to assess losses on HV and LV feeders, and confirmed the feasibility of practically assessing losses on real network.
- Has selected and is rolling out monitoring to further feeders. At the end of March 2017, seven HV and three LV feeders are fully monitored and loss assessments are ongoing, the installation of monitoring to a further 4 HV feeders and seven LV feeders is underway. Installation of all monitoring is expected to be completed by July 2017.
- Has investigated methods of estimating losses using reduced information sets for HV feeders, and a preferred approach identified. This preferred approach has been tested on all seven completed HV feeders, and produces estimates that closely match the measured assessments. Considerations for demonstrating this on a large sample of HV feeders are underway.
- Initially reviewed methods of estimating LV losses using reduced information sets, with further work underway.

1.3 Project Delivery Structure

1.3.1 Project Review Group

The Losses Investigation Project Review Group meets on a bi-annual basis. The role of the Project Review Group is to:

- Ensure the project is aligned with organisational strategy;
- Ensure the project makes good use of assets;
- Assist with resolving strategic level issues and risks;
- Approve or reject changes to the project with a high impact on timelines and budget;
- Assess project progress and report on project to senior management and higher authorities;
- Provide advice and guidance on business issues facing the project;
- Use influence and authority to assist the project in achieving its outcomes;
- Review and approve final project deliverables; and
- Perform reviews at agreed stage boundaries.

1.3.2 Project Resource

WPD are providing full-time project management resource, plus project oversight and direction.

Academic, loss assessment design, and analytical support is being provided by Loughborough University.

Planning and implementation of HV feeder monitoring is provided by ex-WPD staff through agencies. This work is being undertaken in close collaboration with the local WPD Network Services staff.

Lucy Gridkey have provided substation monitoring equipment and is also providing ongoing data collection services for all the HV feeder monitoring equipment and the LV substation monitoring equipment.

Manx Utilities (MUA) is providing planning, implementation and data provision services for the LV feeder monitoring.

WPD has provided EDMI[2] meters from its metering operation. The project has made use of EDMI's technical support under the WPD umbrella.

1.4 Procurement

The following table details the current status of procurement for this project.

Provider	Services/goods	Area of project applicable to	Anticipated Delivery Dates
Loughborough University	Services (academic, loss assessment design, and analytical support)	• HV & LV feeder loss assessment on monitored feeders • Design and development of loss estimation methods for non-monitored HV & LV feeders	Ongoing until the end of the project
Lucy Gridkey	Goods (supply of established MCU520 LV substation monitoring equipment)	• HV & LV feeder loss assessment on monitored feeders	Over the project period, completion expected June 2017.
Lucy Gridkey	Goods (design, development and supply of monitoring at HV supply points, based on MCU520	• HV feeder loss assessment on monitored feeders	Complete Feb 2017.

[2] Meter design and manufacturing company

Provider	Services/goods	Area of project applicable to	Anticipated Delivery Dates
	equipment)		
Lucy Gridkey	Services (data collection for deployed MCU520 equipment)	• HV & LV feeder loss assessment on monitored feeders	Ongoing until the end of the project
MUA	Services (planning, implementation and data provision services)	• LV feeder loss assessment on monitored feeders	Ongoing until the end of the project

Table 1 Procurement Details

1.5 Project Risks

A proactive role in ensuring effective risk management for Losses Investigation is taken. This ensures that processes have been put in place to review whether risks still exist, whether new risks have arisen, whether the likelihood and impact of risks have changed, reporting of significant changes that will affect risk priorities and deliver assurance of the effectiveness of control.

Section 7.1 of this report shows the current top risks associated with successfully delivering Losses Investigation as captured in our Risk Register.

1.6 Project Learning and Dissemination

Project lessons learned and what worked well are captured throughout the project lifecycle. These are captured through a series of on-going reviews with stakeholders and project team members, and will be shared in lessons learned workshops at the end of the project. These are reported in Section 5 of this report.

Initial learning from the LV and HV pilots is the subject of a paper accepted for CIRED 2017.

2 Project Manager's Report

2.1 Project Background

Distribution Network Operators have an obligation to operate efficient and economic networks. As such the effective management of distribution losses is paramount. Current estimates put the technical losses at between 5.8% and 6.6% of electricity delivered ("Management of Electricity Distribution Network Losses" IFI report) worth approximately £900 million across the UK. Approximately £640 million of these losses occur after transformation down to 11kV.

Some improvements with clear cost benefits across the network are being rolled out, as outlined in WPDs Losses Strategy; however these are restricted to broad brush techniques due to a lack of detailed understanding in the variation of losses across our network. As such reductions in losses on existing network cannot be targeted and the network cannot be optimised.

The Losses Investigation NIA project aims to:

- Quantify technical losses on samples of LV and HV network through the application of load monitoring equipment; and
- Establish loss estimation approaches, using a minimum necessary additional information set, that can be widely applied to HV and HV networks.

The project started in April 2015, and was originally due to be complete by December 2017, reporting March 2018.

Key phases to the project are:

- Project mobilisation, partner selection and establishment of appropriate project agreements;
- Initial laboratory testing of proposed load monitoring equipment, and establishment of loss assessment methodologies and calculations;
- Field testing of proposed equipment, installation, data collection, and assessment methods for one pilot HV network, and one pilot LV feeder;
- Installation of monitoring to selected HV and LV feeders;
- Assessment of Losses on monitored HV and LV feeders;
- Development of loss estimation methods for HV and LV feeders, using minimum additional information sets.

2.2 Project Progress

In the period April 2015 to April 2017, the project:

- Has selected Loughborough University as its academic and analytical partner, and has confirmed Manx Utilities (Isle of Man) as its partner for investigating losses on LV networks. Collaboration Agreements have been established with both.
- Has successfully completed initial laboratory testing of the proposed monitoring and measurement arrangements.
- Has successfully completed monitoring for losses on a pilot HV feeder, and a pilot domestic LV feeder.
- Has selected and is rolling out monitoring to further feeders.
- Is assessing losses on the monitored feeders on an ongoing basis.
- Has started consideration of methods of estimating losses using reduced information sets. For HV feeders a preferred approach has been identified, and for LV feeders an initial review has been completed with further work underway.

The introduction of a pilot phase to the project and longer than expected construction period has changed the project end date to July 2018 (reporting by October 2018). This is currently the subject of a project change request.

Selected further details of this progress are discussed in the following sections.

2.3 Loss Assessment Pilots

2.3.1 Progress within this reporting period

Pilot monitoring has been installed on an HV feeder at Milton Keynes in the WPD East Midlands license area. The upstream power flow on the monitored network is measured at a 33/11kV Primary Substation, and the downstream power flows on this network are monitored with equipment installed at each of the Distribution Substations served by the feeder. The Primary Substation monitoring is provided by a project-developed HV variant of Gridkey's MCU 520 substation monitoring equipment. The downstream sensors (established Gridkey MCU 520 LV monitoring devices) are installed on the LV side of the distribution transformers. The end-to-end losses measured in this trial therefore include the 11 kV feeder cable and the 11 kV to LV Distribution Substations.

The losses for each 1 minute sample in the HV pilot period are shown in Figure 1. As expected, the losses vary with the demand, and also with the distribution of load along the feeder (such that higher losses occur if the demand is greater for substations that are electrically further along the feeder). The levels of unbalance for the HV trial feeder were low, particularly for higher demands, and so unbalance made little contribution towards increasing the losses.

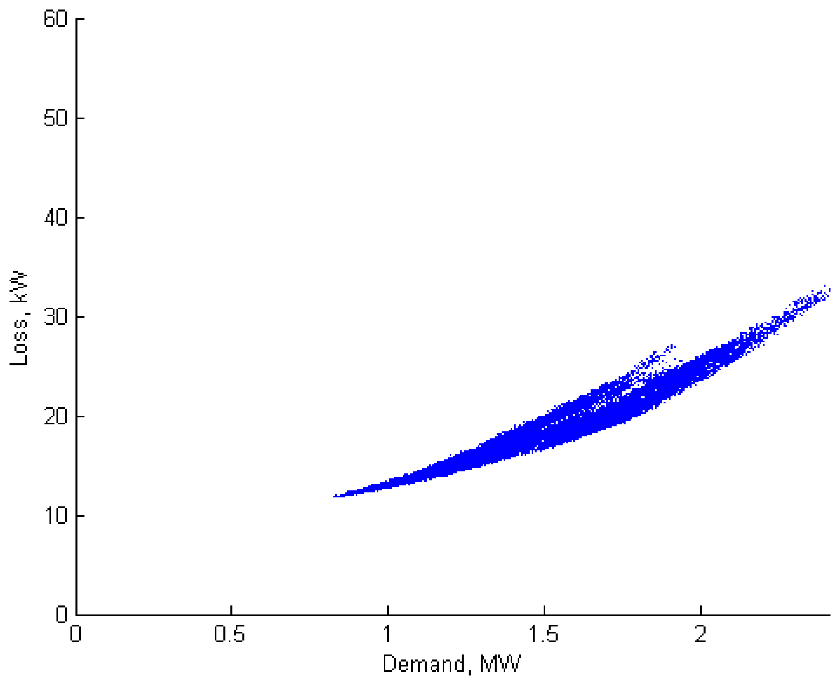

Figure 1 Pilot HV feeder losses for each 1 minute sample calculated with I^2R method

The LV pilot trial uses a network in the Isle of Man where monitoring equipment has been installed on one LV feeder. Upstream power flow to the LV feeder is monitored on the LV side of the Distribution Substation (using established Gridkey Distribution Substation monitoring), and advanced meters (of a type not previously used in the Isle of Man) are installed at each of the 13 customer connections on this feeder to monitor downstream power flow. Of the 13 connections, 11 connections supply domestic customers and the other 2 connections serve public lighting circuits.

The mean losses for the LV trial over a 10 day period in April/May 2016 (with data availability >99%) are shown in Figure 2. The individual loss estimates have a much greater variation than those for the HV trial feeder, with differences due to the changes in the three-phase balance and in the electrical distance of the demand along feeder as individual customer loads switch on and off.

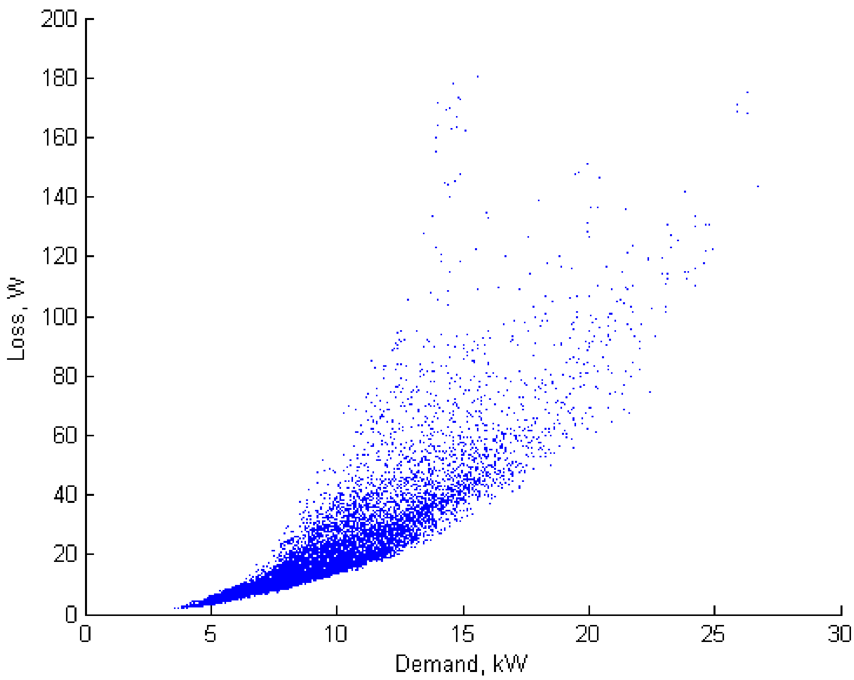

Figure 2 Pilot LV feeder losses for each 1 minute sample calculated with I^2R method

Further details of the pilot feeder assessments are contained in Appendix A of this report. The ongoing analysis of losses on the pilot feeders is discussed in Section 2.5.

The pilot phase of the project generated the following conclusions and recommendations:

- Both HV and LV feeders can credibly be assessed for technical losses, using the implemented reasonably available devices, data collection and data processing arrangements.
- The loss analysis using the I^2R method has a low uncertainty. It is therefore recommended that this method be the primary method to be used for the loss analysis, rather than the power difference method.
- It is also recommended that the additional measurement devices required for the power difference method are maintained. These devices enable consistency checking of the I^2R data, which has proven to be valuable in detecting additional connected loads that would otherwise not be included in the loss analysis.
- Comparisons of assessed losses to other indicators of UK network loss have been demonstrated. These show that the assessed losses on both the HV and LV pilot feeders are less than might have been expected. Further work is underway within the project around this finding.
- It is recommended that the demonstrated devices and preferred processes are rolled out to a selection of HV and LV feeders, in-line with the original project intention, to provide a detailed loss information-set for both HV and LV feeders.

2.3.2 Next steps

Based on the these conclusions and recommendations, the project commenced selection of and roll-out of monitoring to sample HV feeders in the Milton Keynes area, and LV feeders in the Isle of Man.

2.4 Installation of Monitoring to Selected Feeders

2.4.1 Progress within this reporting period

Following the successful pilot, ten further HV feeders and nine more LV feeders were selected for monitoring. These feeders were selected to cover underground, mixed and overhead type feeders. In addition, a range of feeder loads (both overall demand and demand type) and to some extend feeder length within a feeder type were also sought and selected.

