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SMART STREET

Trial Overview

25 April 2018

VERSION HISTORY

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First draft	21 March 2018	B Ingham	0.1	
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CONTENTS

LIST OF ACRONYMS

Acronym	Explanation
CHP	Combined heat and power
CRMS	Control room management system
CSV	Comma separated value file format
CVR	Conservation voltage reduction
DNO	Distribution network operator
DG	Distributed generation
EV	Electric vehicles
HP	Heat pumps
HV	High voltage (11kV/6.6kV)
IET	Institute of Engineering and Technology
LCT	Low carbon technology
LCN Fund	Low Carbon Networks Fund
LV	Low voltage (400V/230V)
OLTC	On load tap changer
PV	Photovoltaic cells
SP5	Spectrum Power 5 (Siemens optimisation software)
VVC	Volt/Var control
XML	Extensible markup language file type

1 INTRODUCTION

1.1 Purpose of document

The purpose of this document is to achieve the associated deliverable related to the following Smart Street **SDRC 9.2.3 – Publish a summary overview of each trial on the Smart Street website by April 2018.**

This document aims to provide a summary of the trials carried out as part of the project and an overview of the results generated.

1.2 What is Smart Street?

Smart Street aimed to utilise advanced real time optimisation software to simultaneously manage high voltage (HV) and low voltage (LV) network assets to respond to customers' changing demands. Voltage management on HV networks aimed to reduce network losses while conservation voltage reduction (CVR) on the LV networks aimed to reduce energy demand. Capacitor banks on the HV network were utilised to help manage network losses by adjusting the network's power factor. On the LV network, a mix of capacitor banks and controlled meshing of networks were integrated to flatten the voltage profile and improve energy efficiency. The meshing of LV networks also aimed to release additional network capacity.

1.3 Conservation voltage reduction (CVR)

Electrical equipment made for the European market, including household appliances and lighting, is designed to operate most efficiently in the region of 220 to 230 volts. This equipment can, however, operate adequately at voltages in the region of 200 volts. If power is delivered at voltages higher than these optimum levels, energy is consequently wasted. Excess voltage can shorten the useful life of electrical equipment, since the excess energy is dissipated as heat. Therefore, optimising network voltages reduces overall energy consumption, improves power quality and extends the life of customers' equipment. Smart Street proposed to optimise network voltages by using CVR on the LV trial networks.

CVR on a distribution network is defined as a reduction of energy consumption resulting from a decrease in feeder voltage. Smart Street proposed to optimise the voltage by utilising on-load tap changing (OLTC) transformers. These transformers were able to regulate the voltage along the feeder while maintaining statutory limits. This allowed for the peak load to be reduced, hence reducing annual energy consumption.

Additionally Smart Street utilised shunt capacitors on the LV feeders to allow for a voltage boost at the end of the circuit to reduce voltage drop. This allowed for a flatter voltage profile, allowing for the OLTC to tap closer to the lower limit.

1.4 LV network meshing

In addition to the proposed CVR techniques, Smart Street assessed the benefits of meshing LV networks to balance load while releasing network capacity at times of high demand.

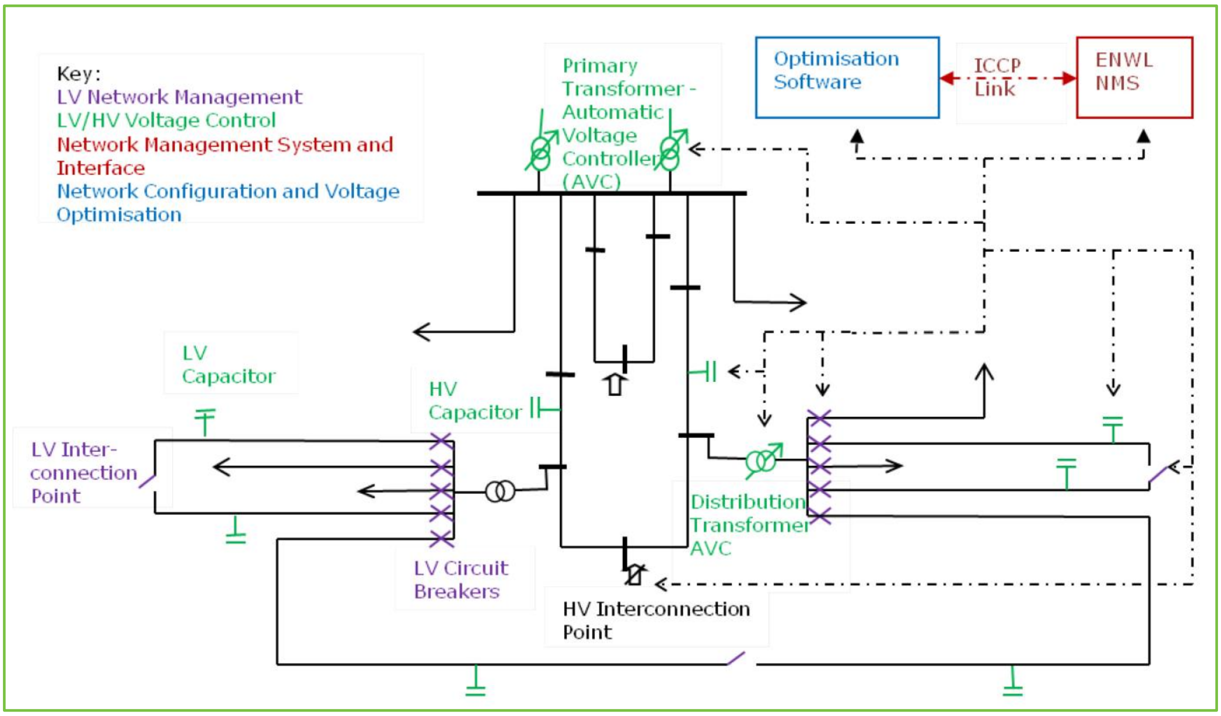
Project partner, Kelvatek, developed new controllable retrofit vacuum switching devices especially for this project. These devices were utilised at the existing distribution boards and in link boxes across the LV trial circuits. The devices have the capability to be remotely controlled allowing sensing of feeder flows and reconfiguration of the LV network.

