SAVE (Solent Achieving Value from Efficiency)

Report 7.1 – SAVE Initial Network Model

Document Ownership

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REPORT

SDRC 7.1: Initial Network Model

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Executive Summary

The Solent Achieving Value from Efficiency (SAVE) project is a Low Carbon Network (LCN) Fund project which is being led by Southern Electric Power Distribution (SEPD) in partnership with DNV-GL, Maingate Systems, University of Southampton, Future Solent, Neighbourhood Economics and EA Technology.

The project aims to trial and establish to what extent energy efficiency measures can be considered as a cost effective, predictable and sustainable tool for managing peak and overall demand as an alternative to network reinforcement. The project targets domestic customers only, and the measures to be trialled will include deploying technology, offering a commercial incentive and taking an innovative approach to customer engagement.

The purpose of this report is to present outputs from the initial Network Modelling Tool (NMT) that has been developed for the SAVE project and meets the Successful Delivery Reward Criteria (SDRC) set out for the SAVE project by providing evidence on SDRC 7.1 “create initial network model and parameters for tool”.

This report introduces the NMT to simulate real-time operation and management of electricity distribution networks allowing network ‘costs and benefits’ to be evaluated with respect to both energy efficiency and traditional network reinforcement methods. Specifically, this report defines the technical functional specifications for the NMT by providing information on inputs, processes and outputs; and illustrates the application of the preliminary version of the NMT to electricity distribution networks of the SEPD licence area.

A number of real-world customer field trials will be completed as part of the SAVE project to assess the effectiveness of four specific energy efficiency interventions in reducing and/or time-shifting demand for electricity in domestic households, i.e. (i) LED installation, (ii) data-informed engagement campaign, (iii) DNO price signals direct to customers plus data-informed engagement, and (iv) community coaching. Since the trials are currently ongoing, customer and/or community behaviour data in response to energy efficiency intervention is not presently available. Accordingly, and for illustrative purposes only, this report assumes that domestic energy efficiency interventions will shape customers’ load in one of three ways: (i) peak reduction; (ii) energy time-shifting; and (iii) energy reduction.

Network analyses were then developed to demonstrate the effectiveness of the energy efficiency interventions in relieving thermal constraints in the substation transformers, relieving thermal constrained power transfer problems in network circuits and relieving voltage constrained power transfer problems. The network analyses were performed with the preliminary version of the NMT on two (i.e. urban and rural) real electricity distribution networks in the SEPD licence area. The network analyses were also used to demonstrate some of the technical functional features of the NMT and their respective application to real distribution networks.

The key conclusions of the analyses can be summarised as follows:

C1. The effect of domestic customers’ energy efficiency interventions in the operation and management of distribution networks can be captured in a consistent manner through the concept of ‘headroom’ (e.g. thermal, voltage, fault level, power quality, etc.).

C2. In the LV urban distribution network without energy efficiency interventions, the thermal headroom of feeders and transformers and voltage legroom are relatively low (i.e. around 15% to 20%) but are within the nominal rating limits of the assets and within the voltage statutory limits respectively.

C3. The network circuits with the lowest levels of thermal headroom (i.e. highest loading) correspond to ‘main’ circuit cables whilst the lowest levels of voltage legroom (i.e. highest levels of voltage drop) are present in the ‘tapered’ circuit cables.

C4. Energy efficiency interventions from domestic customers leading to: reduction of customers’ peak load, time-shifting of customers’ load (i.e. from peak to off-peak) and energy reduction of customers’ load (i.e. overall daily load reduction), contribute to increase the level of thermal headroom of cables and substation transformers and the level of voltage legroom.

C5. The magnitude of thermal headroom released in ‘main’ circuit cables (i.e. feeders) and substation transformers is broadly driven by the total number of individual domestic customers engaged in up taking energy efficiency measures and their ability to reduce load during peak load periods. The magnitude of voltage legroom released also depends on the location of the deployment of energy efficiency measures with respect to the location of voltage drop issues.

C6. Energy efficiency interventions that shape the use of electricity consumption of domestic customers can reduce the utilisation of the network assets and the magnitude of the voltage drop in circuits, benefiting network operation and network investment planning.

C7. The distribution network constraint analysis indicated that the uptake of energy efficiency measures by domestic customers can assist network operators in: managing network constraints in operational timescales by relieving congestion in distribution substations as well as relief thermal and/or voltage constrained power transfer problems; and facilitate outage management and enhance quality and security of supply to critical load customers.

C8. In the LV rural distribution network without energy efficiency interventions, the thermal headroom of feeders and transformers and voltage legroom are relatively high (i.e. around 60% to 80%) resulting in low circuit utilisation and voltage drops. In this context, domestic customers’ energy efficiency innervations are observed to have a limited impact in further releasing network headroom.

C9. The functional requirements for and associated outputs from the initial NMT meet the requirements for SDRC deliverable 7.1 as outlined in the Project Direction for the SAVE project.

Contents

1. Introduction

1.1 Purpose

The purpose of this report is to present the initial Network Modelling Tool (NMT) that has been developed for the Solent Achieving Value from Efficiency (SAVE) project and meets the Successful Delivery Reward Criteria (SDRC) set out for the SAVE project by providing evidence on SDRC 7.1 “create initial network model and parameters for tool”.

1.2 Aims and Objectives

This report aims to introduce the NMT to simulate real-time operation and management of electricity distribution networks allowing network ‘costs and benefits’ to be evaluated with respect to both energy efficiency and traditional network reinforcement methods. Thus, this work can be divided into two main objectives:

- To define the technical functional specifications for the NMT by providing information on inputs, processes and outputs; and
- To illustrate the application of the preliminary version of the NMT on electricity distribution networks in the SEPD licence area.

1.3 Project Background

The SAVE project is a Low Carbon Network (LCN) Fund project which is being led by Southern Electric Power Distribution (SEPD) in partnership with DNV-GL, Maingate Systems, University of Southampton, Future Solent, Neighbourhood Economics and EA Technology.

The project aims to trial and establish to what extent energy efficiency measures can be considered as a cost effective, predictable and sustainable tool for managing peak and overall demand as an alternative to network reinforcement. The project targets domestic customers only, and the measures to be trialled will include deploying technology, offering a commercial incentive and taking an innovative approach to customer engagement.

On completion of the project other Distributed Network Operators (DNOs) will have a suite of tools to assess a particular network’s suitability for demand reduction through energy efficiency measures and to allow informed investment choices to be made between using customer engagement and energy efficiency measures as opposed to traditional technology based measures and ‘smart’ solutions.

A number of real-world customer field trials will be completed as part of the SAVE project to assess the effectiveness of four energy efficiency interventions in reducing and/or time-shifting demand for electricity in a representative sample of the household population of the Solent region. The four intervention methods are:

- LED installation;
- Data-informed engagement campaign;
- DNO price signals direct to customers plus data-informed engagement; and
- Community coaching.

1.4 Network Model Context

The SAVE project aims to produce a network investment decision tool that will allow DNOs to assess and select the most cost efficient methodology for managing electricity distribution network constraints. In particular, the model will consider the effects of different types and degrees of energy efficiency interventions as well as more traditional techniques for network reinforcements as tools for the management of networks by DNOs.