Installation of monitoring equipment has taken longer than expected for the following reasons:

- Monitoring of HV feeders at Primary Substations has required greater than expected development of the project-proposed HV-variant of Gridkey's MCU520 equipment. Initial intentions included the use of existing Rogowski coils to monitor current in separate phase cables. Two issues were encountered with this proposal: (i) the Rogowski coil method measured screen current in addition to phase conductor current, causing an erroneous phase angle measurement; and (ii) selecting feeders with three separate phase cables at the primary proved too restrictive. As a result, current measurement at the Primary substations has been developed to be achieved via high-accuracy clip-on CT's with integral burden resistors measuring the protection CT secondary current. This is now fully in-service.
- Development of monitoring of supplies to HV customers has also been required, and this has largely followed the development of monitoring of HV feeders at Primary Substations
- Greater than expected development of a mounting arrangement for the monitoring of pole-mounted transformers has been experienced. An agreed technical solution and approved installation technique are now available and pole-mounted work will commenced once resource availability has been established.
- The introduction of new meter types and configurations, to the target LV network as both check and revenue devices, has involved more work than was expected.
- Identification and contracting for installation of LV feeder monitoring has taken considerably longer than expected.
- Enhanced levels of customer engagement have been required to smoothly allow the changing of meters and the introduction of advanced meters in domestic circumstances.

To date:

- Seven (of eleven) HV feeders now have monitoring in place and are providing data for loss assessment. Work on all the remaining HV feeders is underway with only pole-mounted sites remaining; and
- Three (of eleven) LV feeders are now monitoring in place and are providing data for loss assessment. Contracts for a further five LV feeders are now in place, planning on all five is well advanced, and installation work is nearing completion on one of these.

Details of the selected HV feeder circuits and installation progress are shown in Table 8 (Appendix B, Page 35), with the LV feeders shown in Table 9 (Appendix B, Page 36).

2.4.2 Next steps

Completion of all HV and LV monitoring work is a high priority and urgent issue for the project. With very recent approval of methods for pole-mounted method for HV feeders, resourcing arrangements will be finalised, and enhanced support of the LV feeder work is currently being provided.

Target date for completion is July 2017.

2.5 Ongoing Assessment of Losses on Monitored Feeders

2.5.1 Progress within this reporting period

Ongoing loss assessment for the monitored feeders has progressively been developed and undertaken since late March 2016, as data from feeders becomes available. The data collation, modelling, calculation and analysis are undertaken by Loughborough University.

Feeder	HV/LV	Assessment start date
Woodlands (Pilot)	HV	21/03/2016
Pilot domestic	LV	26/04/2016
Fox Milne Hotel	HV	28/07/2016
Wavendon Gate Local	HV	01/09/2016
Secondary School Walnut Tree	HV	21/10/2016
Crawley Road Tee Howard Way	HV	02/11/2016
Amway Tongwell	HV	28/11/2016
Ackerman Tongwell Aldrich Drive Tee	HV	12/01/2017
Laxey domestic	LV	26/01/2017
Ramsey domestic	LV	21/03/2017

Table 2 Ongoing Feeder Loss Assessment Commencement Dates

This section provides an overview of the information typically generated on a monthly basis. This information delivers the first key aim of the project (for the feeders available to date), to quantify technical losses on samples of LV and HV network. A snapshot of the loss assessment at the end of March 2017 is shown in Appendix C (from Page 37).

The information generated acts as a foundation for the development of a method to accurately estimate feeder losses, without the need to install the extensive monitoring that has been put in place for these selected feeders.

In any reporting period data availability is monitored. A typical period is shown in Figure 3, where each substation is shown as a horizontal line, and dips from "high" to "low" represent short (typically one minute) periods with no available data.

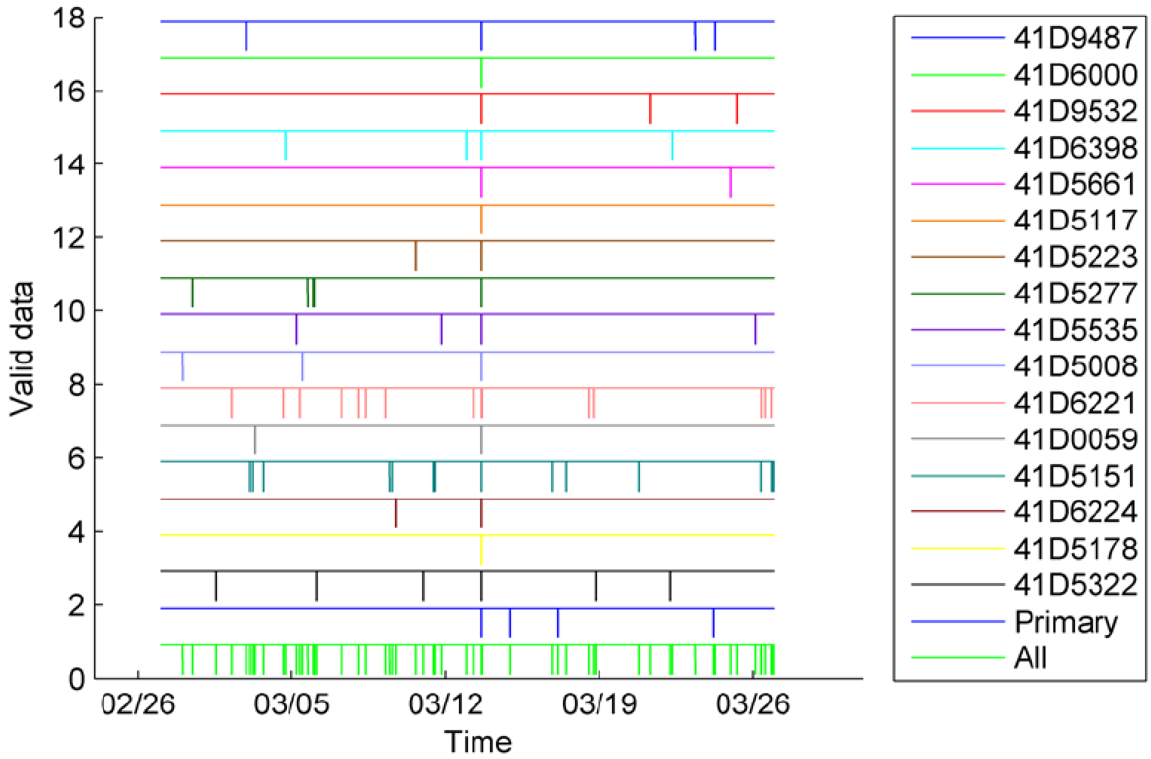

Figure 3 Typical HV Feeder Data Availability (Fox Milne Hotel, March 2017)

The data availability has been improved significantly since initial trial data was available, in collaboration with Lucy Gridkey, the providers of the equipment. The data availability has undergone unprecedented levels of scrutiny by this project at short reporting intervals (1 minute), and a number of issues have been identified. The most significant issues have been resolved, and further improvements are also being worked on by Lucy Gridkey.

Monitoring of feeder load (sample in Figure 4) and distribution of load along the feeder (sample in Figure 5) are established from collected data.

Within Figure 4 the variation in average daily demand can be seen across weeks and across the seasons. Within Figure 5 the variation in demand at different substations can be seen, with this feeder being characterised lower demand from substations closest to the Primary Substation, and two substations having substantial reactive loads.

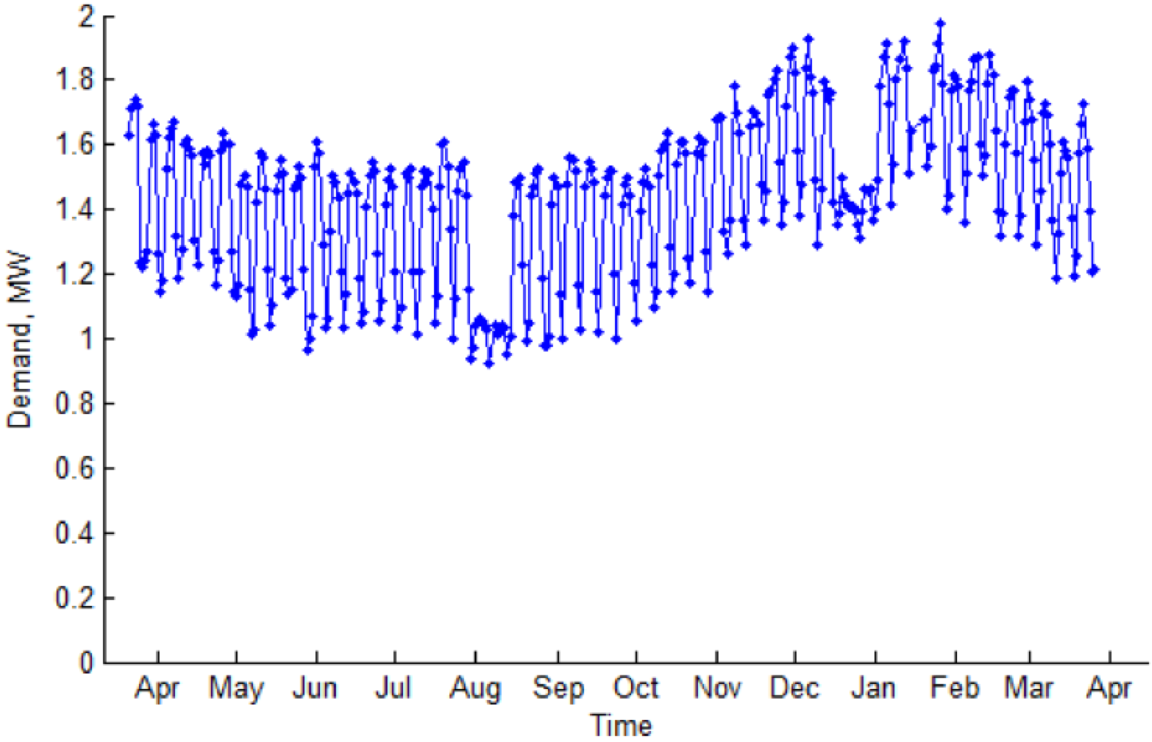

Figure 4 Long term feeder mean daily demand trend (The Woodlands, March 2017)

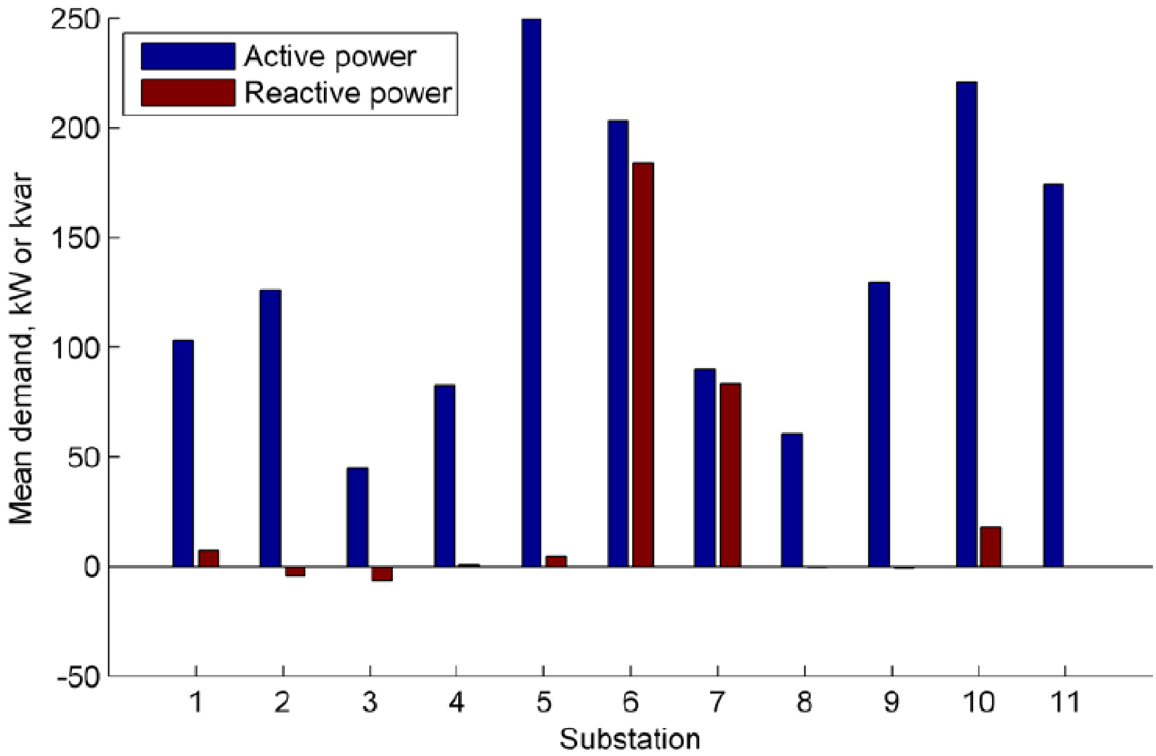

Figure 5 Distribution of Mean Demand Along Feeder (The Woodlands, March 2017)

The loss assessment is being undertaken using a project-bespoke 3-phase network modelling approach that calculates losses via two methods:

- The power difference method calculates the losses by subtracting the measured power delivered out of the network from the measured power input to the network; and
- the I^2R method, uses measurements of the currents and prior knowledge of the network impedances to calculate the losses.

Longer term trends in assessed loss, Figure 6, use the I^2R values, and provide a breakdown of which assets are contributing to the losses (HV cables/overhead lines, distribution transformer no-load losses, and distribution transformer load losses).