1.5 Control systems

Figure 1 shows an example of how the various Smart Street technologies were installed across the trial networks. The optimisation included the ability to optimise for violations, losses and to minimise load as a single Volt/Var Control (VVC) function. The opportunity to mesh the trial networks was also included in this function, but radial configurations were the preferred running arrangement. This was specified to minimise customer outages during electrical faults. Therefore the switching equipment was closed (creating loop or meshed networks) if the objective-function resulted in positive changes to the network above a set threshold.

The optimisation application calculated the optimal procedures to reach the optimisation objectives, which could be different for HV and LV depending on the chosen function. The user could choose if the switching equipment was included or inhibited in the optimisation scheme and only specified remote controlled switches were included in the optimisation.

Figure 1: Smart Street network management



2 TRIAL DESIGN

As defined in the full submission document the five trials explored were:

- LV voltage control
- LV network management and interconnection
- HV voltage control
- HV network management and interconnection
- Network configuration and voltage optimisation.

In order to understand how each of the different types of kit can impact each of the trials, a series of test regimes were devised as shown in Figure 2.1 below.

Figure 2.1: Smart Street trials

Smart Street trial	Test regime
Trial 1: LV voltage control	T1.1 On-load tap changing distribution transformer only
	T1.2 On-load tap changing distribution transformer and capacitor(s) on LV circuits
	T1.3 Capacitors at distribution substation only
	T1.4 Capacitors at distribution substation and on LV circuits

Smart Street trial	Test regime
	T1.5 Capacitor(s) on LV circuits only
Trial 2: LV network management and interconnection	T2.1 LV radial circuits
	T2.2 LV interconnected circuits
Trial 3: HV voltage control	T3.1 Voltage controllers at primary substation only
	T3.2 Voltage controllers at primary substation and capacitors on HV circuits
Trial 4: HV network management and interconnection	T4.1 HV radial circuits
	T4.2 HV interconnected circuits
Trial 5: Network configuration and voltage optimisation	T5.1 Losses reduction
	T5.2 Energy consumption reduction.

- Trials 1 and 3 reduced network losses or energy consumption via a combination of conservation voltage reduction (CVR) and voltage optimisation techniques. The trials tested the voltage control equipment in isolation and in combination to fully assess the benefits of these techniques.
- Trials 2 and 4 compared the benefits of radial and interconnected circuits across the LV and HV trial areas.
- Trial 5 assessed the reduction in losses and energy consumption achieved by the optimisation software.

The trial regimes were designed to apply all of the test criteria while allowing for direct comparison over each trial area at different times of the year. Direct comparisons were also made to the overall benefit of each technology type installed on rural, urban and dense urban networks.

The trials took place over a two-year period using an off/on test regime which resulted in data for both normal network running configurations and for Smart Street operation. This allowed for the two scenarios to be compared and analysed enabling the overall benefits of Smart Street to be calculated. The full trial design is detailed in the network design report on the trials webpage.

2.1 Optimisation

At the core of Smart Street is the ability to simultaneously optimise network configurations and voltage profiles in real time. This will enable utilities and consumers to save energy and lower operating costs by reducing the need to generate additional energy. As a consequence it also helps to lower greenhouse gas emissions and enable a greener network.

Siemens Spectrum optimisation software optimised both interconnected configurations and voltage profiles across HV and LV networks. This trial assessed the reduction in losses and energy consumption achieved by the optimisation software.

The Volt/VAr Control (VVC) application available on Spectrum is able to determine control actions of OLTC transformers, shunt capacitor banks and remote-controllable switches to optimise the network for a chosen function. The specific user-defined functions that are available are:

- Minimise limit violations
- Minimise power losses and limit violations

- Minimise active power consumption (power demand) and limit violations
- Minimise reactive power consumption and limit violations
- Maximise power revenue and minimise limit violations
- Minimise violations and power losses (HV) and active power consumption (LV).

The VVC optimisation consists of three basic components:

- A set of variables
- An objective function to be optimised (minimise or maximise)
- A set of constraints that specify the feasible values of the variables.

The aim of the optimisation routine was to find the total objective function extreme, while satisfying all constraints. These constraints include power flow equations and operational voltage limits. The VVC therefore provides a centralised coordinated control of the network regulating controllers and provides the following modes of operation:

- *Open loop:* The optimal setting/switching orders calculated from VVC are not automatically executed, but available for review in the user interface
- *Closed loop:* The optimal setting/switching orders calculated from VVC are immediately executed after VVC calculation.

For the Smart Street trials the VVC was run in 30-minute closed loop cycles. All VVC commands to OLTC transformers were sent as voltage set-points, while all commands to capacitor banks were in the form of open/close instructions due to the capacitor control interface.

Figure 2.2 highlights the eight-week cycle of the trial combinations; this cycle allows all of the individual trials to be assessed.

Figure 2.2: Summary of optimisation test regimes

	Trial 1	Trial 2	Trial 3	Trial 4
Week 1	Off	Off	Off	Off
Week 2	Off	Off	Off	Off
Week 3	T1.1/T1.3/T1.5	On	T3.1	On
Week 4	T1.2/T1.4/T1.5	On	T3.2	On
Week 5	Off	Off	Off	Off
Week 6	Off	Off	Off	Off
Week 7	T1.1/T1.3/T1.5	On	T3.2	On
Week 8	T1.2/T1.4/T1.5	On	T3.1	On

2.2 Trials summary

The Smart Street test regimes were designed to allow for monthly comparisons of each trial technique over the two-year trial period. 52 weeks of the 'trial-off' period provided baseline data, while 52 weeks of 'trial-on' data aimed to compare the various Smart Street technologies.

These trials were designed to maximise the learning on circuits fitted with OLTCs and substation capacitors which are capable of CVR due to the limited number of test circuits available.

The academic partners analysed the research data and made suggestions for changes to the test schedule to maximise learning.