To this aim, a set of three comprehensive models working in unison will be developed to create an overall software tool that network planners will be able to utilise to manage distribution network challenges more effectively as an alternative to traditional reinforcement. The set of models will include: (i) the customer and community model to represent the behaviour of trial participants in response to energy efficiency interventions; (ii) the network model to simulate the real-time operation and management of real electricity distribution networks ; and (iii) the network investment model to trade-off 'traditional asset based solutions' for network infrastructure development against 'energy efficiency based solutions' whilst considering the technical constraints associated with the operation and management of the network. Figure 1 depicts an overview of the network investment decision tool to be developed throughout the SAVE project.

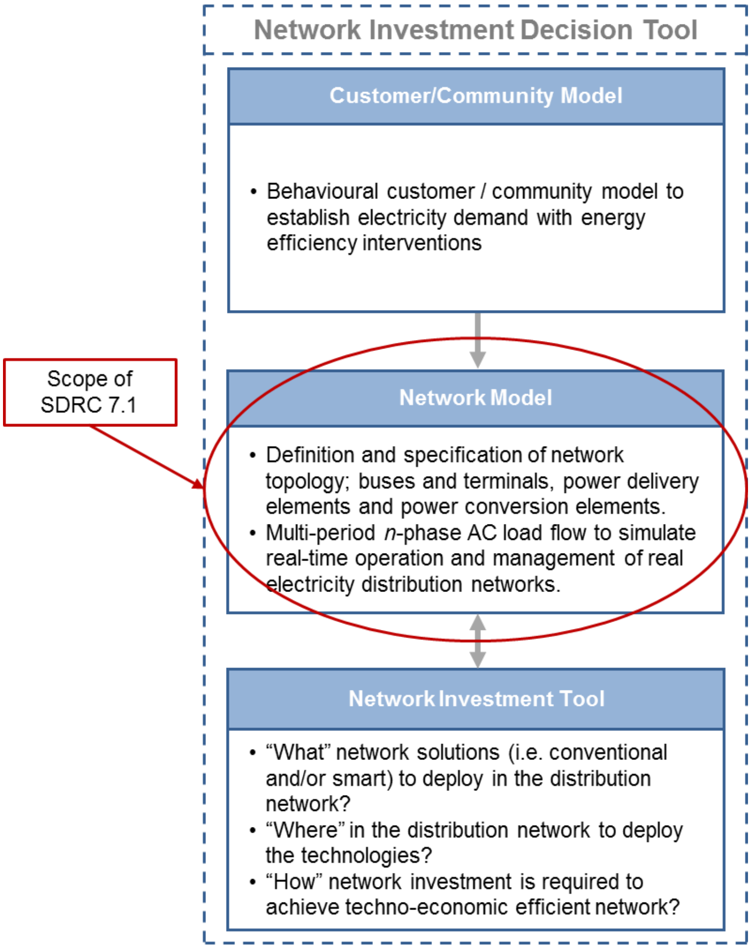


Figure 1 Generic overview of the SAVE modelling tool[1]

As per the SDRC requirement this report only presents information on the NMT to simulate real-time operation and management of electricity distribution networks, as highlighted in Figure 1.

[1] Further information on the customer model can be found in: SDRC 2.1 - Create initial customer model.

It should be noted that the project has an iterative nature and it is therefore expected that learning will be generated throughout the project which may have an impact on the initial views of how the modelling tool assesses the interventions. As such it is prudent to view this report as a baseline to initiate the "scope, specify & design" and "shape & populate" stages of the model development process[2], with the understanding that revisions to the approach may be required as the project progresses.

Further information regarding the development of the NMT will be provided in the following SDRC reports:

- **SDRC 7.2:** Produce updated report, December 2016; and
- **SDRC 7.3:** Produce final report and host a workshop demonstrating the tool, June 2018.

It should be noted that the purpose of this report is to fulfil the requirements of SDRC 7.1 "create initial network model and parameters for tool". Further information on the customer model can be found in: SDRC 2.1 - Create initial customer model.

1.5 Structure of the Report

The structure of this report is as follows:

- **Section 2:** Provides an overview of the suite of tools that constitute the network investment decision tool that the SAVE project aims to deliver.

- **Section 3:** Details the functional requirements for the NMT to simulate real-time operation and management of electricity distribution networks.

- **Section 4:** Applies the preliminary version of the tool to electricity distribution networks of the SEPD licence area.

- **Section 5:** Concludes the report by summarising the key messages of the work carried out.

[2] EA Technology, 2014. "Modelling Quality Assurance Guidelines", EA Technology, March 2014.

2. SAVE Network Investment Decision Tool

The SAVE project will develop a set of comprehensive models working in unison, to deliver an overall software modelling tool that network planners will be able to utilise to manage electricity distribution network challenges more effectively as an alternative to traditional reinforcement. This overarching network investment decision tool will allow DNOs to assess and select the most cost efficient methodology for managing distribution network constraints. In particular, the modelling tool will consider the effects of different types and degrees of energy efficiency interventions as well as more traditional techniques for network reinforcements as tools for the management of networks by DNOs.

Figure 1 depicts a detailed overview of the network investment decision tool to be developed throughout the SAVE project.