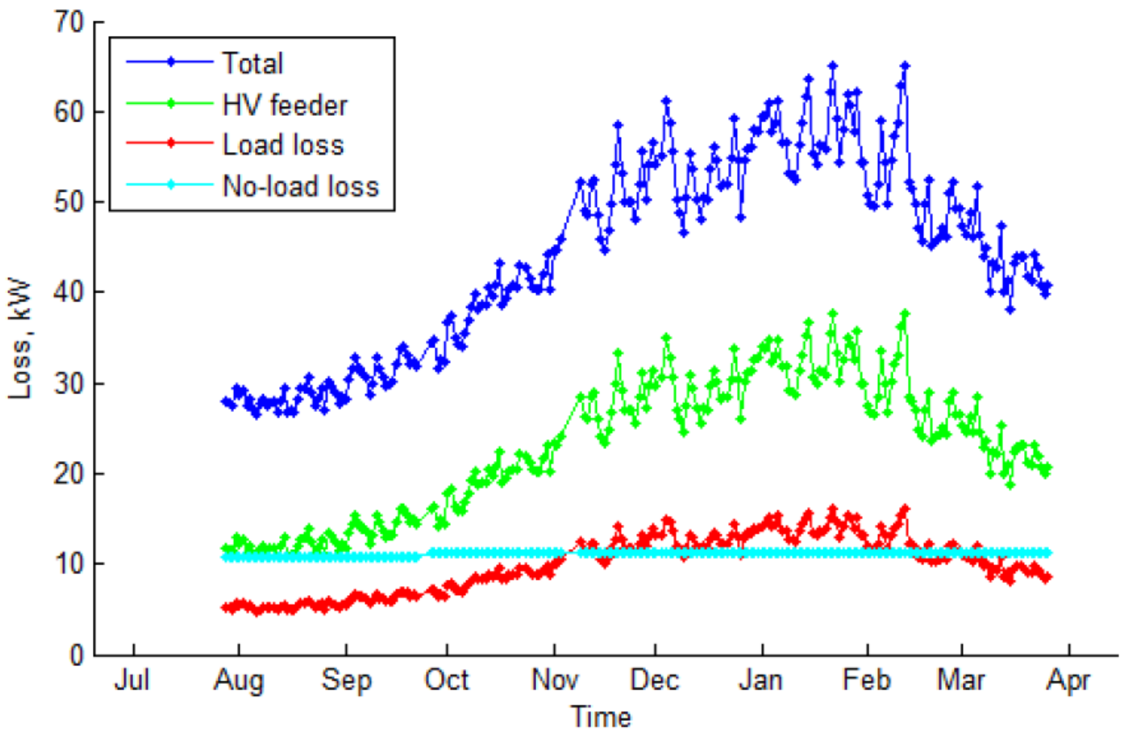

Figure 6 Long term Mean Daily I^2R calculated Loss (Fox Milne Hotel, March 2017)

On a monthly basis, one minute sample plots of loss vs demand are produced with losses shown in absolute and percentage terms (Figure 7 and Figure 8).

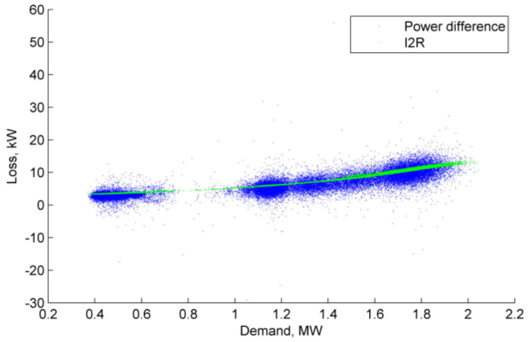

Figure 7 March 2017 Loss, kW vs demand (Amway Tongwell HV feeder)

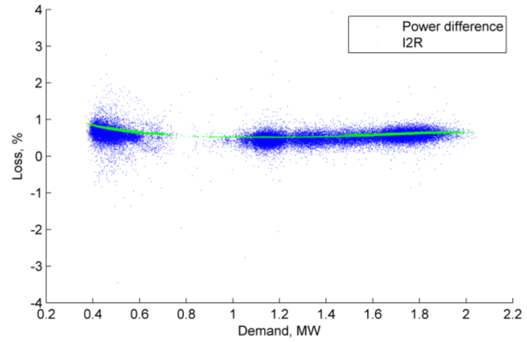

Figure 8 March 2017 Loss, % vs demand (Amway Tongwell HV feeder)

Analysis and comparisons of the loss and characterising factors for each feeder are underway and will be completed once representative data for all feeders is available. This includes comparison to existing indicators of loss (i.e. Line Loss Factors) and previously prepared reports. In general, it is recognised that these assessments of technical loss are lower than might have been expected, and this is forming part of the further analysis work.

2.5.2 Next steps

The analysis outline above and in Appendix C will be completed for the remaining feeders, as they become available.

Following this, the analysis and comparison of the loss and characterising factors for each feeder, with comparison to existing indicators of loss (i.e. Line Loss Factors) and previously prepared reports will be completed.

2.6 Development of loss estimation methods for HV and LV feeders

2.6.1 Progress within this reporting period

The development of a method to estimate feeder-specific losses using a minimum information set is the second key aim of the project.

The HV feeder loss assessment information described in Section 2.5 and shown in Appendix C has been used to consider how specific feeder losses could be reasonably accurately assessed without the need to install additional monitoring equipment.

A preferred method of estimating feeder losses has been established, and this results in:

- a reasonable agreement between loss assessment using monitoring data and an initial estimate of losses using raw load information; and
- a very high degree of agreement if corrections are made to errors that exist in the initially available load information.

The preferred HV feeder loss assessment method contains the following key steps:

- Assembly of input data;
- Assembly of a representative 365 day load model for each substation on the feeder;
- Preparation of a load flow model with a data flow control script (an example is IPSA with Python based scripts); and
- Run the load flow scripts.

Further details on the key aspects of pre-existing information or learning from the project that have been used in developing the estimation approach, and expanded information on the key steps are contained in Appendix D.

Table 3 presents the results from loss estimation for the available seven HV feeders.

Initial work has been undertaken to verify that an IPSA model with appropriate data flow control and load flow calculation control scripts could be used. To date, a single HV feeder for a single day (48 HH periods) has been used to demonstrate that scripting is reasonably achievable and that comparable results (to Loughborough project-bespoke model) are achievable. This exercise resulted in high precision agreement between the IPSA model and the Loughborough model, and it has been concluded that this presents a realistic assessment implementation approach. Further work will follow.

To date, the majority of development work has been undertaken on HV feeders because this is where a reasonable amount of project data is now available. Initial considerations of LV feeders have also been made, and the following points are note:

- There is less certain information about network connectivity and resultant intermediate LV branch lengths;
- there is significant variation in demand within minutes, and from one minute to the next;
- there is significantly more transient and persistent phase unbalance;
- with time, the implementation of advanced metering will significantly change the amount of information available.

It is therefore anticipated that the LV feeder loss estimation will involve the following further activities in addition to those for HV feeder loss estimation.

- Network estimation (not required to significant extents for HV)
- Enhanced Load estimation (whilst required at HV, further factors will be required e.g. sub-division of estimated substation loads between LV feeders, phase connection and unbalance)

HV Feeder	Loss Assessment (using monitoring data)	Initial Loss Estimate	Revised Loss Estimate
Woodlands			
Mean feeder demand, MW	1.59	1.62	1.61
Loss power, kW	20.2	21.4	20.4
Loss percentage, %	1.27	1.33	1.27
Fox Milne Hotel			
Mean feeder demand, MW	2.60	2.50	2.50
Loss power, kW	53.3	47.5	51.2
Loss percentage, %	2.05	1.90	2.05
Wavendon Gate Local			
Mean feeder demand, MW	0.95	0.94	No
Loss power, kW	8.6	8.4	Revisions
Loss percentage, %	0.90	0.90	Made
Secondary School Walnut Tree			
Mean feeder demand, MW	3.10	2.99	2.99
Loss power, kW	40.8	38.6	38.6
Loss percentage, %	1.32	1.29	1.29
Crawley Road Tee Howard Way			
Mean feeder demand, MW	2.73	2.72	No
Loss power, kW	22.8	22.6	Revisions
Loss percentage, %	0.84	0.83	Made
Amway Tongwell			
Mean feeder demand, MW	1.20	1.23	1.23
Loss power, kW	7.3	10.8	7.7
Loss percentage, %	0.60	0.87	0.63
Ackerman Tongwell Aldrich Drive Tee			
Mean feeder demand, MW	0.86	0.79	No
Loss power, kW	10.8	9.8	Revisions
Loss percentage, %	1.26	1.24	Made

Table 3 Comparison of Feeder Losses using monitoring data and estimation method

2.6.2 Next steps

The next steps in developing the loss estimation methods are divided according to HV and LV feeders.

For HV feeders:

- Continued development of a large-scale capability to assess HV feeders. This is likely to be through the use of an existing large IPSA model from the Equilibrium project and the use of revised load information for this geographic area that already exists;
- Application of the developed methodology to all HV feeders as they become available; and
- Demonstration of the capability to assess large numbers of HV feeders.

For LV feeders:

- Development of approaches to LV network estimation (e.g. estimation of points of service connection along an LV main, estimation of phase for single phase loads, and estimation of resultant LV branch lengths);
- Development of approaches to LV load estimation; and
- Development of overall calculation methodologies.

3 Progress against Budget

3.1 Overview of Progress against Budget

Spend Area	Budget (£k)	Expected Spend to Date (£k)	Actual Spend to Date (£k)	Variance to Expected (£k)	Variance to Expected %
LV Feeder Monitoring	£496	£125	£135	-£10	-8%
HV Feeder monitoring	£1,007	£615	£666	-£51	-8%
Analysis	£425	£201	£201	£0	0%
Design & Project Management	£417	£193	£193	-£0	0%
Contingency	£235	£0	£0	£0	0%
Total	£2,580	£1,134	£1,196	-£61	-5%

Table 4 Progress Against Budget

3.2 Comments around variance

1. Variance to Expected Spend for LV feeder monitoring is due to recent efforts to accelerate delivery of work, and is the value of work delivered ahead of most recent expectations.
2. Variance to Expected Spend for HV feeder monitoring is due to equipment delivery ahead of most recent expectations.

4 Progress towards Success Criteria

At inception, the project identified five success criteria. These criteria are listed in Table 5 with commentary on progress towards completion.

Project Success criteria	Commentary on progress
1) Construction of fully monitored HV and LV networks	HV Feeders - 7 of 11 are now fully constructed and providing data. All ground-mounted monitoring on the remaining feeders is also in place, and the pole-mounted monitoring is scheduled for completion by the end of June 2017. LV feeders – 3 of 11 are now fully constructed and providing data. A further 2 feeders are in progress and will provide data during April 2017. The remaining feeders will be progressively constructed by the end of June 2017. Further details are contained in Appendix B.
2) Measurement of network losses on monitored feeders	Ongoing loss assessments based on full monitoring data are available for 7 from 11 HV feeders, and 3 from 11 LV feeders. This includes both loss assessment via a "Power Difference" method (measurement of network losses), and assessment via an I^2R method (accurate modelling of the feeders). A snapshot of the Loss assessments for these feeders is shown in Appendix C.
3) Accurate modelling of losses with full information	
4) Several models with limited data sets created and tested	Various approaches to estimating feeder specific losses have been considered and tested to date. For HV feeders, a preferred approach has been developed that delivers high degrees of agreement to monitoring data assessments. Details of this are described in Section 2.6 and in Appendix D. For LV feeders, initial assessment of key similarities and differences to the successful HV approach has been made. Work on an LV approach is ongoing.
5) Conclusion on level of information needed to accurately predict losses	Draft Conclusions on the level of information required for HV feeders are available (Appendix D - Assembly of input data), and will continue to be tested as all HV feeders provide data and representative data for all seasons becomes available. Conclusions on LV feeder specific loss estimation will follow.

Table 5 Progress towards project Success Criteria

5 Learning Outcomes

Extensive learning has emerged from the project to date, and much of this is detail-oriented and associated with calculations. Early and draft conclusion-style learning is emerging and will be formalised as the project progresses towards completion. Selected learning is noted in Table 6, with a comprehensive list of learning provided in Appendix E.

Area of Learning	Learning
Pilot Approach	• The introduction of phased testing and implementation has been successful in reducing project risk at an early stage/limited implementation cost, and in minimising re-work during the roll-out of monitoring to the selected feeders. It has however, affected original project timescales. Further details on learning from the use of the pilot approach are contained in Appendix E 1.
Loss calculations	• Two methods of loss calculation have been identified: a power difference method in which the power delivered by the network is subtracted from the power supplied as an infeed, and an I^2R method in which the currents from each network outfeed are combined in a power-flow analysis to calculate the current in each network branch. This allows the total I^2R losses to be calculated. • The I^2R method has been adopted as the primary loss calculation approach for the losses investigation project. Loss calculations using the power difference method are then used as a validation check. • Differences between average values of losses from the power difference method and the I^2R method exist for some feeders and are the subject of ongoing investigation and refinement (e.g. addition of meter power consumption to the I^2R method to improve comparability to power difference method). Further details on learning associated with loss calculations are contained in Appendix E 2.
Instrumentation	• The adopted EDMI meters have been configured in an unusual manner to collect the required data. The developed configurations successfully collect one minute data averages for a wide range of parameters (29 parameters in the case of a three-phase meter), but retain this data for a relatively short period of time on a first-in-first-out basis (21 days) and the quantity of data that requires transmitting on a daily basis takes material periods of time over GPRS[3] connections (three plus minutes, depending on the efficiency of the data collection approach). • Current measurements using Rogowski coils placed around HV cables are affected by currents in the sheaths. Although this has

[3] General Packet Radio Service, the mobile data service on 2G and 3G cellular communications systems.