3 REVISED TRIAL PLAN

Due to safety-related equipment issues affecting the deployment of the various technologies during the initial phase of the trial period a decision was made to run the on periods with all installed equipment available to optimisation software. This meant a modification to the original trial plan, although the two-week on, two-week off approach was maintained.

Following the initial analysis by our academic partners it was shown that the optimisation software was not performing as anticipated. After a period of discussion with Siemens as to how best to adjust the parameters of the Spectrum Power 5 (SP5) system a solution was found. This delay necessitated a further modification to the trial regime, which was developed in conjunction with the academic partners to ensure that the maximum amount of data was generated during the remaining time. In this new schedule Wigton was left un-optimised for the duration to act as a control while the other areas had various combinations of devices enabled to understand the effect of the various permutations.

Figure 3.1: New trial regime

Week	**Trial Areas**										
	Denton East		**Egremont**		**Green Street**		**Hindley Green**		**Longsight**		**Wigton**
	NLTC	**OLTC**	**NLTC**	**OLTC**	**NLTC**	**OLTC**	**NLTC**	**OLTC**	**NLTC**	**OLTC**	
31	Caps HV meshing	OLTC HV meshing	Caps HV meshing	OLTC HV meshing	Caps + Lynx	OLTC	Caps	OLTC	Caps + Lynx HV meshing	OLTC + Caps + Lynx HV meshing	No CVR
32	Caps + Lynx HV meshing	OLTC + Caps HV meshing	Caps HV meshing	OLTC + Caps HV meshing	Caps + Lynx	OLTC + Caps + Lynx	Caps	OLTC	Caps + Lynx HV meshing	OLTC + Caps + Lynx HV meshing	
33	Caps HV meshing	OLTC HV meshing	Caps HV meshing	OLTC HV meshing	Caps + Lynx	OLTC	Caps	OLTC	Caps + Lynx HV meshing	OLTC + Caps + Lynx HV meshing	
34	Caps + Lynx HV meshing	OLTC + Caps HV meshing	Caps HV meshing	OLTC + Caps HV meshing	Caps + Lynx	OLTC + Caps + Lynx	Caps	OLTC	Caps + Lynx HV meshing	OLTC + Caps + Lynx HV meshing	
35		OLTC		OLTC		OLTC		OLTC		OLTC	
36	Caps + Lynx HV meshing	OLTC + Caps HV meshing	Caps HV meshing	OLTC + Caps HV meshing	Caps + Lynx	OLTC + Caps + Lynx	Caps	OLTC	Caps + Lynx HV meshing	OLTC + Caps + Lynx HV meshing	
37	Caps HV meshing	OLTC HV meshing	Caps HV meshing	OLTC HV meshing	Caps + Lynx	OLTC	Caps	OLTC	Caps + Lynx HV meshing	OLTC + Caps + Lynx HV meshing	

4 EVALUATING THE BENEFITS OF THE SMART STREET SOLUTION

4.1 Data transfer and analysis summary

For the optimisation software to run successfully SP5 needed the measured voltage and current at strategic points on the network as well as an awareness of the states of all devices. The analogue data was collected on a one-minute average and stored in the Spectrum historian along with a record of any changes of state.

Each month the data was extracted from the historian system in a comma separated values (csv) format and transferred to the academic partners via Electricity North West's secure file transfer system. To assess the impact and benefits of Smart Street, the academic partners used this data to create and validate models as well as conducting a direct assessment of the data to assess the benefits of optimisation.

Trial 1: LV voltage control

Trial 1 looked at the LV voltage control techniques optimised by SP5 and quantified the benefits of LV voltage optimisation. The academic partners modelled the LV trial networks to calculate and quantify the benefits of the voltage control techniques. In particular they carried out analysis and modelling of the trial networks to develop CVR and voltage optimisation models and to calculate the reduction of losses and demand. The data collected during Trial 1 was used to validate and improve these LV models.

Trial 2: LV network management and interconnection

The academic partners modelled the LV trial networks to produce practical rules to determine optimal locations for interconnection. Further rules were developed for network operation, taking into account the characteristics of the meshed feeders, different penetrations of low carbon technologies (LCTs), and coordination with voltage regulation devices. Simulations were also carried out to quantify the potential impact on a customer's electrical installation of interconnecting LV networks while managing voltages within a tighter band. This work was reviewed by the Institute of Engineering and Technology (IET) wiring regulations group.

Trial 3: HV voltage control

This trial collected monitoring data across the HV trial networks, which was used to quantify the benefits of the HV voltage control techniques. The academic partners modelled the HV trial networks to calculate and quantify the benefits of these control techniques. The circuit data was used to validate the results of the modelling.

Trial 4: HV network management and interconnection

This trial collected monitoring data across the HV trial networks, which was used to quantify the benefits of the Smart Street network management and interconnection techniques. The data collected during Trial 4 was used to validate and improve the HV network models that were used to develop practical rules to determine the most suitable location of voltage control equipment and optimal scenarios for HV interconnection.

Trial 5: Network configuration and voltage optimisation

This trial used all the data collected in the previous four trials to calculate the overall reduction in losses and energy consumption, comparing the Smart Street network with the historical network. The trial also quantified the trade-off in performance between reducing losses on the HV network and the implementation of CVR on the LV network. The learning outcomes will be used to publish the specifications, settings and configuration parameters required to optimise the operation of the distribution networks.