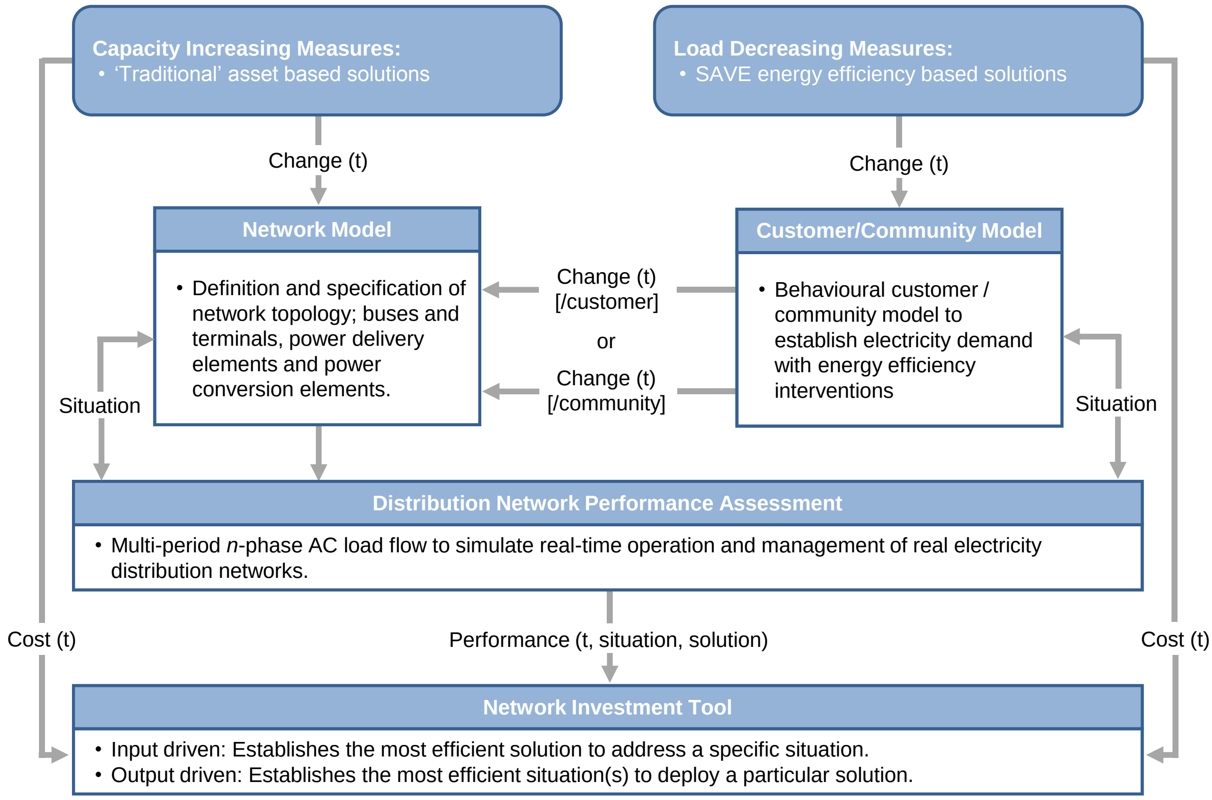


Figure 2 Detailed overview of the SAVE modelling tool[3]

[3] Based on "Figure 1" of the "Scope of works" document of the "SAVE Network Modelling ITT", Reference: 14.0617, Scottish Southern Electric Power Distribution, 2014.

3. Network Model Tool Requirements

3.1 Overview

This section presents an overview of the NMT and its constituent parts and then details the key functional requirements of the NMT.

The primary purpose of the NMT is to allow network planners to assess the potential effect of the SAVE energy efficiency interventions as alternative options to conventional interventions for network operation and development. In this regard, the three core functions of the NMT are to:

- Perform assessments using sets of 'network templates' (e.g. representative networks), to represent a variety of different types of low voltage (LV) distribution networks, allowing DNOs to understand the effect of SAVE energy efficiency interventions on a wider scale;

- Assess the effect of SAVE energy efficiency interventions on specific LV distribution networks by using a network builder tool; and

- Understand the impact of SAVE energy efficiency interventions on the HV and EHV system by assessing the effects of the interventions against aggregated load data (e.g. multiple distribution substations).

The interactive NMT will use Microsoft Excel as the main user interface and will be integrated with network assessment tools (i.e. load flow engines) to assess the performance of the networks against a variety of scenarios. Figure 3 displays a generic overview of the NMT.

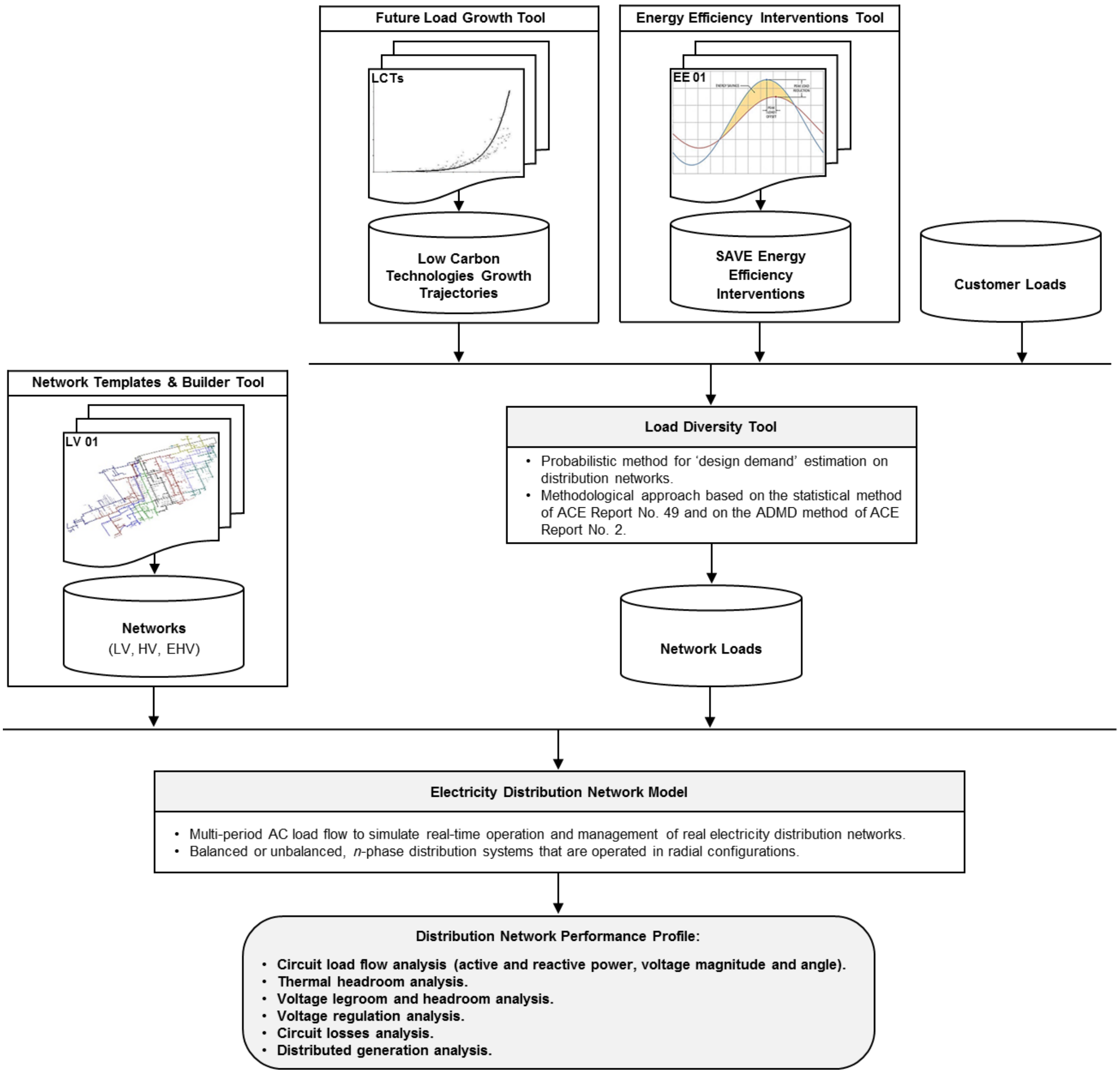


Figure 3 Generic overview of the network modelling tool

Figure 3 illustrates that the NMT will be comprised of a number of modules as follows:

- A set of network templates that represent a broad range of LV distribution network types.
- A network builder tool to allow a network planner to model a specific LV area by defining the main assets and nodes of a network. This will allow specific networks to be developed by modifying existing templates or by starting from scratch.
- An intervention modelling tool to simulate various network interventions, which will include:
    - Customer interventions trialled in the SAVE project;
    - A broad range of conventional network solutions such as impedance lowering (cable overlaying, feeder splits), asset replacement, load transfer to a different feeder, etc.; and
    - Some viable novel network interventions trialled under LCN Fund projects, to allow comparison between the SAVE customer interventions and other innovative solutions which are not yet deployed as Business as Usual.