Area of Learning	Learning
	minimal impact on the amplitude measurement, the measured phase angle is offset from the true value. This causes errors in the measurement of active and reactive power and in the phase angle of currents that are combined in the power-flow analysis for the I^2R loss calculations. A further sensor type was developed in collaboration to resolve this issue. Further details on learning associated with instrumentation are contained in Appendix E 3.
HV feeder losses	• Differences in the level of loss on sample HV feeders are emerging (see Appendix C). Further differences are expected as the mixed and overhead feeders start to provide data. These differences will be further reviewed as the project progresses. • Losses for the HV feeders considered so far appear lower than references sources (WPD generic LLF[4] values, Imperial College/Sohn Associates "Management of electricity distribution losses" and a 2008 E.ON Loss Calculation Study). This difference is still being investigated and will be reviewed again as a wider diversity of feeders is included in the trial. • The transformer no-load losses are a significant proportion of the total for feeders where the customers connect at LV. Depending on the number of HV connections, transformer no-load losses are between 10% and 60% of the total. Further details on learning associated with instrumentation are contained in Appendix E 4.
LV feeder losses	• Early indications of differences in the level of loss on sample LV feeders are emerging (see Appendix C). Further differences are expected as the industrial and commercial feeders and overhead feeders start to provide data. These differences will be further reviewed as the project progresses. • Losses for the LV feeders considered so far appear lower than the references sources (WPD generic LLF values, Imperial College/Sohn Associates "Management of electricity distribution losses" and a 2008 E.ON Loss Calculation Study). This difference is still being investigated and will be reviewed again as a wider diversity of feeders is included in the trial. • The losses due to self-consumption by the advanced meters have been included. This makes a significant contribution to the losses, ranging from 40% to 75% of the total for the data available to date.

Table 6 Illustrative and key learning

[4] Line Loss Factor: means the multiplier which, when applied to generation or demand on the distribution system, converts the data to an equivalent value at the transmission system boundary inclusive of distribution system losses

6 Intellectual Property Rights

A complete list of all background IPR from all project partners has been compiled. The IP register is reviewed on a quarterly basis.

7 Risk Management

Our risk management objectives are to:

- Ensure that risk management is clearly and consistently integrated into the project management activities and evidenced through the project documentation;
- Comply with WPDs risk management processes and any governance requirements as specified by Ofgem; and
- Anticipate and respond to changing project requirements.

These objectives will be achieved by:

- ✓ Defining the roles, responsibilities and reporting lines within the Project Delivery Team for risk management;
- ✓ Including risk management issues when writing reports and considering decisions;
- ✓ Maintaining a risk register;
- ✓ Communicating risks and ensuring suitable training and supervision is provided;
- ✓ Preparing mitigation action plans;
- ✓ Preparing contingency action plans; and
- ✓ Monitoring and updating of risks and the risk controls.

7.1 Current Risks

The Losses Investigation Risk Register is a live document and is updated regularly. There are currently 10 live project related risks. Mitigation action plans are identified when raising a risk and the appropriate steps then taken to ensure risks do not become issues where reasonably possible. Table 7 provides details of the project's top five current risks. For each of these risks, a mitigation action plan has been identified and the progress of these are tracked and reported.

Details of the Risk	Risk Rating	Mitigation Action Plan	Progress
Required work on OH HV feeders may require additional product development or introduction of further/amended Standard Techniques to manage H&S	50	This risk has materialised. Extensive consultation on the required development of a revised arrangement and associated installation has occurred. Close collaboration with manufacturer has been maintained.	A revised mounting arrangement and associated installation procedure has now been internally approved. Time taken to achieve this has caused a delay in the installation of pole-mounted monitors on HV feeders.
Customer concerns associated with advanced meters.	30	At a modest scale, this risk has materialised. As a result, greater customer engagement has been implemented to mitigate further concerns.	Greater customer engagement arrangements have been employed for recent implementations and will be for all further implementations.
Overall losses assessment methodology has uncertainties that are too large for the intended purpose.	15	Adoption of Pilot approach. Retention of both power difference and I^2R calculation methods.	The successful pilots largely mitigated impact of this risk, and as each feeder is checked with initial data, the risk of material impact diminishes further.
Unavailability of Distribution Transformer parameters /insufficiency of type values for loss assessment.	18	Maintenance of both power difference (independent of assumptions on transformers) and I^2R method (dependent on transformer assumptions) as a cross-check to identify if transformer values are material issues.	Whilst differences do exist between power difference and I^2R values, they are not sufficiently large to threaten findings from the project. Work on establishing and validating transformer parameters/ assumptions continues.
Captured EDMI meter data cannot be adequately transmitted to a central data store for required roll out	12	Project plan always included the implementation of a volume meter data collection system. Collaborative testing of the proposed system.	Volume data collection system has been pre-installation tested, and a number of issues identified and resolved. Installation and commissioning are now underway.

Table 7 Top five current risks (by rating)

Figure 9 provides a snapshot of the risk register, detailed graphically, to provide an on-going understanding of the projects' risks.

Likelihood = Probability x Proximity						
	Certain/Imminent (21-25)	0	1	0	0	0
	More likely to occur than not/Likely to be near future (16-20)	0	0	0	0	0
	50/50 chance of occuring/ Mid to short term (11-15)	0	0	0	0	0
	Less likely to occur/Mid to long term (6-10)	0	2	1	0	0
	Very unlikely to occur/Far in the future (1-5)	0	2	3	0	1
		1. Insignificant changes, re-planning may be required	2. Small Delay, small increased cost but absorbable	3. Delay, increased cost in excess of tolerance	4. Substantial Delay, key deliverables not met, significant increase in time/cost	5. Inability to deliver, business case/objective not viable
		Impact				

	Minor	Moderate	Major	Severe	
Legend	7	2	1	0	**No of instances**
Total	10				No of live risks

Figure 9 Snapshot of Risk Register

Figure 10 provides an overview of the risks by category, minor, moderate, major and severe. This information is used to understand the complete risk level of the project.

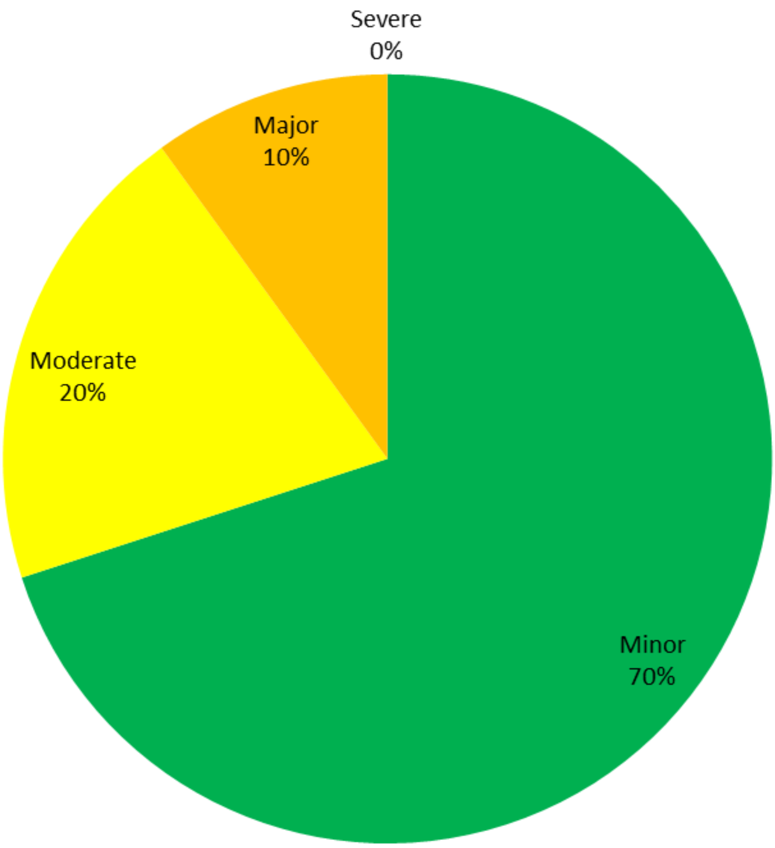

Figure 10 Graphical view of Risk Register by Risk Category

8 Consistency with Project Registration Document

The scale, cost and timeframe of the project has remained consistent with the registration document, with the exception to the change to the project end date. A copy of the original registration document can be found >>following this link[5]<<.

As discussed in Section 2.2, the introduction of a pilot phase to the project and longer than expected construction period has changed the project end date to July 2018 (reporting by October 2018). This is currently the subject of a project change request.

9 Accuracy Assurance Statement

This report has been prepared by the Losses Investigation Project Manager (Chris Harrap), reviewed and approved by the Future Networks Manager (Roger Hey).

All efforts have been made to ensure that the information contained within this report is accurate. WPD confirms that this report has been produced, reviewed and approved following our quality assurance process for external documents and reports.

[5] http://www.smarternetworks.org/NIA_PEA_PDF/WPD_NIA_005_3113.pdf

Appendix A Loss Assessment Pilots

Pilot monitoring has been installed on an HV feeder at Milton Keynes in the WPD East Midlands license area. The upstream power flow on the monitored network is measured at a 33/11kV Primary Substation, and the downstream power flows on this network are monitored with equipment installed at each of the Distribution Substations served by the feeder. The Primary Substation monitoring is provided by a new (HV variant) of Gridkey's MCU 520 substation monitoring equipment. The downstream sensors (established Gridkey MCU 520 LV monitoring devices) are installed on the LV side of the distribution transformers. The end-to-end losses measured in this trial therefore include the 11 kV feeder cable and the 11 kV to LV Distribution Substations.

The LV pilot trial uses a network in the Isle of Man where monitoring equipment has been installed on one LV feeder. Upstream power flow to the LV feeder is monitored on the LV side of the Distribution Substation (using established Gridkey Distribution Substation monitoring), and advanced meters (of a type not previously used in the Isle of Man) are installed at each of the 13 customer connections on this feeder to monitor downstream power flow. Of the 13 connections, 11 connections supply domestic customers and the other 2 connections serve public lighting circuits.

Collectively, the HV and LV pilot trials therefore provide an end-to-end loss measurement that is representative of the distribution networks between the Primary Substations and the customer.

The measurement data is stored as one minute averages within the monitoring equipment and then collected periodically by GPRS-based data connections. For the advanced meters, the number of measurement parameters (e.g. power, voltage, current, averages, maximums, minimums etc.) and the selected time resolution of the measurement data defines the volume of data collected and requiring transmission. This volume is constrained by the memory size within the instruments and the time/resource needed to download the data. For both the HV and LV pilot trial, 1 resolution of 1 minute has been selected, so as to minimise any errors in estimating the losses due to under-sampling the time variation of the demand. The number of meter measurements points has been consequentially selected to make maximum use of device memory.

The collected data has been forwarded to Loughborough University for analysis of the losses. Two loss analysis methods have been used: 1) estimation of the losses based on the power difference between the single upstream power flow and the total downstream power flows on the network and 2) estimation of the losses using an I^2R calculation primarily based on current measurements at each downstream point on the networks. Additional information is needed for use with the I^2R method in order to specify the resistance of each network branch and to define the connection topology such that the currents on the un-monitored branches within the network can be calculated. The load losses and no-load losses of the transformers must also be specified. Significantly difference tolerances in assessed losses arise from the two different methods, the I^2R method having lower (better) tolerances.

The mean end-to-end losses in the HV feeder over a 27 day period in March/April 2016 (with >99% data availability) have been estimated using the I^2R method as 1.23% of the delivered power. An uncertainty of ±0.06% of the delivered power or ±5% of the mean losses applies to this estimate.

The losses for each 1 minute sample in the HV pilot period are shown in Figure 11. As expected, the losses vary with the demand, and also with the distribution of load along the feeder (such that higher losses occur if the demand is greater for substations that are electrically further along the feeder). The levels of unbalance for the HV trial feeder were low, particularly for higher demands, and so unbalance made little contribution towards increasing the losses.

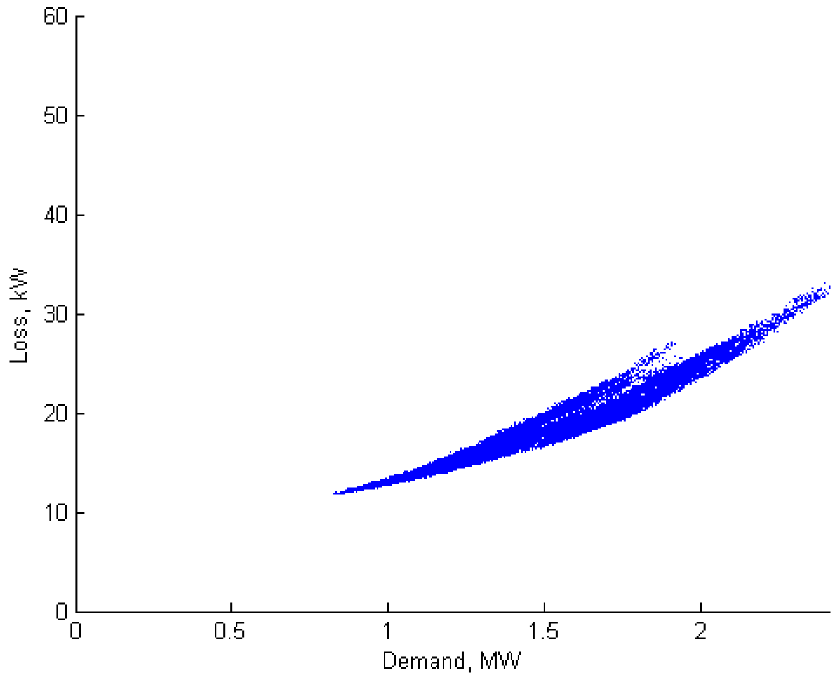

Figure 11 Pilot HV feeder losses for each 1 minute sample calculated with I^2R method

Using the I^2R method, the losses from the HV trial can be calculated separately for the HV feeder cable and for the Distribution Substations. The mean losses in the HV cable were estimated as 0.26% of the delivered power (line loss factor of 1.0026), a figure that is approximately one quarter of the losses indicated by the generic line loss factors from the WPD schedule of charges (around 1%). A previous loss study also suggested a higher figure (0.69%). Over the measured period, the losses for the HV feeder cable, which is believed to have typical levels of demand, were therefore much lower than previous estimates would suggest. It should be emphasised that this is a single feeder finding, and wider conclusions should not be drawn.

The mean losses for the distribution transformers on the HV trial feeder were calculated as 0.97% of the delivered power (line loss factor 1.0098). This is approximately half of the losses predicted by the generic line loss factors (around 2%) but consistent with the estimates from the previous loss study (1.11%).