Academic work

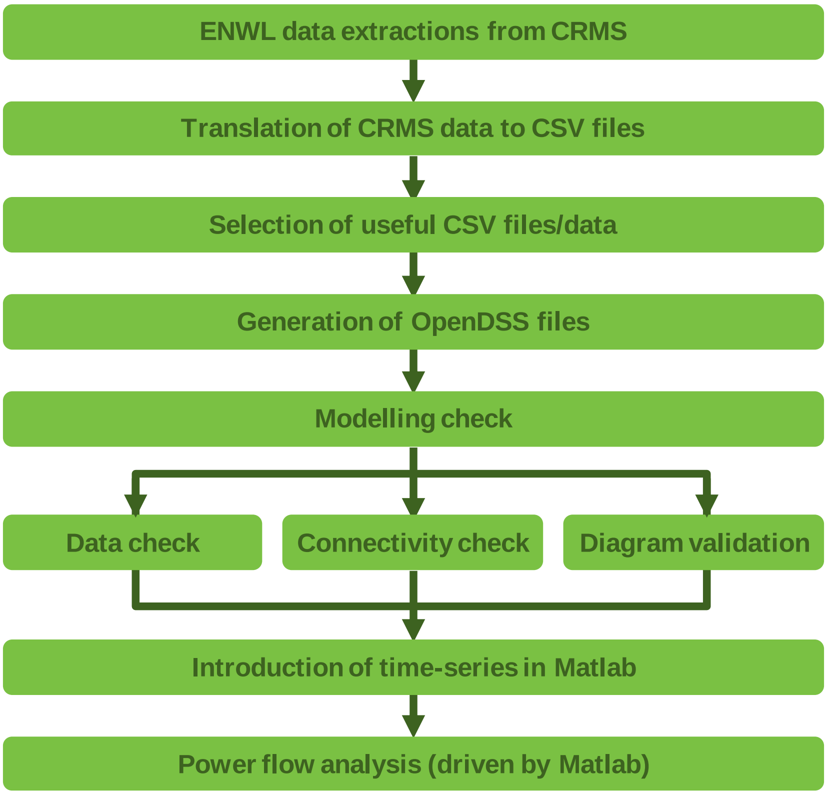
The University of Manchester and Queens University, Belfast were contracted to conduct the analysis work required to assess the five different trials. The research was split into three work packages. One work package covered Trials 1, 3 and 5; the second covered Trials 2 and 4. The third work package produced the cost benefit analysis and carbon impact studies.

4.2 Development of network models

The University of Manchester developed the HV and LV network models which were used by all three work packages of the academic research to analyse the impact and benefits of Smart Street. Electricity North West provided the HV and LV networks as an extract from Electricity North West's control room management system (CRMS) in extensible markup language (XML) format.

To complete the analysis the universities chose to use OpenDSS which is an open source software package to solve power flows, harmonics analysis and fault current calculations in electrical distribution systems. This software is able to solve unbalanced networks and can be driven from other software, such as Matlab. One of the main characteristics of OpenDSS is the ability to represent the time dimension (daily and yearly simulations with different time steps) in networks with distributed generation. This is important to quantify the impacts of intermittent sources (PV, micro-CHP, etc.) and loads (EV, HP etc.) on distribution networks. Figure 4.1 details the steps taken to convert the XML files to a format suitable for OpenDSS.

Figure 4.1: Conversion of XML files to OpenDSS



ENWL data extractions from CRMS

Translation of CRMS data to CSV files

Selection of useful CSV files/data

Generation of OpenDSS files

Modelling check

Data check

Connectivity check

Diagram validation

Introduction of time-series in Matlab

Power flow analysis (driven by Matlab)

The XML data was read into Matlab by using the 'xmlread' function and the data was categorised by type (ie transformers, switches and fuses) and stored in different matrices. The data matrices were written into csv files where all elements are arranged in rows and all element features are arranged in columns.

Some of the csv files produced were not required for the OpenDSS modelling and those that were required contained data elements that were also superfluous. Therefore the next step identified and extracted the useful files and data elements to create readable txt files for OpenDSS. The txt files were generated using Matlab.

Once the OpenDSS files were generated, a check of each model was carried out by:

- Checking the data to ensure the generated OpenDSS files were correct and complete
- Checking the connectivity checks to ensure all elements in the networks were connected and no isolated zone existed
- Validating against network diagrams to ensure all the elements were connected in the right position.

In order to assess the effect of CVR and the impacts of LCTs in distribution networks, it was necessary to perform time-series power flow analyses with high resolution load and LCT models. This required not only adequate profiles but also load models to cater for voltage dependencies.

4.2.1 Load modelling

Domestic load profiles based on the CREST tool produced by Loughborough University were applied to the models. For non-domestic customers, profiles based on data from ELEXON were used.

Electricity North West's First Tier LCN Fund project Low Voltage Network Solutions provided a methodology to generate realistic PV profiles and this methodology was used to provide the PV profiles for this analysis.

Scottish and Southern Energy's Second Tier LCN Fund project My Electric Avenue produced real data on EV charging. This data was coupled with statistical analysis on when the car is charged, how many cars are being charged as well as the initial and final state of charge to give a range of profiles for this analysis.

Once the models were complete a test power flow analysis was carried out to prove the models worked.

4.2.2 Adopted methodology

Data analysis was based on a Monte Carlo approach, which caters for the stochastic nature of demand and generation and for tackling the unknown location of LCTs in distribution networks. The Monte Carlo method can be defined as a computational algorithm that depends on repeated random sampling of unknown parameters to acquire numerical results. Monte Carlo methods are usually used in mathematical problems such as optimisation and the generation of draws from a probability distribution. It is very useful in situations where the application of a deterministic algorithm is not representative, such as in the case of unknown locations/sizes/behaviour of PVs or EVs in the network.