- Load flow engines that will allow a multi-period AC load flow for balanced or unbalanced, *n*-phase distribution systems that operate in radial, looped or meshed configurations.

- A future load growth tool to assess the likely effects of the SAVE energy efficiency interventions on a LV area against future load growth driven by Low Carbon Technologies (LCTs).

- A customer model interface to take input from the Customer and Community models to describe each type of customer (e.g. demographics) and loading information.

- An investment appraisal interface to provide the output in the required format to the Network Investment Tool.

- A HV and EHV tool to allow the user to estimate the effect of the SAVE energy efficiency interventions on upstream assets.

- A probabilistic method to take account of the observed variation in intervention performance and the level of diversity where customer numbers within a network area are too low to accurately use average data.

A key requirement of the SAVE Network Modelling Tool is the ability to be operated from a standalone computer without the need to connect to any remote infrastructure; this will greatly increase the prospect of further use by other Great Britain (GB) DNOs. The tool front end will be based on 'Microsoft Excel', with the core aspects of the user interface through 'Windows Forms' to improve usability. The tool will be integrated with network assessment tools (load flow engines) to assess the performance of networks against a variety of scenarios. The tool will be subject to a licence on project completion, however, this will be free to use for all GB DNOs.

3.2 Functional Requirements of the Network Model

This subsection expands on the aforementioned NMT modules by providing a more detailed view of their respective technical function specifications.

3.2.1 User interface

An intuitive user interface will be developed in 'Microsoft Excel' based on a combination of user forms and direct cell entry offering an interactive and user friendly environment. The user interface will be developed with the intent of enabling the user to complete modelling work without specific training. In contrast, the software modules will be coded using 'Microsoft Visual Basic for Applications' (VBA) and/or 'Microsoft Visual C#. NET' to ensure computational accuracy, efficient memory management and speed.

The user interface will deliver flexibility and easy customisation to allow the user to quickly change a variety of settings to run different scenarios such as:

- Run a single period (e.g. year) or multi-period assessments

- Select the networks to run the assessment:

    - Single network, selection of network templates or custom built network.

- Energy efficiency intervention scenarios:

    - SAVE interventions vs. conventional network performance;

    - SAVE interventions vs. conventional network reinforcement options; and

    - SAVE interventions vs. other smart solutions.

3.2.2 Network templates

The NMT will include default network templates to represent the large proportion of SEPD's LV networks that would be affected by the SAVE project with a focus on circuits that supply predominantly domestic customers. The network templates will provide a detailed nodal representation of entire LV network areas (i.e. distribution transformers and all downstream feeders, rather than single feeders.) together with associated assets (i.e. transformers, cables, busbars, shunts, etc.). The NMT will provide a set of network templates that can be customised by the user through modifying the existing templates and/or removing or adding new templates ones.

3.2.3 Network builder

The network builder module will allow a network planner to model a specific low voltage area by defining the main assets, associated technical parameters and nodes of a network. Specific networks may be developed by modifying an existing template or by starting from scratch.

The network builder will enable the user to build a representation of LV network areas in varying degrees of realism and accuracy depending on the purpose of the assessment to be performed. For instance, the user would be able to input variables through the network builder such as:

- Nodes (from and to);
- Asset type (transformer, cable etc.);
- Asset information (transformer and cable ratings for both feeder and service cables, impedances, etc.);
- Customer information (type of customer, annual consumption, load shape, etc.);
- Phase allocation; etc.

Figure 4 depicts a modelling example of a LV distribution network area.

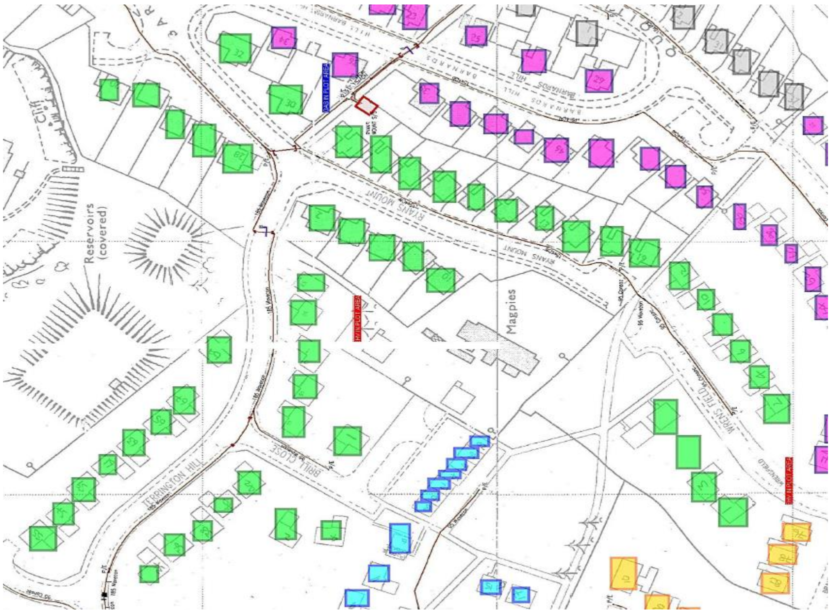


Figure 4 Example of a LV distribution network area

Table 2 Network parameters specification

From node	To node	Asset	Length	Customers	Phase allocation
Feeder 1 (Green)					
1	-	Tx 500kVA	–	–	120˚ Three Phase
1	10	Cable Wave 185 Al	30	2 x customer type URLC	–
10	11	Cable 0.15 Al	130	9 x customer type URSC	Balanced
11	12	Cable Consac 95 Al	90	11 x customer type URSC	Balanced
10	20	Cable Wave 185 Al	100	5 x customer type URMC	10% red weighting
10	30	Cable Wave 95 Al	250	21 x customer type URSC	10% red weighting
Feeder 2 (Purple)					
…	…	…	…	…	…

3.2.4 Intervention modelling

The intervention modelling module will simulate various network interventions required for the SAVE project. This module will allow comparison between the SAVE energy efficiency customer interventions and conventional network solutions as alternatives for distribution network development. The intervention modelling module will simulate the following interventions with the objective of reducing and/or time shifting demand for electricity:

- **Intervention 1:** The use of LED lighting to reduce overall power consumption, especially in the evening peaks;
- **Intervention 2:** The use of an enhanced engagement campaign to reduce overall power consumption;
- **Intervention 3:** The use of an enhanced engagement campaign along with Time of Use (ToU) rebates providing customers with incentives to shift their power consumption to different times of day; and
- **Intervention 4:** The use of community coaching providing engagement with customers to either reduce power consumption or shift usage to different times of day.

The intervention modelling module will enable the interventions to be compared to conventional network solutions, which are as follows:

- Impedance overlaying (cable overlaying, feeder splits);
- Asset replacement; and
- Load transfer to a different feeder.