The mean losses for the LV trial over a 10 day period in April/May 2016 (with data availability >99%) were calculated using the I^2R method as 0.21% of the delivered power (line loss factor 1.0021). An uncertainty of ±0.02% of the delivered power or ±10% of the mean losses applies to this estimate. The individual loss estimates have a much greater variation than those for the HV trial feeder, with differences due to the changes in the three-phase balance and in the electrical distance of the demand along feeder as individual customer loads switch on and off. The variation in the losses for individual 1 minute samples during the pilot period is shown in Figure 12.

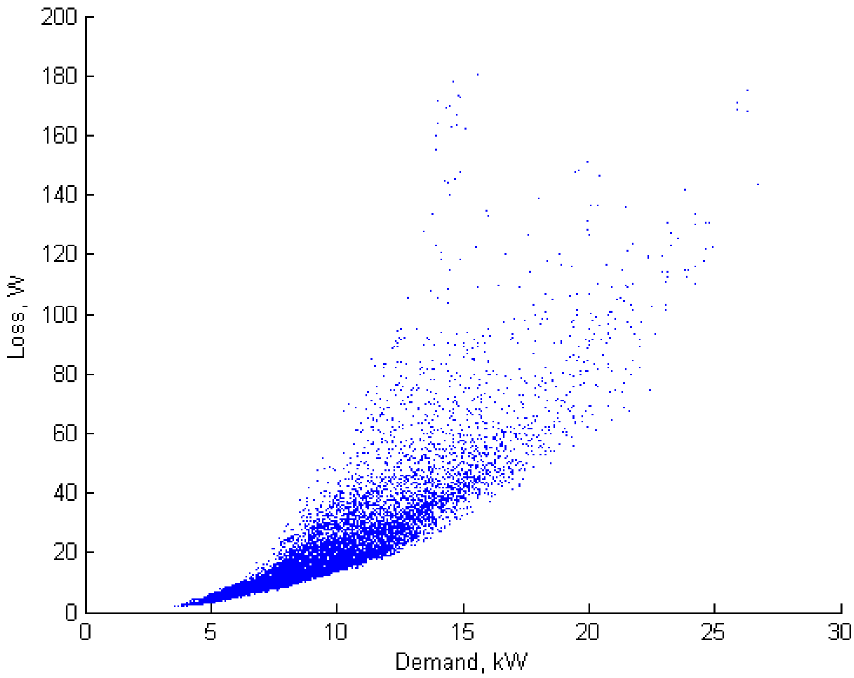

Figure 12 Pilot LV feeder losses for each 1 minute sample calculated with I2R method

The mean losses were very much lower than previous LV network estimates with the generic line loss factors suggesting over 2% (although these figures also include non-technical losses) and a previous loss study suggesting 1.29%. The LV trial feeder may have unusually low losses as the cable between the substation and the nearest customer connection is relatively short and has a large conductor size (300 mm^2) considering the routinely connected load.

The loss analysis method has also been able to highlight inconsistencies in the network database, correctly identifying one connection point that was recorded as being on the wrong phase and also that the initial network data had omitted a customer connection.

Figure 13 compares the loss calculations from the power difference and the I^2R method for the LV trial feeder. For both the HV trial feeder and the LV trial feeder, losses calculated using the power difference method are subject to much wider tolerances. For the power difference method, the tolerance on assessed loss is based on uncertainty in the measured power (i.e. modest percentages of large numbers), whereas the tolerance on assessed loss for the I^2R method is based on calculated component losses (i.e. modest percentages of small numbers). Therefore the I^2R method of loss calculation is fundamentally very much less sensitive to the same intrinsic instrument tolerances.

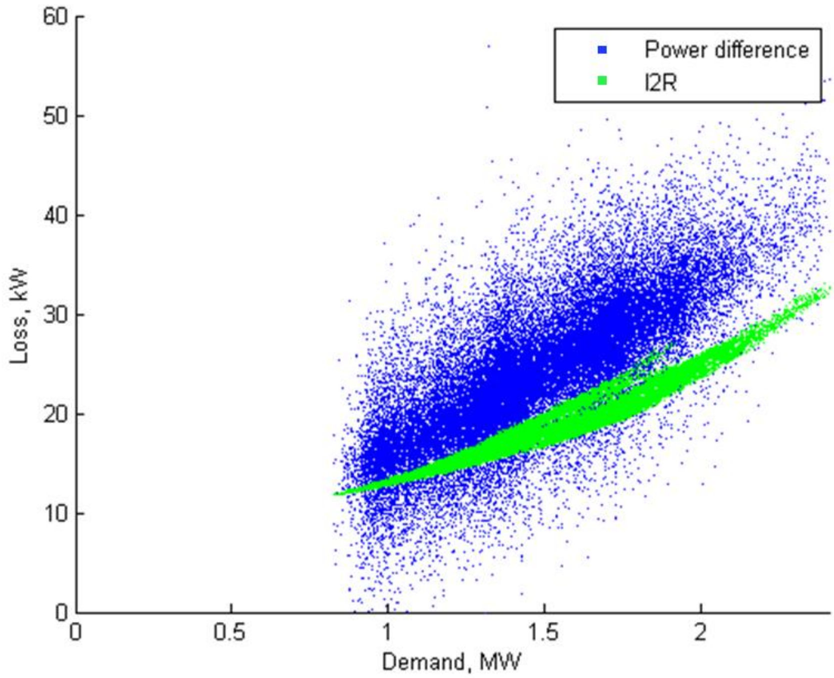

Figure 13 Pilot HV feeder losses for each 1 minute sample calculated with the power difference method and with the I^2R method

Appendix B Installation of Monitoring to Selected Feeders

Appendix B 1 HV feeder progress

Progress with selection and installation of monitoring devices on HV feeders is summarised in Table 8.

Feeder	Overview	Detailed Feasibility	Primary Sub work	Secondary Sub work
Pilot feeder *- 940037-02 (Marlborough Street: The Woodlands)*	*UG2A, 4.8km.* *11 GM Subs.*	*Complete*	*Complete*	*Complete.*
940043-03 (Fox Milne: Fox Milne Hotel)	UG2B, 13.3km. 16 GM Subs.	Complete	Complete	Complete.
940046-03 (Wavendon Gate: Wavendon Gate Local)	UG1B, 2.1km. 8 GM Subs.	Complete	Complete	Complete
940046-08 (Wavendon Gate: Secondary School Walnut Tree)	UG2A, 8.5km. 13 GM Subs, 2 HV sites.	Complete	Complete	Complete – including 2 HV sites
940041-10 (Newport Pagnell: Howard Way Tee Crawley Road)	UG1A, 3.8km. 3 GM Subs, 3 HV sites.	Complete	Complete	Complete – including 3 HV sites
940041-08 (Newport Pagnell: Amway Tongwell)	MA1A, 19% OH, 2.4km. 4 GM Subs, 7 HV sites.	Complete	Complete	Complete
940041-09 (Newport Pagnell: Ackerman Tongwell Tee Aldrich Drive)	MB1A, 29% OH, 8.3km. 7 GM Subs, 4 PM sites.	Complete	Complete	In-progress (1 PM remaining)
940041-04 (Newport Pagnell: Riverside Park)	MA2A, 10% OH, 8.6km. 12 GM Subs, 2 HV sites, 7 PM sites.	Complete	Complete	In-progress (all GM complete, all 7PM remaining)
940046-02 (Wavendon Gate: The Avenue)	MB2A, 37% OH, 12.0km. 8 GM Subs, 2 HV sites, 11 PM sites.	Complete[6]	Complete	In-progress (all GM complete all 10 PM remaining)
940036-11 (Wolverton: Energy from Waste RMU C))	MC1B, 76% OH, 15.7km. 7 GM Subs, 14 PM sites.	Complete	Complete	In progress (all GM complete, all 14 PM remaining)
940045-04 (Olney: Silver End Olney)	OH1B, 87% OH, 23.9km. 6 GM Subs, 23 PM sites.	Complete	Complete	In progress (all GM complete, all 23 PM remaining)

Table 8 Installation Progress for monitored HV feeders

[6] So far as reasonably practicable – some of the transformer data that would routinely collected during the feasibility stage is not available (for obvious access reasons), and will be collected at Gridkey installation.

Appendix B 2 HV feeder progress

Progress with selection and installation of monitoring devices on LV feeders is summarised in Table 9.

Feeder	Overview	Feeder Contract	Feasibility & Modelling Info	Secondary Sub work	Meter work	Data Available
Pilot feeder – around Douglas	*277m u/g mains cable* *187m u/g service cable* *11 domestic – 1ϕ* 2 St. Ltg. Pillars – *1ϕ*	*Complete*	*Complete*	*Complete*	*Complete.*	*Yes*
Dom#1 – Laxey	u/g mains cables u/g service cables 57 domestic - *1ϕ*	Complete	Complete	Complete	Complete	Yes
Dom#2 - Ramsey	57 domestic - *1ϕ*	Complete	Complete	Complete	Complete	Yes
I&C#1 – Peel Feeder A	10 - *3ϕ* 1 – 1 *ϕ*	Complete	Ongoing	Ongoing	In progress	First data expected w/c 2017/05/12
I&C#1 – Peel Feeder B	6 - *3ϕ* 12 - 1*ϕ*	Complete	Ongoing	Ongoing	In progress	First data expected w/c 2017/05/12
I&C#2 – Balthane	3 - *1ϕ + 14* - *3ϕ*	Complete	Ongoing	Ongoing	To follow	First data expected w/c 2017/05/19
I&C#3 – Snugborough	10 - *1ϕ + 8* - *3ϕ*	Complete	Ongoing	Ongoing	To follow	First data expected w/c 2017/05/26
OH#1 – Santon o/h	19 – *1ϕ*	Complete	To follow	Ongoing	To follow	First data expected w/c 2017/07/07
Dom#3 – Santon u/g	43 domestic - *1ϕ*	Complete	Ongoing	Ongoing	To follow	First data expected w/c 2017/07/07
OH#2 – TBC	TBC					July 2017
OH#3 – TBC	TBC					July 2017

Table 9 Installation Progress for monitored HV feeders

Appendix C Ongoing Loss Assessments

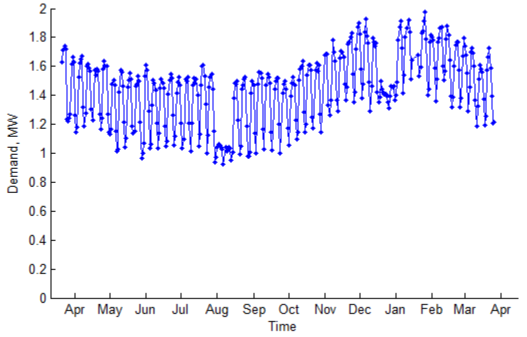

Figure 14 Long term mean daily feeder demand (Woodlands HV feeder)

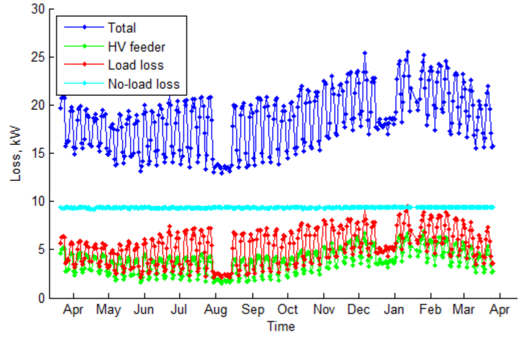

Figure 15 Long term mean daily loss (Woodlands HV feeder)

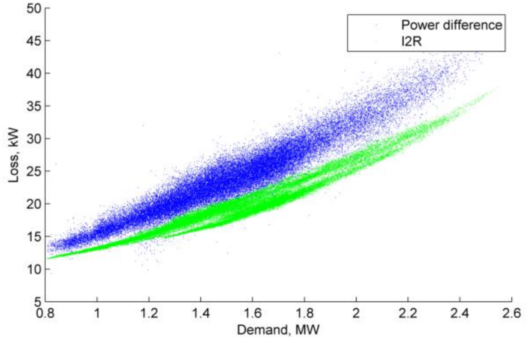

Figure 16 March 2017 Loss, kW vs demand (Woodlands HV feeder)

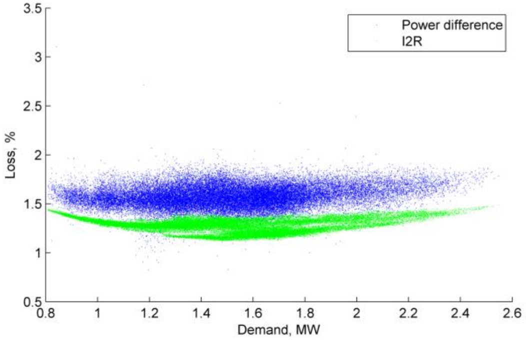

Figure 17 March 2017 Loss, % vs demand (Woodlands HV feeder)

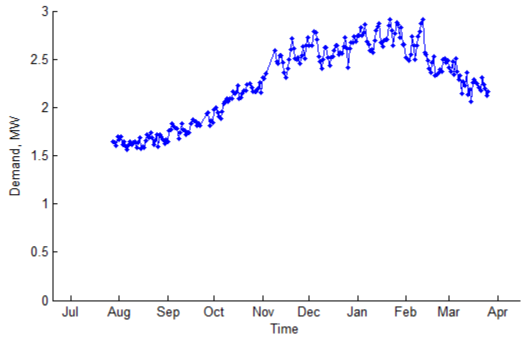

Figure 18 Long term mean daily feeder demand (Fox Milne Hotel HV feeder)

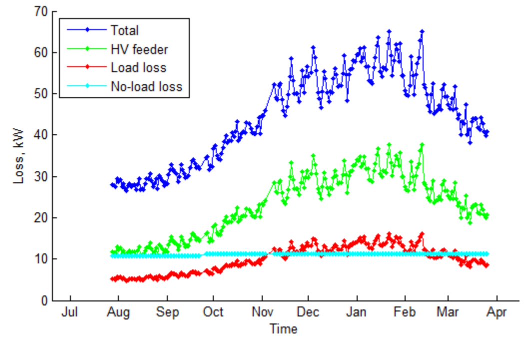

Figure 19 Long term mean daily loss (Fox Milne Hotel HV feeder)