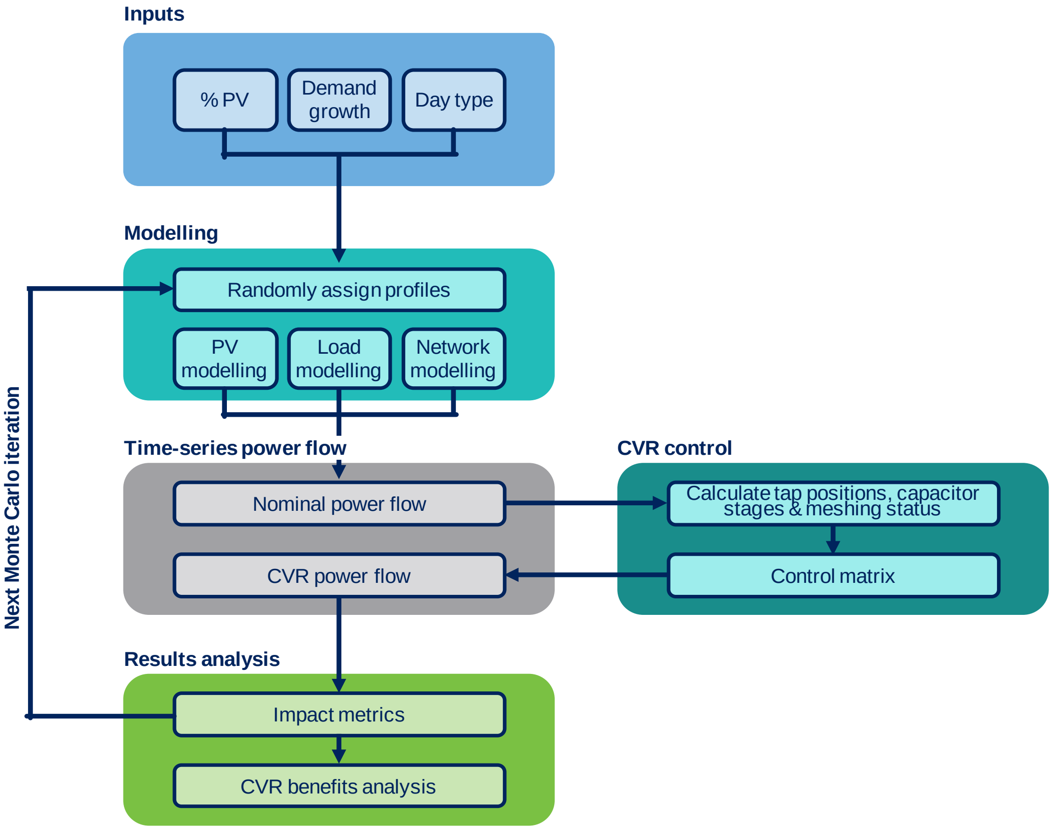
Two pools of 1,000 individual domestic profiles for PC1 and PC2 customers were randomly generated for the type of day (season/day of the week) to be assessed with their corresponding time-varying load models using the CREST tool. Non-domestic loads were represented by ELEXON profiles.

In order to model PV profiles, a set comprising the 30 sunniest irradiation curves of 2012 from the Whitworth Meteorological Observatory of The University of Manchester was considered. It was assumed that all the PV systems will get the same irradiation as the length of the LV networks do not exceed 1 km. Statistics from 2014 showed that the domestic scale PV panels currently installed in the UK have a distribution of 1%, 8%, 13%, 14%, 14%, 12% and 37% of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0kW, respectively. This distribution of PV sizes was used for power flow simulations when allocating PV panels.

A representative pool of 1,000 EV profiles was generated using the methodology described earlier.

The Monte Carlo method was then applied to the 38 Smart Street LV networks to assess the impact of LCTs and benefits of operational actions. The steps to carry out the Monte Carlo analysis are summarised in Figure 4.2 and listed below.

Figure 4.2: Flow chart for modelling process



- The operational statuses of capacitors, switches and tap changers were set.
- Random demand profiles were selected from the pool and allocated to each domestic customer respecting their profile class.
- A random irradiance from the pool of 30 days was taken.
- A percentage of the total customers were randomly assigned a PV panel according to the statistics detailed above. All the customers shared the same irradiance.
- A percentage of the total customers were randomly assigned an EV profile.
- A one-minute resolution time series power flow was performed using OpenDSS.
- Impact metrics were calculated from power flow results.
- When assessing the impact of an operational action (eg tap position for CVR) the process was repeated from step 2 to give the same initial conditions.
- The process was repeated from step 1 a predefined number of times.

The metrics listed below were calculated after every Monte Carlo simulation. The median and standard deviations were obtained for each metric when all the simulations were complete. The latter contains the required information to conclude about any impact and benefit.

- Percentage of customers with voltage problems
- Utilisation factor of transformers
- Percentage of overloaded cables/lines
- Location of overloaded cables/lines
- Energy losses
- Total energy
- CVR factor.

4.2.3 Modelling scenarios

As well as assessing the impact Smart Street has on today's network it was important to understand the benefits for future networks with different levels of demand and generation, as well as the impact it has for different types of networks.

The outputs from the trials were used by the universities as inputs to a model to assess the benefits of Smart Street across a range of scenarios. These were developed to ensure all network types and demand variations were covered for current and future scenarios.

Figure 4.3: Models and scenarios

Modelled 54 scenarios

Three networks	**Three optimisation modes**	**Two day types**	**Three years**
Dense urban Urban Rural	Mode 1 – OLTCs Mode 2 – OLTCs and capacitors Mode 3 – OLTCs, capacitors and meshing	Winter weekday Summer weekday	2017 2035 2050

The combinations of all the above criteria resulted in 54 scenarios modelled and analysed.

In order to project the demand and generation growth for years 2035 and 2050, an average was taken of the four National Grid Future Energy Scenarios which resulted in 20% and 40% PV penetration and multiplication factors of 1.0535 and 1.1859 for demand.

5 BENEFITS

5.1 Energy consumption benefits

The charts below demonstrate the reduction in energy consumption achievable using the Smart Street method.

- Optimisation 1 is with only the primary and distribution on-load tap changers active
- Optimisation 2 is with the on-load tap changers and all capacitors active
- Optimisation 3 is with on-load tap changers, capacitors and interconnection active ie all devices.