3.2.5 Scenario builder

The scenario builder module will enable the user to select the:

- Interventions to compare (e.g. ‘do-nothing’, ‘conventional’, ‘SAVE intervention’, etc.);
- Network or network templates to consider for the assessment; and
- Set of requirements defining what the outputs will look like.

3.2.6 Load flow engine

Load flow engines will allow a full half-hourly or single value (ADMD style) steady state voltage and current analysis of LV networks, from the distribution transformer to feeder ends to be completed. Thus, the NMT will utilise two load flow engines which are as follows:

- DEBUT: is a familiar, trusted and very well understood piece of software that provides voltage drops and asset utilisations from customer load models. Developed by EA Technology, it is implemented in Fortran and, unlike most load flow tools, DEBUT uses a unique calculation process to take account of diversity following the ACE49 design method. This method is not easily replicated in iterative load flow methods (e.g. Newton Raphson). As most DNOs use DEBUT in some capacity, its inclusion in this tool will allow easy benchmarking against existing design practices.

- EGD (Embedded Generation for Distribution): was originally developed by EA Technology to allow the assessment of generation in the WinDEBUT software, again familiar to all DNOs. The EGD module is a traditional load flow engine utilising the common Newton Raphson iterative method. The main reason for including it in this proposal is that the code is readily adaptable for alternative uses, such as advanced probabilistic methods, and it allows us to model generation on LV circuits.

The inclusion of both load flow engines will enable the outputs from the NMT to be validated against DEBUT which is well proven and trusted.

3.2.7 Future load growth module

The future load growth module will assess the likely effects of the SAVE energy efficiency interventions on LV area against future load growth due to LCTs. This module will hold load profiles for common LCTs and use sets of uptake probabilities to map LCT connections onto the LV feeders. Hence, the module will allow the user to model the impact of the following LCTs on load growth:

- Heat pumps;

- Electric vehicles; and

- Solar photovoltaic generation.

The future load growth module will enable the user to perform assessment over multiple years from the templates, or custom built networks, to capture the year-on-year variability associated with the rate of growth of LCTs.

The module will also allow the user to map the various interventions on to the network in the appropriate year to derive a more accurate understanding of not just what intervention provides benefits but also when the reinforcement would be required.

3.2.8 Customer / community model interface

The customer/community model interface will take input(s) from both the customer and community models. The interface is currently being agreed with the University of Southampton who are responsible for completing the customer and community models. The following requirements below will need to be refined and are therefore subject to change.

- The customer model interface will be via a semi-automated link so inputs can be transferred into the Modelling Tool.

- The customer model interface will take the form of direct links to other ‘Microsoft Excel’ tools, developing a ‘csv’ file loader for data exchange or developing an XML interface.

- An aggregation layer will convert source data into a form usable by the modelling tool. This will take granular input data on customer demand, intervention response, variability of demand and response, customer type (e.g. demographic).

- The aggregation layer will be scaled to allow processing of up to five thousand individual customer demand profiles and two hundred substation monitoring records over one year.

- The processing of customer records by the aggregation functions is expected to be performed infrequently, in terms of performance it will be run as an overnight routine.

3.2.9 Network investment model interface

A network investment model interface will provide the output in the required format to the Network Investment Tool.

The network investment model interface will be via a semi-automated link for results to be ported out of the Modelling Tool. The interface will take the form of direct links to other 'Microsoft Excel' tools, developing a 'csv' file loader for data exchange or developing an XML interface.

The specific output format is to be defined but will contain:

- Details of the scenario run by the modelling tool.

- Key Performance Indicators for the network(s) subject to assessment.

- Utilisation (kW peak / Rating) of distribution transformers and conductors.

- Voltage performance against statutory levels and feeder volt drop limits (as per SEPD design policy).

- The benefit of the interventions modelled:

    - Peak demand reduction (kW); and

    - Annual energy transfer reduction (kWh).

- Information on the lifetime benefit of the interventions (dependant on the LCT scenario, if applicable).

3.2.10 HV and EHV Module

The HV and EHV module will allow the user to estimate the effect of the SAVE energy efficiency interventions on upstream networks and assets. The module will provide a method of aggregating the effects of the SAVE interventions based on multiple LV network areas (e.g. select x Network Type A + y Network Type B), and/or on the number and type of domestic customers connected to the specific part of the LV network system. This module will also provide SEPD planners with an understanding of the quantity of interventions needed to achieve a desired level of demand reduction.

3.2.11 Probabilistic method

The interventions that the NMT must simulate will have a variability associated with their performance. This variability can be represented in a number of statistical ways and further work will be completed with the University of Southampton to define an acceptable approach that accurately describes the risk and can be readily modelled.

A probabilistic method will be implemented to take account of the observed variation in intervention performance and the level of diversity where customer numbers within a network area are too low to accurately use average data will be developed.

The probabilistic method used in DEBUT will be employed in the network model tool. The aggregation layer will process data from the customer model to generate DEBUT compatible load profiles with statistical diversity factors. The method employed within the network model tool will be subject to review for fitness for purpose as project learning is generated, and is therefore subject to change. This module will use data from the customer model to define load profiles and standard deviations within the aggregation process.

3.2.12 Load profiles

The NMT will store and use load data for each customer type:

- Half hourly load profiles for each month for each customer type;
- A method of accounting for the local variation of conventional household demand (probabilistic method), either due to the customer type or lack of diversity;
- An ADMD value (a single figure, useful for speeding up assessments);
- The effect of the SAVE interventions for the customer type; and
- A method of accounting for the local variation of the SAVE interventions (probabilistic method).

3.2.13 Overall modelling approach

The following requirements relate to the overall modelling approach that will be taken for the development of the NMT:

- The NMT will consider effects on a 365 x 48 x half-hour basis over the course of an entire year on a simulated network. The tool will only consider steady-state voltage and thermal performance. Transient effects, harmonics or similar analyses are not required.
- The NMT will estimate network performance in terms of available capacity (kW) until voltage or thermal constraints are reached or the amount by which this capacity has been exceeded, whilst operating the network in accordance with the relevant provisions of the 1) Electricity Safety, Quality and Continuity Regulations, 2) Engineering Recommendation P2/6 (note: P2/6 is due for revision during the course of this work, the revision should be correctly replicated in this model, as appropriate) and 3) the other requirements of the Distribution Licences and Distribution Code.
- The NMT will estimate the effects of different types and degrees of energy efficiency intervention as well as more traditional techniques for reinforcements on the local, low voltage network and also at higher voltages (nominally, 11kV, 33kV and 132kV). To some extent, the effects of interventions are likely to be observed at all voltages – as such the model will identify the network performance and associated changes at all relevant voltages.
- Analysis at the Low voltage level will consider the effects of local network topology, connection location, connection phase allocation and phase imbalance.
- The NMT will be reliant upon data supplied from the Customer and/or Community Models.
- The NMT will treat the individual energy requirements of customers independently.
- The NMT will treat the customers' propensity to change energy use in response to energy efficiency interventions independently.