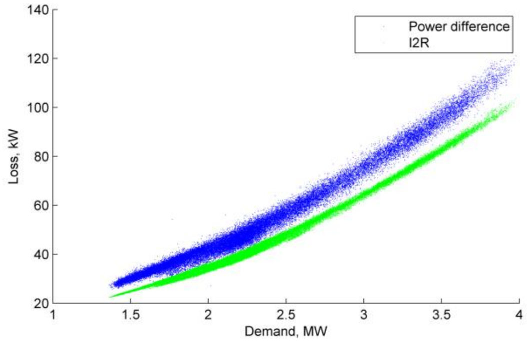

Figure 20 March 2017 Loss, kW vs demand (Fox Milne Hotel HV feeder)

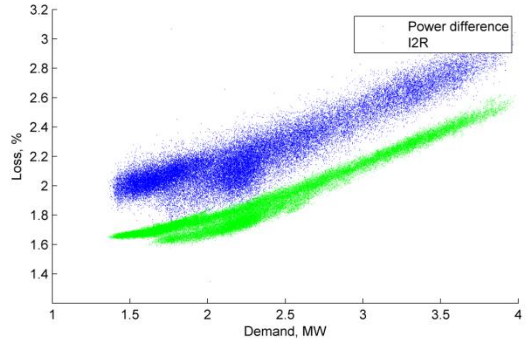

Figure 21 March 2017 Loss, % vs demand (Fox Milne Hotel HV feeder)

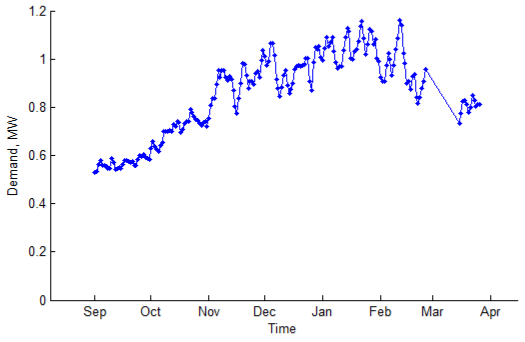

Figure 22 Long term mean daily feeder demand (Wavendon Gate Local HV feeder)

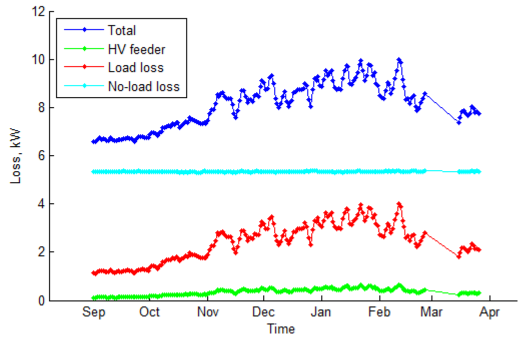

Figure 23 Long term mean daily loss (Wavendon Gate Local HV feeder)

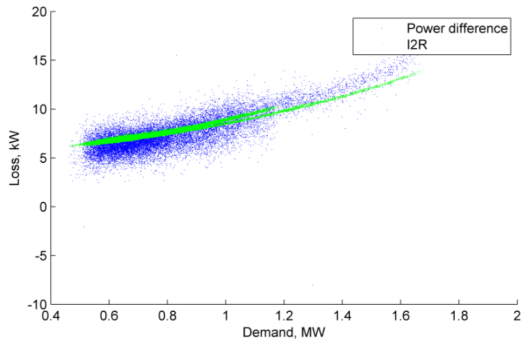

Figure 24 March 2017 Loss, kW vs demand (Wavendon Gate Local HV feeder)

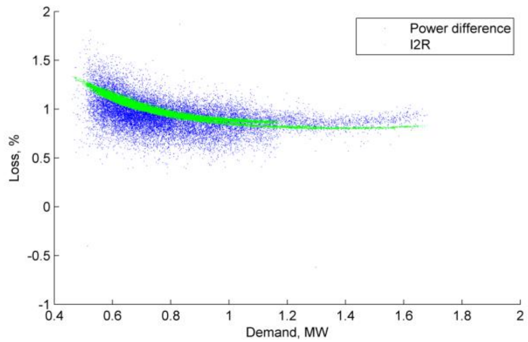

Figure 25 March 2017 Loss, % vs demand (Wavendon Gate Local HV feeder)

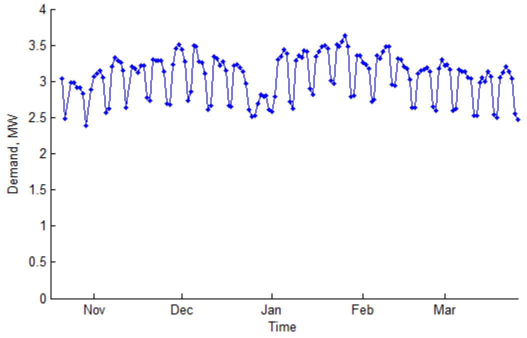

Figure 26 Long term mean daily feeder demand (Secondary School Walnut Tree HV feeder)

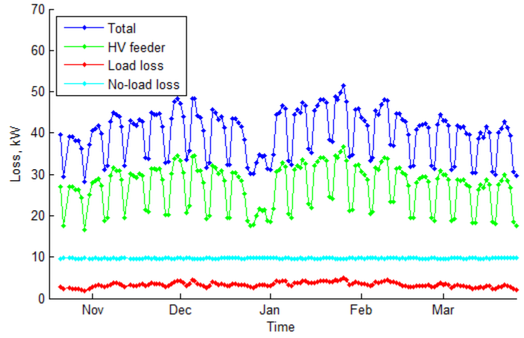

Figure 27 Long term mean daily loss (Secondary School Walnut Tree HV feeder)

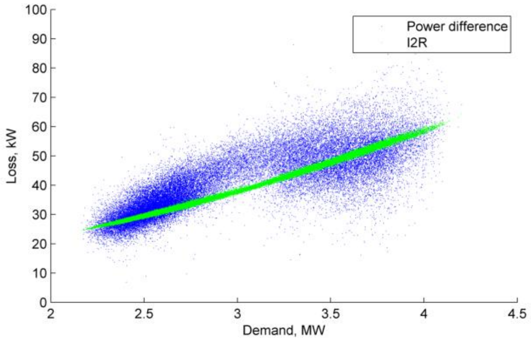

Figure 28 March 2017 Loss, kW vs demand (Secondary School Walnut Tree HV feeder)

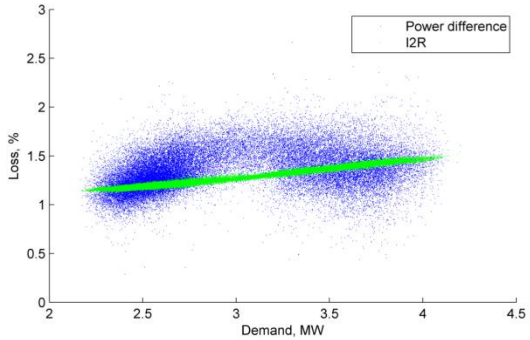

Figure 29 March 2017 Loss, % vs demand (Secondary School Walnut Tree HV feeder)

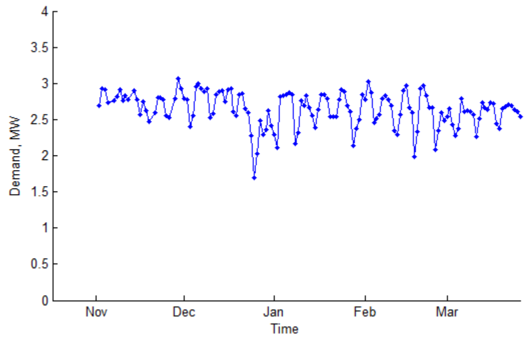

Figure 30 Long term mean daily feeder demand (Crawley Road Tee Howard Way HV feeder)

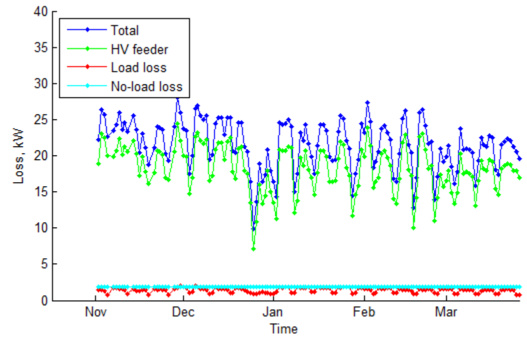

Figure 31 Long term mean daily loss (Crawley Road Tee Howard Way HV feeder)

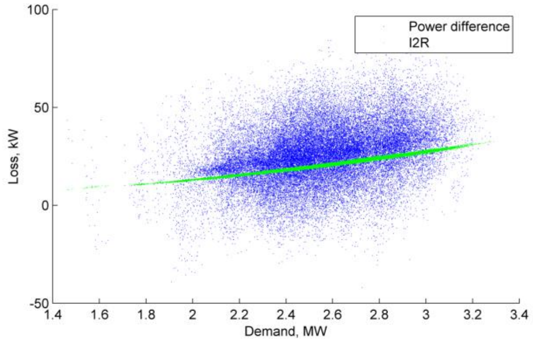

Figure 32 March 2017 Loss, kW vs demand (Crawley Road Tee Howard Way HV feeder)

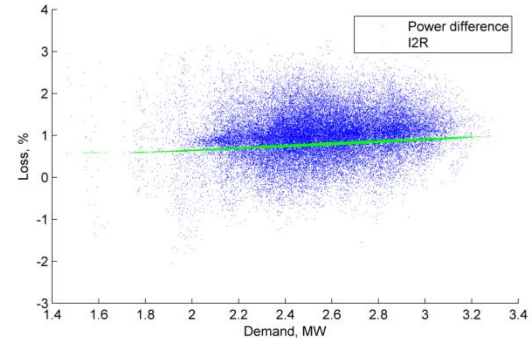

Figure 33 March 2017 Loss, % vs demand (Crawley Road Tee Howard Way HV feeder)

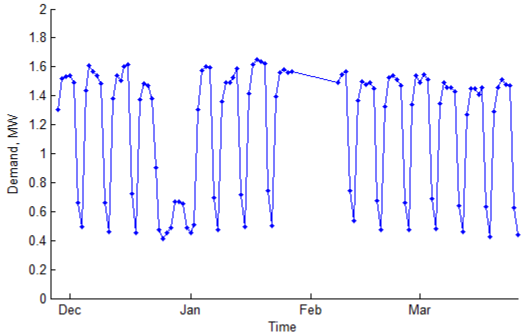

Figure 34 Long term mean daily feeder demand (Amway Tongwell HV feeder)

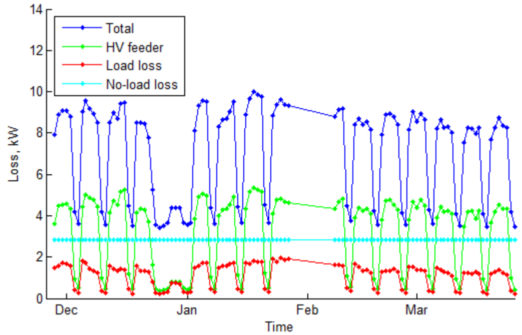

Figure 35 Long term mean daily loss (Amway Tongwell HV feeder)

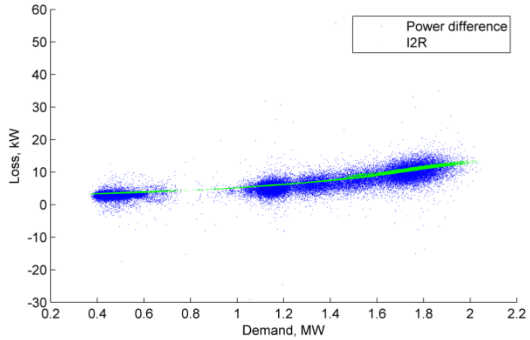

Figure 36 March 2017 Loss, kW vs demand (Amway Tongwell HV feeder)

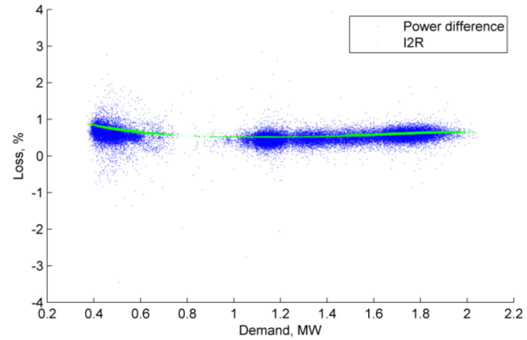

Figure 37 March 2017 Loss, % vs demand (Amway Tongwell HV feeder)

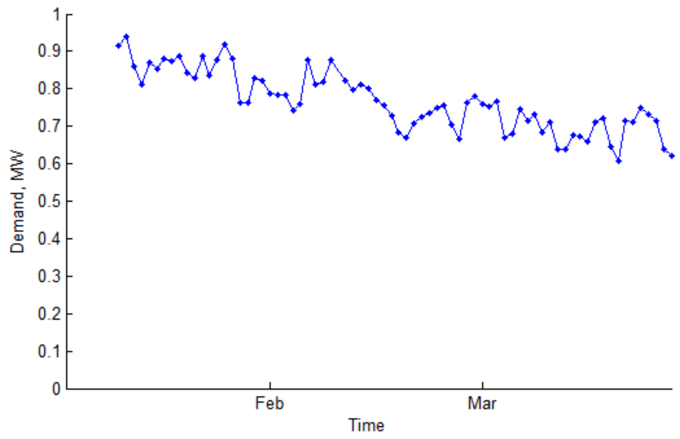

Figure 38 Long term mean daily feeder demand (Ackerman Tongwell Aldrich Drive Tee HV feeder)