Figure 5.1: Energy consumption reduction in 2017

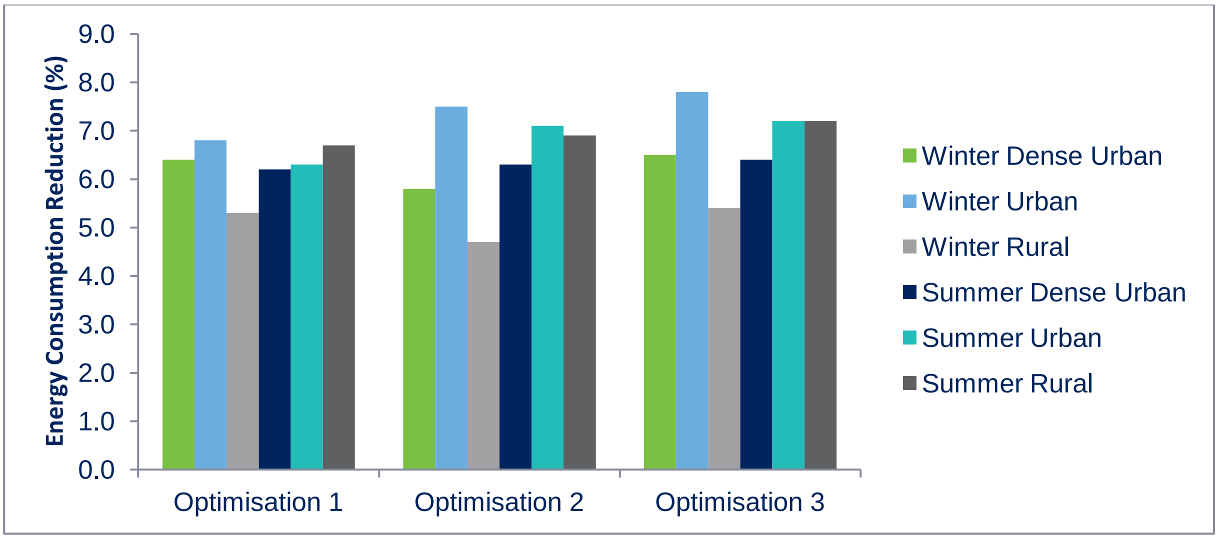


Figure 5.2: Energy consumption reduction in 2035

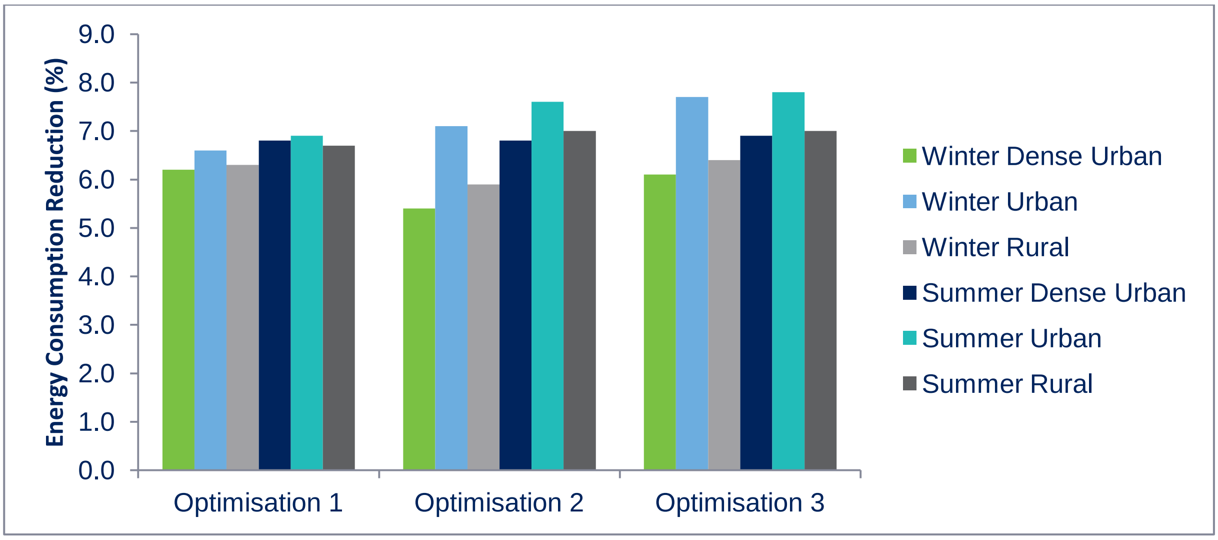
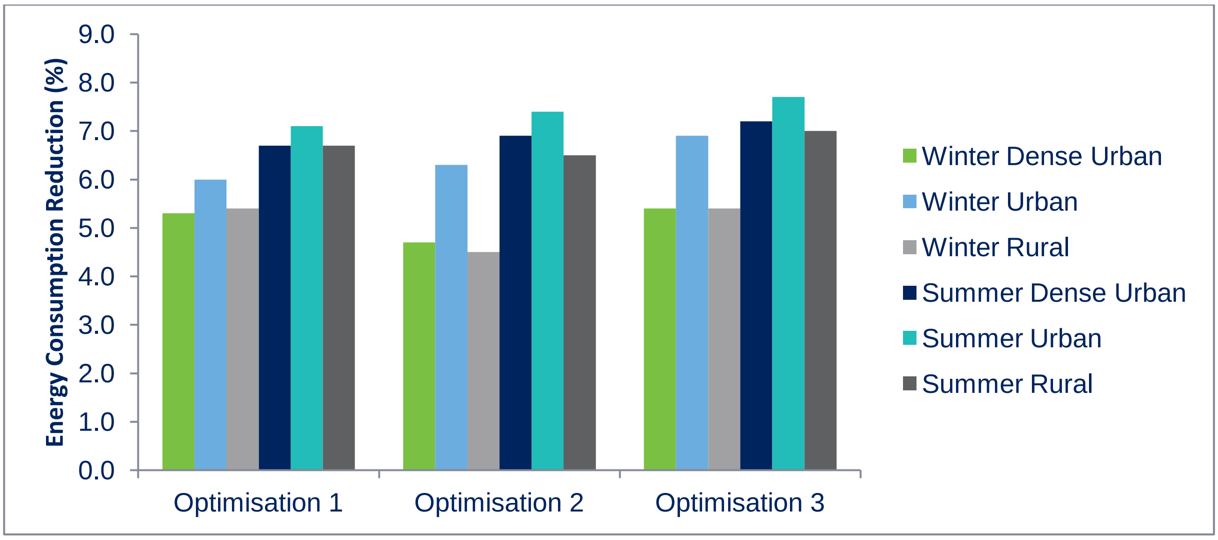


Figure 5.3: Energy consumption reduction in 2050



As can be seen from the charts, Smart Street can deliver around 5 – 8% energy consumption reduction.