- It is likely the energy requirements and propensity to change will be defined as a series of probabilistic functions. In the first instance, before the necessary volume of data has been recorded to inform the Customer and Community Models, actual metered data may be supplied to the NMT in place of data from the Customer and Community Models.

- The precise point of connection within a low voltage network for individual customers will not be known.

- The NMT will estimate the range of possible effects given for a defined mix of customers as informed by the Customer and/or Community Models for all combinations of connection location.

- If required, externally observable characteristics of customer distribution may be considered as a modelling input to be agreed with and supplied by SEPD.

- Given the probabilistic nature of customer energy use, propensity to change and the estimations required for the allocation of customers to specific points of connection – it is assumed the NMT will define network performance estimates using a similarly probabilistic function.

- The NMT will compare energy efficiency interventions with more traditional techniques for reinforcements on the local, low voltage network and also at higher voltages.

- EA Technology will define the range of traditional (capacity increasing) techniques that are used for comparison and will encode their nature and effect on network performance into the NMT for automatic comparison.

- A user should not be required to set-up or define these techniques but should be able to clearly understand how these techniques have been applied by the model and adjust if necessary.

- The NMT will enable users to configure their own network(s) therefore ensuring the model can be readily adjusted to reflect local circumstance and practice across all UK DNOs.

- The network configuration parameters should encompass both the characteristics of network under assessment as well as the nature of traditional techniques used in comparisons.

- The NMT will be interactive to allow the user to explore any number of possible scenarios or circumstances.

- The parameters should encompass both the characteristics of network under assessment as well as the nature of traditional techniques used in comparisons.

- Whilst the NMT and the traditional techniques used in comparisons will be based on a simulated network, the nature of results and the process by which they have been established will be transparent and readily interpretable.

- Modelling transparency is an important factor in ensuring that subsequent strategic and policy actions drawn from this work are properly grounded in fact.

- The project will trial energy efficiency interventions on an iterative basis with the first iteration being used to refine the second iteration. Prior to the first iteration, target energy efficiency messages will be defined by considering the base-case levels of performance from the network model. In advance of this, and as an indication of the type of message to be revealed by the NMT, an initial set of messages have been prepared from a highly generalised understanding of network need. The NMT will take inputs from the Customer/Community Analysis. Depending on scale and complexity, it may be reasonable for these interactions to be via a manual (cross-typed) transfer of details (low tens of numbers) or using standardised file structures (larger exchange of details). The specification of the interface will be driven by the need for user convenience but also the iterative nature of the project's models.

- The NMT will provide outputs to the network investment tool interface. Depending on the scale and complexity, it may be reasonable for these interactions to be via a manual (cross-typed) transfer of details (low tens of numbers) or using standardised file structures (larger exchange of details). The specification of the interface will be driven by the need for user convenience but also the iterative nature of the project's models.

- The NMT will be implemented using standard office software (i.e. Microsoft Office or similar), readily available desktop analysis software or commonly used power analysis software.

- The NMT will be designed to be installed and operate on standard office computers.

4. Application of the Network Model

4.1 Introduction

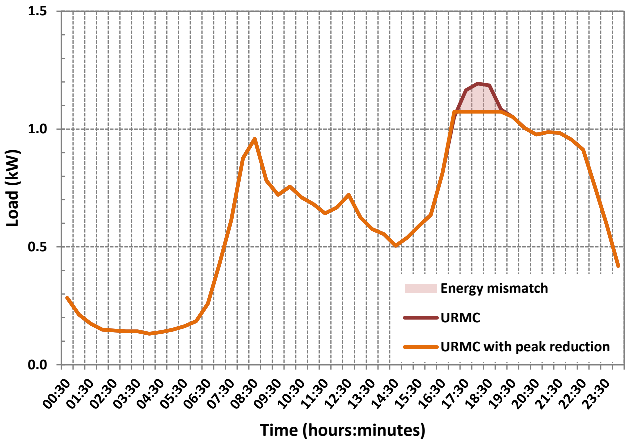
This section applies the preliminary version of the NMT to quantify and assess the impact of different domestic energy efficiency interventions in the operation and management of real electricity distribution networks in the SEPD licence area. Furthermore, the section demonstrates some of the technical functional features of the NMT and their respective application to real distribution networks.

Specifically, the section first illustrates the potential effect of domestic customers' energy interventions in their respective electricity consumption profile. Subsequently, the section applies these modified electricity consumption profiles to two LV distribution networks (i.e. urban and rural) to investigate their impact in network operation and development. Finally, the section explores the uptake of domestic customers' energy efficiency interventions to support network constraints management. It should be noted that outcomes of the analyses performed in this section are provided for illustrative purposes only.

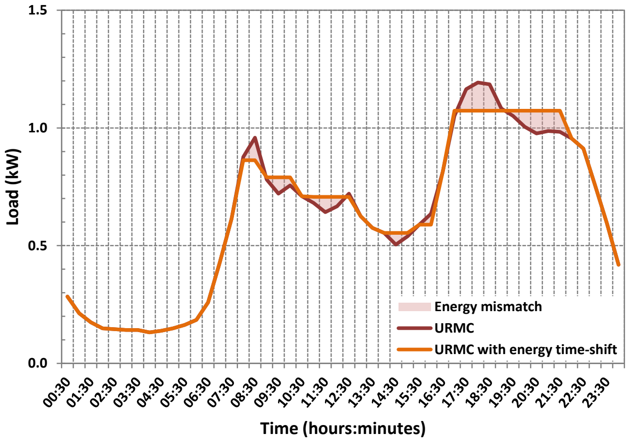
4.2 Energy Efficiency Interventions

The SAVE project has been designed to quantify and assess the relative value to electricity distribution networks of using different domestic energy efficiency interventions that reduce or modify demand. These interventions will compete against conventional network solutions (e.g. traditional reinforcement) as alternative options for the development of the network, for managing network constraints and network operation. Figure 5 illustrates the potential effect of domestic customers' energy interventions in their respective daily load profile. It is noted that the load curve used to represent the electricity consumption of a domestic consumer was extracted from ACE Report No. 49[4] standard for the planning and design of LV radial distribution networks, demands and voltage regulation. The load curve characterises an average domestic consumer with an UnRestricted tariff and Medium Consumption (i.e. URMC).

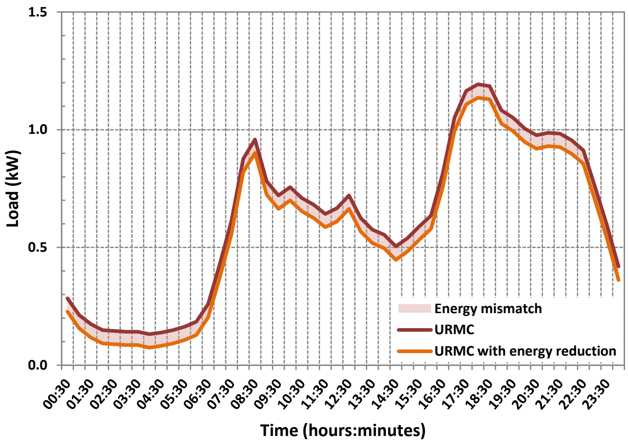
[4] ENA, 1981. "Report on Statistical Method for Calculating Demands and Voltage Regulations on LV Radial Distributions Systems", ACE Report No. 49, Energy Networks Association, 1981.