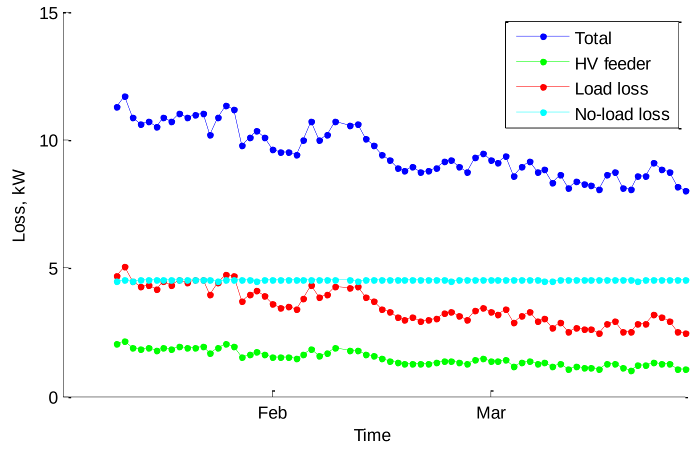

Figure 39 Long term mean daily loss (Ackerman Tongwell Aldrich Drive Tee HV feeder)

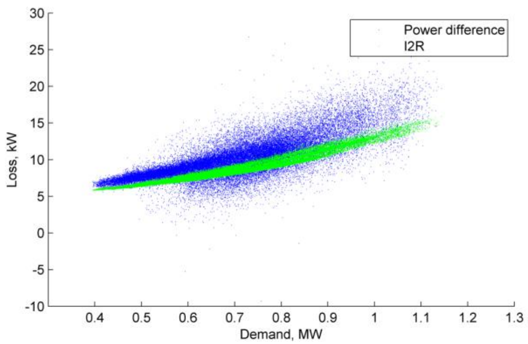

Figure 40 March 2017 Loss, kW vs demand (Ackerman Tongwell Aldrich Drive Tee HV feeder)

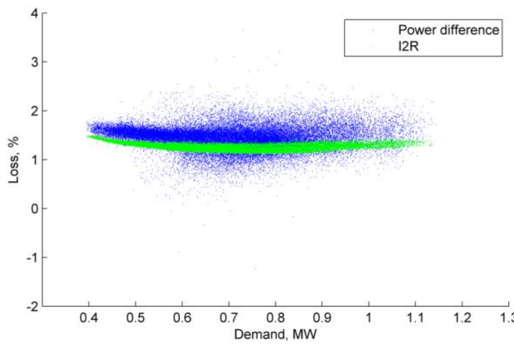

Figure 41 March 2017 Loss, % vs demand (Ackerman Tongwell Aldrich Drive Tee HV feeder)

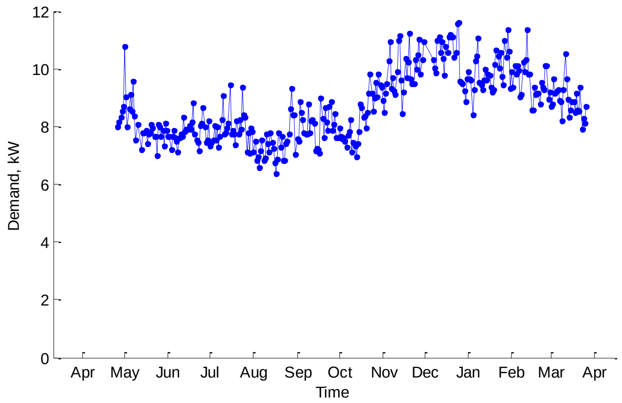

Figure 42 Long term mean daily feeder demand (Domestic Pilot LV feeder)

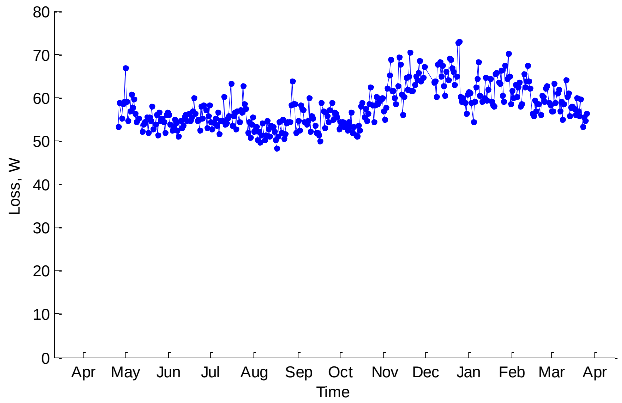

Figure 43 Long term mean daily loss (Domestic Pilot LV feeder)

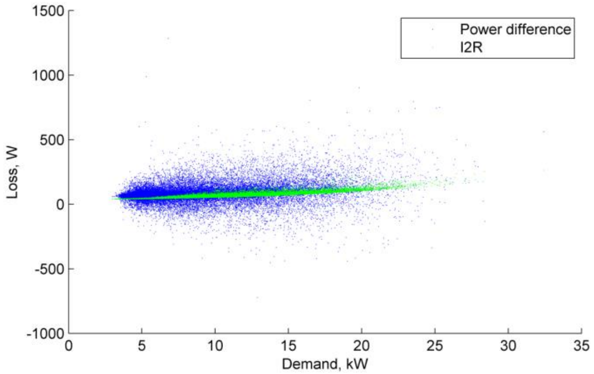

Figure 44 March 2017 Loss, kW vs demand (Domestic Pilot LV feeder)

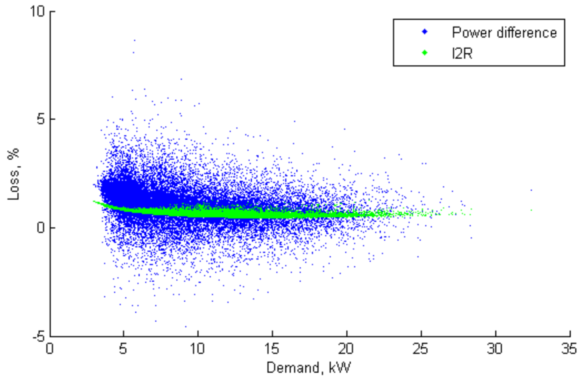

Figure 45 March 2017 Loss, % vs demand (Domestic Pilot LV feeder)

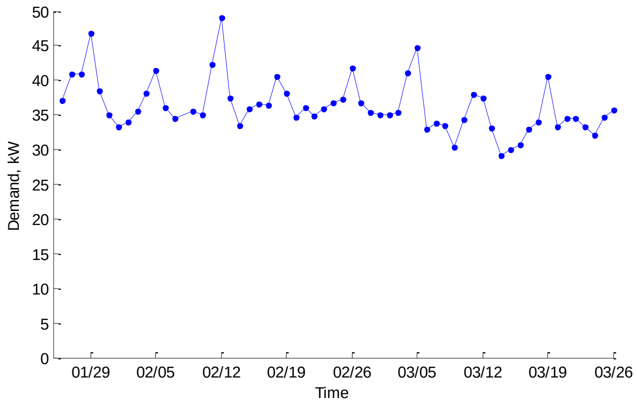

Figure 46 Long term mean daily feeder demand (Laxey Domestic LV feeder)

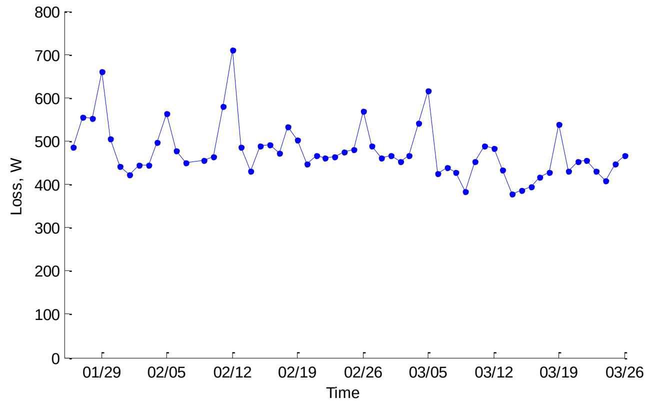

Figure 47 Long term mean daily loss (Laxey Domestic LV feeder)

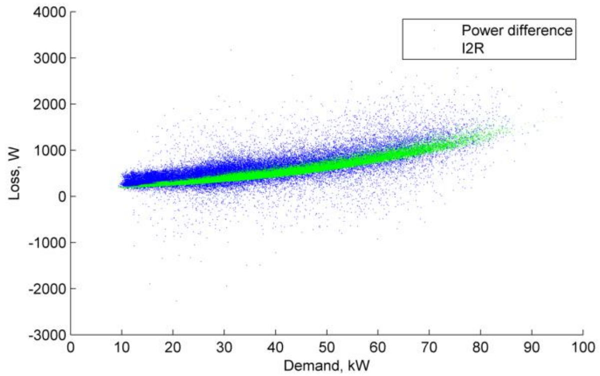

Figure 48 March 2017 Loss, kW vs demand (Laxey Domestic LV feeder)

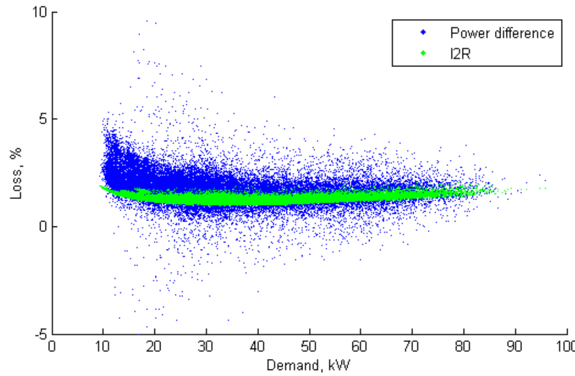

Figure 49 March 2017 Loss, % vs demand (Laxey Domestic LV feeder)

Not yet available.

Figure 50 Long term mean daily feeder demand (Ramsey Domestic LV feeder)

Not yet available.

Figure 51 Long term mean daily loss (Ramsey Domestic LV feeder)

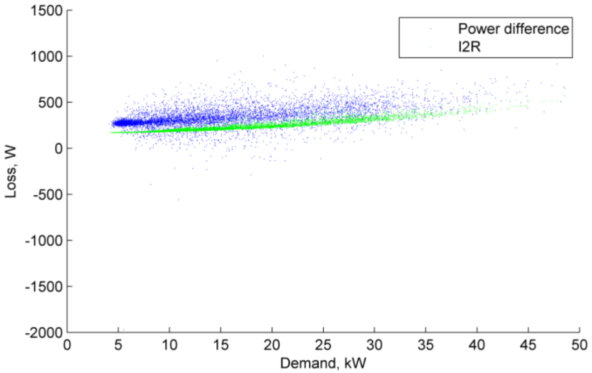

Figure 52 March 2017 Loss, kW vs demand (Ramsey Domestic LV feeder)

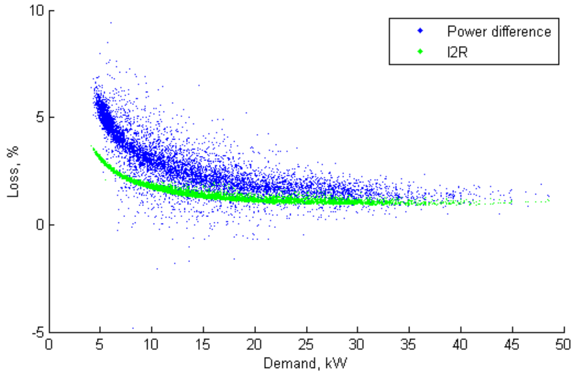

Figure 53 March 2017 Loss, % vs demand (Ramsey Domestic LV feeder)

Appendix D Loss estimation methodology details

The preferred approach for HV feeders is built on the following pre-existing information or learning from the project:

- Loss is proportional to the square of the feeder current – this is seen as an increasing gradient in the charts of Loss, kW vs demand in Appendix C;
- Variation in the level of loss for a particular level of demand on a feeder is driven by variation in the distribution of load along a feeder. This can often characteristically occur at differ times of the day/different days of the week between commercial/industrial load and domestic load;
- Load across phases is relatively balanced on the HV feeders; and
- The HV load is relatively consistent from one minute to another creating the potential to half hour periods for estimation purposes.
- That HV network information is available and relatively reliable
- That Customer information is reasonably available and relatively reliable
- That average feeder demand (L2) is available

The preferred HV feeder loss assessment method contains the following key steps:

- Assembly of input data:
    - A feeder model is assembled comprising of: Distribution Substation nodes, with HV feeder branch lengths, and conductor cross-sections;
    - Distribution Substation Node information is assembled comprising of type of distribution supply point (i.e. HV or LV); and for LV supply points, estimates or actual values for distribution transformer load and no-load losses;
    - Half hourly (HH) load information aggregated by Distribution Substation Node;
    - Non-half hourly (NHH) estimated annual consumptions aggregated by Profile Class and Distribution Substation Node;
    - Elexon Profile Class profiles; and
    - Half hourly average feeder demand derived from the Supervisor Control and Data Acquisition (SCADA)
- Assembly of a representative 365 day load model for each substation on the feeder
    - An initial estimate of demand for each substation of each half hour period in a representative year is calculated from the HH data and the NHH EAC data combine with Elexon profiles;
    - The initial estimate of demand is compared to the measured value of SCADA feeder demand; and
    - The initial estimate of demand is scaled to match the measured value of SCADA feeder demand. This is achieved by scaling only the NHH element of the estimated load.
- Preparation of a load flow model with a data flow control script (an example is IPSA with Python based scripts)

  - Preparation of feeder models within the load flow calculation environment or scripts to import feeder and node information into the load flow calculation environment;
  - Scripts to import the load circumstances, 365*48 half hour periods in a representative year;
  - Scripts to initiate the load flow calculations; and
  - Scripts to export loss assessments resulting from load flow calculations for each half hourly period.
- Run the load flow scripts

Appendix E Learning Outcomes

Appendix E 1 Pilot Approach

- The implementation of phased testing and implementation has been successful in reducing project risk at an early stage/limited implementation cost, and in minimising re-work during the roll-out of monitoring to the selected feeders. The initial lab testing ruled out the use of one proposed device for this project, and allowed development of basic loss calculation approaches. The implementation of a pilot HV feeder and pilot LV feeder confirmed basic feasibility of assessing losses from measurement and modelling, refined calculations and data validation methods and developed confidence in meeting key success criteria for the project.
- For the HV feeder pilot, a level of instrumentation redundancy, using different manufacturer's devices and different communication routes was employed. This was delivered inexpensively through re-use of previous innovation project devices, and eliminated delays when further development work was required on the preferred measurement device at Primary Substations.
- Use has been made of temporarily fitted additional instrumentation to validate and cross-check unexpected measurements. This is has again been inexpensive as the instrumentation was from previous innovation projects. The use of temporary instrumentation has identified faulty installations of instrumentation, and faulty current sensors.
- The LV feeder pilot utilised meter data collection capabilities of the meter manufacturer's standard management software. This proved to be a highly cost efficient means of collecting initial pilot data, and the benefits of adopting simple and cost effective solutions for proof-of-concept work was demonstrated.