Larger voltage reductions are observed in the summer scenarios as:

- Energy consumption is less in summer than in winter which results in a lower voltage drop giving more headroom for voltage reduction
- PV generation increases the feeder voltage which provides more headroom for voltage reduction.

With the demand growth and PV growth in 2035 and 2050, the reduction of energy consumption is slightly increased in summer, but decreased in winter on all three networks.

Applying interconnection in optimisation 3 has provided larger voltage reduction, energy reduction and loss reduction. Adding capacitors gives more energy reduction in the summer scenarios.

The voltage at the primary substation was reduced by 1 – 4% by using the primary OLTC. Further voltage reduction was achieved by adding the LV off-load and on-load tap changers. This gave a total voltage reduction at the customer side of around 5 – 8% and overall energy reduction of 5 – 8%. This results in an average CVR factor roughly equal to 1, which means the relationship between voltage reduction and energy saving is roughly linear.

These results assume that DNOs would optimise the position of the off-load tap changers as the demand/generation changes – this could occur seasonally. If it is assumed that the off-load tap changers remain at a static value until 2050, the reduction in energy consumption is lower at around 1 – 4%. Therefore it is more beneficial to optimise the voltage as demand changes.

Analysis of the measured data showed a reduction in energy consumption of around 6 – 8% which provides further validation to the modelling work.

5.2 Losses benefits

The charts below demonstrate the reduction in losses achievable using the Smart Street method.

- Optimisation 1 is with the primary and distribution on-load tap changers active
- Optimisation 2 is with the on-load tap changers and all capacitors active
- Optimisation 3 is with on-load tap changers, capacitors and interconnection active ie all devices.