(a) Peak reduction



(b) Energy time-shifting



(c) Energy reduction

Figure 5 Potential effect of domestic customers' energy interventions in domestic load

Figure 5a displays a reduction in peak load as a result of energy interventions. For instance, this peak reduction may be associated with a decrease of the temperature set point (i.e. thermostat setting) of the electric heating system. The magnitude and shape of the load profile with peak reduction is provided for illustrative purpose only.

Figure 5b depicts the impact of customers' energy interventions as time-shifting load. In these circumstances, customers may decide to postpone the use of electric appliances to times outside of the peak periods. Thus, Figure 5b shows a reduction in energy consumption during the morning and evening peaks and a respective increase outside the peak periods.

Figure 5c shows the impact of customers' energy interventions as an overall reduction of the daily electricity consumption. For example, the reduction in domestic customers' electricity requirements may relate to customers switching off electric equipment that otherwise would normally be in standby mode (e.g. media equipment).

A number of real-world customer field trials will be completed as part of the SAVE project to assess the effectiveness of four specific energy efficiency interventions in reducing and/or time-shifting demand for electricity in domestic households, i.e. (i) LED installation; (ii) data-informed engagement campaign; (iii) DNO price signals direct to customers plus data-informed engagement; and (iv) community coaching. Since the trials are currently being set up, customer and/or community behaviour data in response to energy efficiency intervention is not presently available. Accordingly, and for illustrative purposes only, this report assumes that the effect of domestic energy efficiency interventions will shape customers' load in a similar manner to that described in Figure 5.

4.3 Low Voltage Urban Electricity Distribution Network

This subsection applies the NMT to quantify and assess the impact of different domestic energy efficiency interventions in the operation and management of a real electricity distribution network in the SEPD licence area. The analysis assumes that the uptake of energy efficiency measures from domestic customers shapes their load curve in one of the three possible ways previously introduced, i.e. (i) peak reduction; (ii) energy time-shifting; and (iii) energy reduction. The subsection will demonstrate some of the technical functional features of the NMT and their respective application to real electricity distribution networks.

4.3.1 Overview of the LV network performance without energy efficiency interventions

The example LV network is a 3 phase, underground urban network. It is supplied through an 11/0.4kV, 500kVA transformer serving 323 domestic customers. The substation has three main outgoing feeders with feeder 1 serving 50 customers, feeder 2 serving 147 and feeder 3 serving 126 customers. The domestic customers comprise of flats, mid-terraced and semi-detached houses. The magnitude and shape of their electricity consumption is modelled in accordance with the ACE Report No. 49 standard for the planning and design of LV radial distribution networks. As a result, the load curve used in the analysis characterises an average domestic customer of URMC type. Figure 6 displays the schematic representation of the LV urban electricity distribution network used in the application of NMT and associated analysis.

Figure 6 Schematic representation of the LV urban electricity distribution network

In order to ensure that the impacts of the domestic customers' load with and without energy efficiency interventions are captured and analysed in a consistent manner the concept of "headroom" has been used. Headroom refers to the difference between the load experienced on a network, and the rating (i.e. cable laid directly in ground) of that network. If the rating exceeds the load, then there is a positive amount of headroom and reinforcement is not required. However, once load exceeds the rating then the headroom figure becomes negative and reinforcement to release additional headroom must be undertaken. The advantage to using headroom in this way is that it allows numerous parameters to be discussed with a common base. For the purpose of this analysis, headroom is evaluated for two different parameters: thermal and voltage. Based on the concept of headroom, the effect of customers' load on these parameters can be captured simultaneously. For instance, if a particular customer load contributes to a reduction in both thermal and voltage legroom, this can be easily identified.

In the specific case of voltage, the concept of legroom has also been introduced. As the voltage in the network has to be maintained within the statutory limits (i.e. lower and upper limits) specified in the ESQCR[5], legroom refers to the difference between the voltage experienced on a network, and the statutory lower voltage limit of that network.

[5] Statutory Instruments, 2002, No. 2665, "The Electricity Safety Quality and Continuity Regulations".

The network analysis has been performed with the initial NMT developed for the SAVE project. Table 3 presents a summary of the minimum levels of headroom and legroom available across the circuits of the three feeders that form the LV urban electricity distribution network. These levels of headroom and legroom are attained for the most overloaded network circuits in a specific half hour during the central winter period (as in ACE Report No. 49).

Table 3 Circuit headroom and legroom for the LV network

Thermal headroom		Voltage legroom
Cables	Transformers	
16%	20%	22%

It can be seen in Table 3 that the level of circuit headroom available to transfer power from the substation to the local domestic customers is relatively low. For instance, the lowest thermal headroom of all circuits that constitute the network feeders is estimated to be 16% whilst the transformer at the substation is characterised by a thermal headroom of around 20%. The minimum voltage legroom of all the network circuits is about 22%. These levels of thermal headroom and voltage legroom are mainly driven by the network being located in a dense populated area and by the long length covered by the network circuits. Nonetheless, it should be noted that the thermal headroom for feeders and transformers are within the nominal rating limits of the assets whilst the voltage legroom is within the voltage statutory limits for this LV network.

This analysis can be disaggregated to circuit levels in order to identify whether abnormal (e.g. overloading) conditions exist in the network. Accordingly, Table 4 details the minimum levels of thermal headroom across the circuits of the three feeders that form the LV urban distribution network under analysis. These levels of thermal headroom are observed in the five most overloaded network circuits of each feeder.

Table 4 Circuit thermal headroom for the LV network

Feeder	Circuit	Customers	Phases	Length	Type	Headroom
1	1	29xURMC	R: 34%; Y: 34%; M: 31%	175m	0.15mm^2-CU-290A	64%
	2	-	-	15m	185mm^2-WAVE-335A	69%
	3	-	-	130m	185mm^2-WAVE-335A	69%
	4	-	-	30m	185mm^2-WAVE-335A	69%
	5	-	-	5m	185mm^2-WAVE-335A	69%
2	6	-	-	2m	185mm^2-WAVE-335A	16%
	7	-	-	50m	185mm^2-WAVE-335A	39%
	8	-	-	39m	185mm^2-WAVE-335A	56%
	9	-	-	25m	185mm^2-WAVE-335A	56%
	10	-	-	25m	185mm^2-WAVE-335A	71%
3	11	17xURMC	R: 29%; Y: 34%; M: 31%	2m	185mm^2-WAVE-335A	28%
	12	-	-	50m	185mm^2-WAVE-335A	28%
	13	-	-	80m	185mm^2-WAVE-335A	36%
	14	-	-	30m	185mm^2-WAVE-335A	36%
	15	-	-	30m	185mm^2-WAVE-335A	36%

As shown in Table 4 that the levels of thermal headroom for network circuits are all within the nominal rating limits. The lowest level of thermal headroom and therefore the highest utilisation is observed in feeder 2, circuit 6. Feeder 2 supplies the highest number of domestic customers out of the three feeders of the LV network under consideration.