Appendix E 2 Loss calculations

- Two methods of loss calculation have been identified: a power difference method in which the power delivered by the network is subtracted from the power supplied as an infeed, and an I^2R method in which the currents from each network outfeed are combined in a power-flow analysis to calculate the current in each network branch. This allows the total I^2R losses to be calculated.
- Losses are evaluated in terms of the total losses over the three phases. Although it is possible to relate the measurements to a loss in each phase conductor, this adds an unnecessary complication where unbalanced currents are considered in Dy11 transformers. Furthermore, current and voltage measurements from HV customer connections use the two-watt-meter method, for which calculations of the loss per phase rely on an assumption that the VTs perfectly balanced. By considering the total power loss over the three phases, no additional assumptions are required.
- Assuming representative errors for the current and voltage sensors, a sensitivity analysis has demonstrated that the sensor tolerances can cause the losses estimated using the power difference method to appear significantly higher or lower than in

reality. The losses can appear to be negative if the power input to the network is under-estimated or the power at the outfeeds is over-estimated.

- The impact of these sensor tolerances is much less severe with the I^2R method of loss calculation. However, this method requires accurate information to describe the network topology and also to define the cable resistances and transformer losses.
- The I^2R method has been adopted as the primary loss calculation approach for the losses investigation project. Loss calculations using the power difference method are then used as a validation check to ensure that differences between the two approaches are consistent with the expected impact of the current and voltage sensor tolerances.
- Differences between average values of losses from the power difference method and the I^2R method still remain and are the source of ongoing investigation and refinement (e.g. addition of meter power consumption to the I^2R method to improve comparability to power difference method).

Appendix E 3 Instrumentation

- The GridKey loggers and EDMI advanced meters have a basic accuracy of ±1%, but higher tolerances apply for low currents, low power factors, or with distortion. These tolerances therefore have a similar magnitude to the percentage errors expected for distribution feeders.
- GridKey loggers have been adopted for measurements at the distribution and primary substations. These loggers use an arithmetic mean algorithm (rather than an RMS) to calculate the average current over the 1 minute reporting intervals. This has the disadvantage that losses are under-estimated in the conductors for which the currents are measured. However, the use of arithmetic mean averaging has the benefit that currents from multiple loggers can be summated without the over-estimation that would result if a Root mean square RMS average had been used.
- The adopted EDMI meters have been configured in an unusual manner to collect the required data. The developed configurations successfully collect 1 minute data averages for a wide range of parameters (29 parameters in the case of a three-phase meter), but retain this data for a relatively short period of time on a first-in-first-out basis (21 days) and the quantity of data that requires transmitting on a daily basis takes material periods of time over GPRS connections (three plus minutes, depending on the efficiency of the data collection approach).
- The EDMI advanced meters also use an arithmetic mean algorithm when calculating the average current in each 1 minute reporting interval. This will cause the losses in the service cables to be under-estimated in I^2R loss calculations and a compensation factor is therefore required.
- Tollgrade loggers have a reporting interval of 15 minutes and need a consistent flow of significant current in order to provide regular data. They were therefore not considered suitable for use in this trial.
- The eMS Sub.net loggers have been found to use an RMS current averaging algorithm. Although this is different to the arithmetic mean averaging used by the GridKeys, these loggers were found to be appropriate for measurements at primary

substations where the demand is highly aggregated and so differences in the averaging algorithm have minimal impact.

- The eMS Sub.net loggers could not be configured for use with current sensors that could be clipped around metering current transformers at HV customer connection sites. A bespoke version of the GridKey logger was developed for this purpose.
- Current measurements using Rogowski coils placed around HV cables are affected by currents in the sheaths. Although this has minimal impact on the amplitude measurement, the measured phase angle is offset from the true value. This causes errors in the measurement of active and reactive power and in the phase angle of currents that are combined in the power-flow analysis for the I^2R loss calculations.
- Although the GridKey loggers do not directly record the current distortion, this can be derived from the recorded active and reactive power data and from the voltage amplitude. This has been verified by comparison of the estimated THD with measured harmonic data recorded using a PM7000 power quality analyser.
- The instrumentation deployed has been configured to operate with the comparatively rare and demanding averaging period of one minute. Coupled with the high degree of scrutiny of individual measurement points from multiple devices for the same point in time, the reliability of the Gridkey devices in delivering values for each minute of every day was required ongoing work.
- Achieving satisfactory levels of time synchronisation between multiple remotely deployed devices from different manufacturers, collecting data at more than one data centre/time server has proved challenging. This is especially the case as all remote devices are connected via GPRS, and has significant potential delays in the transmission of time synchronising messages.

Appendix E 4 HV feeder losses

- Differences in the level of loss on sample HV feeders are emerging (see Appendix C). Further differences are expected as the mixed and overhead feeders start to provide data. These differences will be further reviewed as the project progresses.
- Losses for the HV feeders considered so far appear lower than the mean losses indicated in the 2008 E.ON Loss Calculation Study. The HV cable losses are mostly lower than figures from the study and the total distribution transformer losses are lower in all cases. However, the loss study used different assumptions for the transformer parameters and had predicted higher no-load losses and lower load losses.
- The losses for the HV feeders considered so far are lower than the losses for the HV feeder and distribution transformers stages included in the generic LLF calculations. This difference is still being investigated and will be reviewed again as a wider diversity of feeders is included in the trial.
- The transformer no-load losses are a significant proportion of the total for feeders where the customers connect at LV. Depending on the number of HV connections, no-load losses are between 10% and 60% of the total.
- For the urban and suburban feeders considered so far, the losses are not significantly affected by unbalance. Using the I^2R method, losses are only reduced by up to around 2% of the loss power if a balanced calculation is used in place of

calculations that include unbalance in the demand and in the cable impedances. Losses for rural feeders with single-phase branches are likely to be subject to greater differences.

- The calculation of losses with the I^2R method is also affected by the cable reactances. However, there is little difference between calculations assuming cross-linked polyethylene (XLPE), paper insulated corrugated aluminium sheath (PICAS) or paper insulated lead covered steel wire armoured (PILCSWA) cable geometries provided that the resistance is accurately specified.
- The transformer load losses increase by approximately 4% per 10° C rise in temperature. Loss calculations using the I^2R method are therefore dependent on the transformer temperature. Data from the previous FALCON project has been used to indicate appropriate operating ranges.
- The outfeed current for the HV feeder trials are measured on the LV side of the transformers and so do not include the transformer magnetising currents. The magnetising currents have been estimated and found to be very small compared to the load currents. Loss calculations using the I^2R method are therefore insensitive to errors in the assumed magnetising currents.
- HV feeder losses calculated using half-hourly current data are not significantly different from results calculated using the 1-minute resolution provided by the measurements. The loss calculations are less sensitive to the time resolution of the demand data where many individual current loads are aggregated. (This is therefore not the case for the LV feeders.).
- The 1-minute time resolution used for the measurement trials has proved highly useful in detecting errors in the instrumentation configuration and short-term changes to the feeder network configurations. Many of these effects are visible as step-changes in the demand which would have been masked by the demand averaging with half-hourly data.
- The I^2R method allows the voltage at each distribution substation to be calculated and compared with the voltage measured by the GridKey loggers. This method can be used to determine the transformer tap settings which in some cases have differed from the expected values.
- An approximate estimate of the HV feeder losses can be obtained using a simple method in which a level of demand is assigned to each distribution transformer as a proportion of its rated power. Transformer loading statistics obtained from the measurements are used to select representative values for the mean demand. This method requires knowledge of the network topology, transformer parameters and cables, but uses no electrical measurements from the feeder itself. The percentage losses estimated using this basic method are within 10%-30% of the losses calculated using the I^2R method with measured current data.
- A more detailed estimation method has also been developed in which half-hourly billing data is used to provide data for the contribution to the total demand that is metered. Half-hourly current and voltage measurements from the primary substation are obtained from SCADA Data. The non-metered demand is modelled using Elexon profiles and scaled such that the total current matches the measured

current at the primary substation. Percentage losses calculated using this method, and using validated network data, are within 5% of the measured percentage losses.
- The more detailed estimation methods relies on accurate data to assign half-hourly metering data to the correct substation. This is subject to database errors. Experience from the 7 HV feeders considered so far suggests that these database errors add an uncertainty of around ±15% to the estimated percentage losses.

Appendix E 5 LV feeder losses

- Early indications of differences in the level of loss on sample LV feeders are emerging (see Appendix C). Further differences are expected as the industrial and commercial and overhead feeders start to provide data. These differences will be further reviewed as the project progresses.
- Losses for the LV feeders considered so far are lower than the mean losses indicated in the 2008 E.ON Loss Calculation Study. However, this study predicted a wide spread of percentage losses and the measured losses are within this range.
- The losses for the LV feeders considered so far are lower than the losses for the LV distribution stage included in the generic LLF calculations. This difference is still being investigated and may relate to the inclusion of non-technical losses in the LLF calculations.
- The losses due to self-consumption by the advanced meters have been included, assuming a nominal 3 W per single-phase meter and 7 W per three-phase meter. This makes a significant contribution to the losses, ranging from 40% to 75% of the total.
- The majority of the I^2R losses occur in the feeder cable sections closest to the substation where the aggregated demand is greatest.
- The losses in the service cables range from 5% to around 15% of the total, and around 20% to 50% of the total I^2R losses (excluding metering).
- Losses in the cables to public lighting circuits have so far been negligible.
- The loss power is proportional to the square of the current and so it might be expected that losses are dominated by the peak demands. In practice, much of the lost energy relates to lower demand currents that occur for a much greater proportion of the time. For the pilot trial feeder, 90% of the losses occurred when the feeder demand was below 2/3 of the peak.
- For a given level of demand current, losses vary significantly according to the distribution of currents along the feeder, the unbalance, and the phase angle. Of these factors, the load distribution is the most significant, followed by the level of unbalance.
- The losses for the LV trial feeders are more dependent on unbalance than for the HV feeders.
- The mean reactive power demand for LV customers is highly variable. Many customers have a high mean reactive power demand, but this may be either capacitive or inductive. Mean power factors are typically between 0.93 and unity.
- LV feeder losses calculated using the I^2R method with half-hourly current data are under-estimated by around 20% compared to losses calculated at 1-minute resolution. With 10-minute data the losses are under-estimated by around 13%. The

1-minute averaging used for the trials also causes some degree of error and this is estimated to be around 2% of the losses without any impacts of averaging.

- Harmonic distortion was found to increase the losses in the pilot trial feeder by approximately 5% compared to losses at the fundamental frequency alone. The I^2R method closely approximates the total loss power at all frequencies by using the measured RMS of the current waveform (which includes the harmonics) to define the current amplitude.
- Although the I^2R method closely approximates the loss power in watts, a correction can be made to allow for the impact of harmonics on the percentage losses. This is needed as currents at harmonic frequencies deliver negligible power. Correcting for this error increased the percentage losses for the pilot feeder by approximately 5%.
- As with the HV feeder, variations in the cable reactances have minimal impact on loss calculations using the I^2R method. However, the losses are increased if the AC resistance effects are included in the cable impedance calculations. For the larger cable sizes, the AC resistance is up to 15% higher than the DC resistance. A finite element method has therefore been used to calculate the impedance matrices for all cable types such that the AC resistance effects can be taken into account.
- The current at the distribution substation can be calculated using the I^2R method and also measured using the GridKey logger. Comparisons of the calculated and measured current have been invaluable in identifying unmetered loads that had not been included in the measurement configuration.
- Loss calculations using the I^2R method require input data to define the network topology. It has been demonstrated that an approximation to this topology can be derived from geographic information system GIS diagrams where knowledge of the customer locations is used to resolve ambiguities in the point-to-point connectivity of the feeders in the drawing.
- The current difference calculation gives a closer agreement if both the calculated and measured currents include only the fundamental frequency. The current at the fundamental frequency can be calculated from the measured RMS amplitude and from current distortion data.
- The I^2R method also allows the voltage at each LV customer to be calculated and compared with the voltage measured by the advanced meters. A voltage correlation method has been developed that allows clock synchronisation errors to be corrected.
- The voltage correlation method and also allows the phase assignment of each customer to be determined. The three-phase voltage from the substation is used as a reference. A number of customer phase assignments in the supplied network data have been corrected using this method.
- The current distortion for customer loads reduces as the magnitude of the load increases. Current distortion is therefore high for lower-powered loads that remain on for most of the time, but much lower for higher-powered loads that are switched on for short periods.
- A similar trend applies to the power factor which can be highly variable when the load current is low. Higher powered loads tend to be resistive in character.