Figure 5.4: Losses reduction in 2017

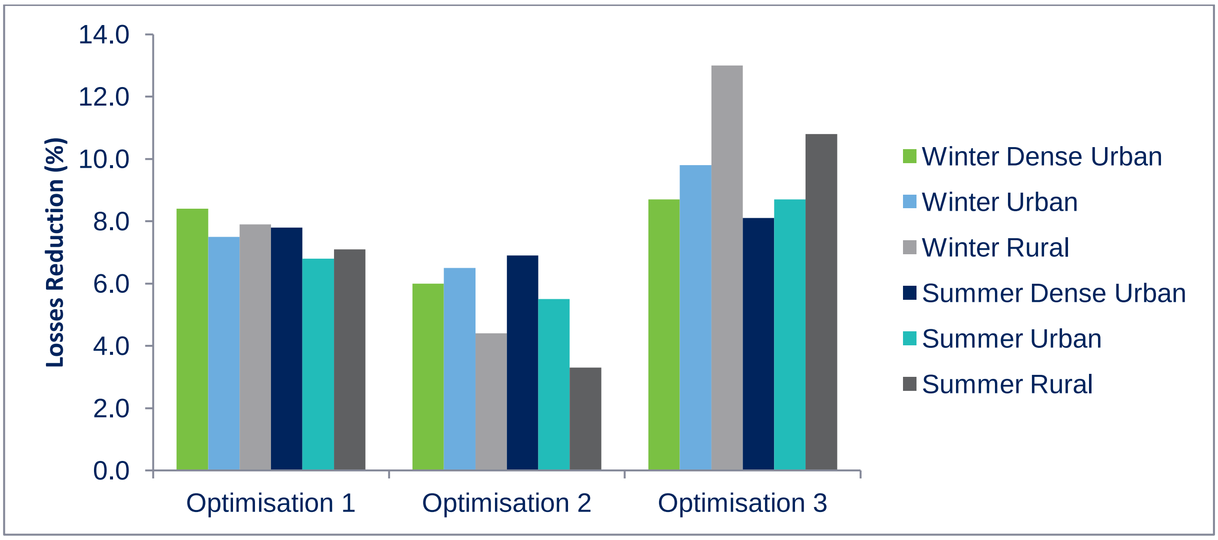


Figure 5.5: Losses reduction in 2035

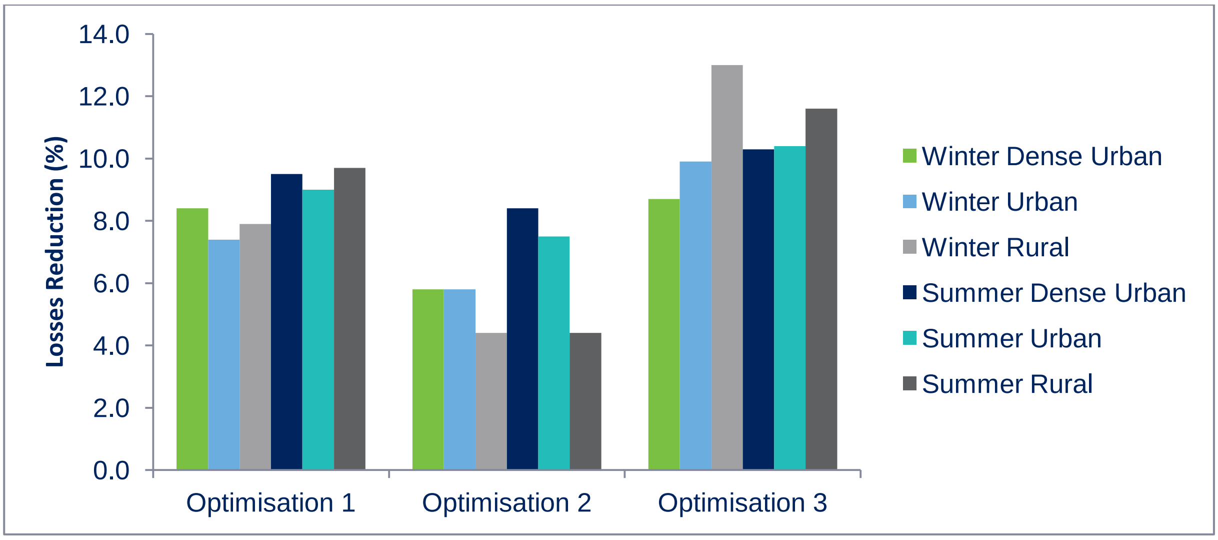
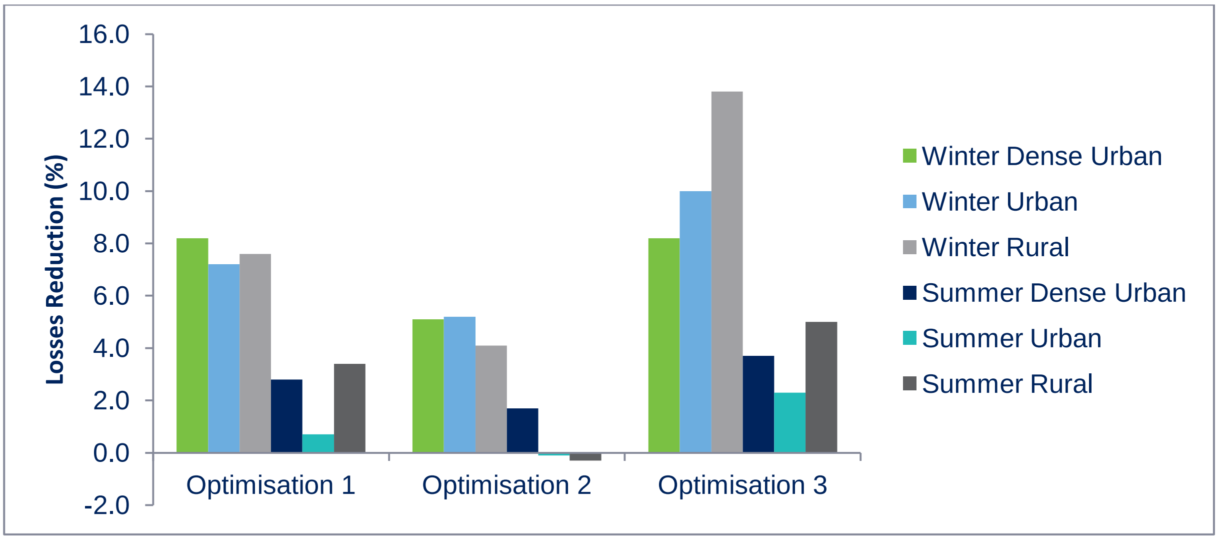


Figure 5.6: Losses reduction in 2050



The addition of capacitors to the voltage control has a negative effect on loss reduction whereas interconnection gives a positive effect. Interconnection offers a similar benefit to losses to the use of the on-load tap changers, but it does give more benefit on rural networks.

The effects increase with demand and generation growth until a ‘tipping point’ is reached due to the penetration of PV and subsequent reverse power flows; after this point the losses reduction reduces.

Optimisation 2 provides the lowest loss reduction as the reactive power provided by LV capacitors is too large when compared to the reactive power required by the network. In 2050 negative loss reductions are seen in summer scenarios for the urban and rural networks.

5.3 Trade-off between energy consumption versus losses

The analysis has shown that trade-off between energy consumption versus losses varies with the time of day and with the load on the network. However, the much larger scale of energy consumption reduction compared to losses means that the most effective solution is dominated by energy consumption. This means that it is better to optimise for energy consumption but this will still deliver a reduction in losses.

It should be noted that while the overall trade-off patterns are similar, there are some clear differences between the use of capacitors and tap position with the different load scenarios. The HV capacitor and tap positions of the OLTC transformer combine in order to help flatten the voltage profile for each load scenario. When the HV capacitors contribute more to the system (especially in the summer load scenarios), lower tap positions are selected on the OLTC transformers and vice versa.

To show the benefit of optimising off-load tap changers, further analysis was conducted. If the off-load tap changers are not changed the analysis showed fewer feasible solutions as there is less headroom for the primary transformers tap changers to be adjusted. In addition the magnitude of energy consumption and loss reduction is much less than when the off-load tap changers are optimised.

5.4 Voltage control

The analysis carried out demonstrates that optimised control of voltage setpoints for tap changers can offer significant benefits for energy consumption and losses. Optimising setpoints as the demand and generation changes provides greater benefit than just applying global setpoints. Given the positive benefits that tap changers have proven to offer, Electricity North West has amended its distribution transformer specification to include them as an option.

The capacitors were selected based on analysis using Electricity North West's current planning policy. This policy assumes a voltage drop along the feeders which could be boosted by a capacitor. When the trials were conducted it was noticed that the voltage drop is almost negligible which meant that the capacitors were rarely required to maintain the voltage. From the academic analysis it can be seen that capacitors can provide benefits for energy consumption but they have a negative effect on losses. It may be that future demand, generation and network topology means that a capacitor will offer benefits, but based on these findings it is not currently Electricity North West's intention to deploy them at scale.

5.5 Interconnection

Interconnecting feeders brings benefits in terms of voltage regulation and utilisation factor of the feeders. The equivalent impedance of the interconnected feeders is smaller than just the feeder with the largest impedance which results in smaller deviations from the LV busbar voltage.

There are only certain conditions in which the network and customers would benefit from being interconnected to improve the voltage and feeder utilisation. At other times keeping the interconnection point closed would subject more customers to interruptions in the event of a fault. Therefore using the optimisation routine to only close the interconnection point when required offers benefits to both customers and the network operator.

5.6 Impact on customers' supplies

The University of Manchester, Queen's University, Belfast and project partner TNEI analysed all the power quality metrics with the different optimisation modes. The majority of the metrics were improved by voltage control and/or interconnection. Fault levels did increase with interconnection but no networks in the Smart Street trial area increased beyond current design levels. When deploying interconnection at scale it would be beneficial to check the fault level, particularly as demand and generation increases.

To provide validity to this analysis it was submitted to the IET Wiring Regulations working group for review and feedback. They ran a four-week consultation on the work followed by a workshop to discuss the findings.