Table 5 introduces the minimum levels of voltage legroom across the circuits of the three feeders that form the LV urban distribution network under analysis. These levels of voltage legroom are observed in the five most overloaded network circuits of each feeder.

Table 5 Circuit voltage legroom for the LV network

Feeder	Circuit	Customers	Phase	Length	Type	Legroom
1	16	9xURMC	Balanced	54	0.04mm^2-CU-140A	22%
	17	7xURMC	R: 43%; Y: 29%; M: 29%	52	0.04mm^2-CU-140A	27%
	18	5xURMC	R: 20%; Y: 40%; M: 40%	50	0.06mm^2-CU-175A	37%
	19	–	–	25	0.15mm^2-CU-290A	45%
	20	–	–	55	0.15mm^2-CU-290A	47%
2	21	10xURMC	R: 30%; Y: 40%; M: 30%	20	35mm^2-AL-125A	57%
	22	5xURMC	R: 40%; Y: 20%; M: 40%	32	185mm^2-WAVE-335A	57%
	23	5xURMC	R: 40%; Y: 40%; M: 20%	36	185mm^2-WAVE-335A	58%
	24	4xURMC	R: 25%; Y: 50%; M: 25%	28	95mm^2-WAVE-235A	58%
	25	5xURMC	R: 40%; Y: 20%; M: 40%	1	35mm^2-AL-125A	58%
3	26	–	–	29	95mm^2-WAVE-235A	33%
	27	30xURMC	Balanced	15	95mm^2-WAVE-235A	33%
	28	1xURMC	R: 100%	7	35mm^2-AL-125A	35%
	28	12xURMC	Balanced	5	35mm^2-AL-125A	37%
	30	–	–	38	185mm^2-WAVE-335A	37%

As shown in Table 5 that the levels of voltage drop in the network circuits are all within the statutory limits. The lowest level of voltage legroom and consequently the highest voltage drop is observed in feeder 1, circuit 16 corresponding to the furthest circuit away from the substation (i.e. ≈520m) for the LV network under analysis.

It can be observed from Table 4 and Table 5 that the network circuits with the lowest levels of thermal headroom (i.e. highest loading) correspond to ‘main’ circuit cables whilst the lowest levels of voltage legroom (i.e. highest levels of voltage drop) are present in the ‘tapered’ circuit cables.

4.3.2 Overview of the LV network performance with energy efficiency interventions

This subsection explores the impact of different domestic energy efficiency interventions in the operation and management of the example LV urban distribution network. This impact is quantified by establishing a comparison with the network performance without energy efficiency interventions (i.e. Subsection 4.3.1). The analysis considers that the uptake of energy efficiency measures from domestic customers shapes their load curve in one of the three possible ways as previously introduced, i.e. (i) peak reduction; (ii) energy time-shifting; and (iii) energy reduction. Furthermore, the analysis assumes that 30% of the total number of domestic customers present in the network engage in energy efficiency interventions. These customers have been distributed accordingly across the three feeders in the example LV network.

Peak reduction

The effect of domestic customers’ energy efficiency interventions in their respective daily load profile is assumed to result in different magnitudes of peak reduction, i.e. 5%, 10% and 15% reduction. It is stressed that these magnitudes of load change (i.e. power and/or energy) have been selected for illustrative purposes only. Figure 7 illustrates the effect of domestic customers’ energy efficiency interventions in their respective daily load profile through peak reduction. The load curve used to represent the electricity consumption of a domestic consumer without energy efficiency interventions was extracted from ACE Report No. 49 and represents an average domestic customer of the URMC type.

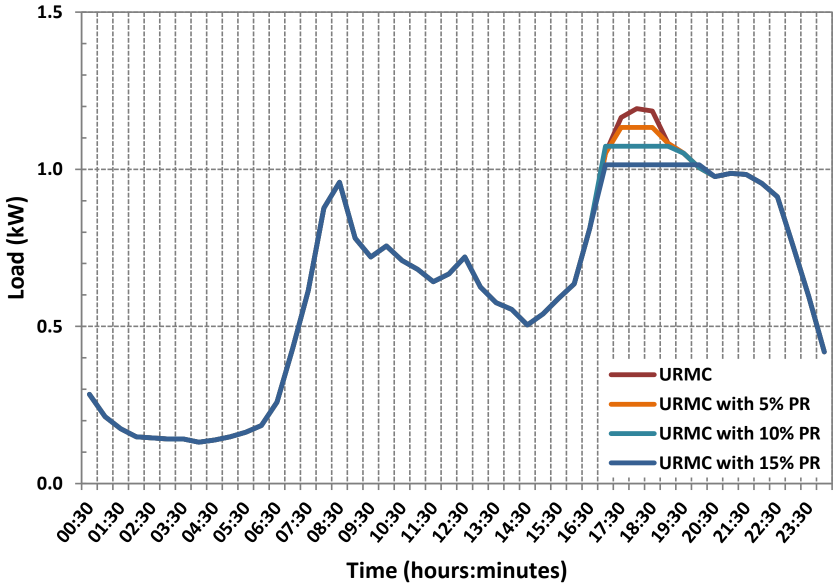
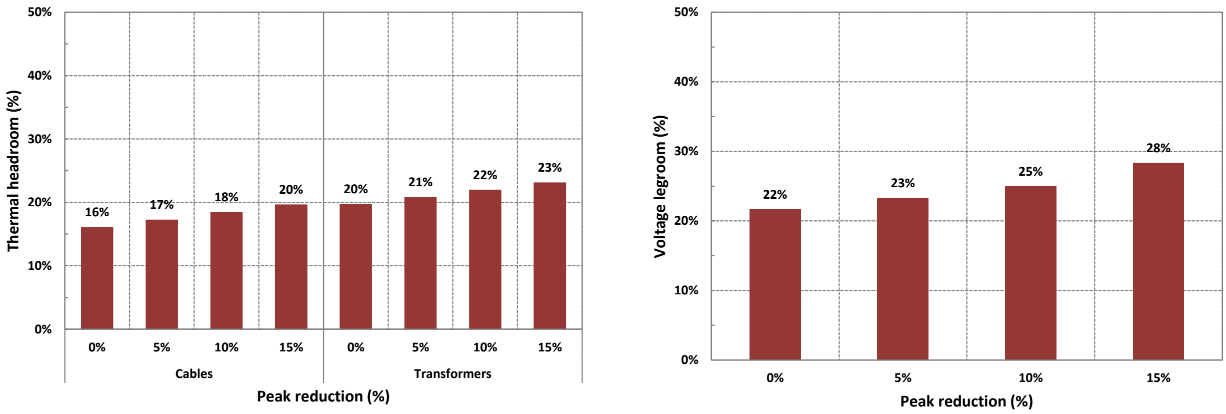


Figure 7 Peak Reduction (PR) in domestic customers' load

Figure 8 introduces the minimum levels of headroom and legroom available across the various circuits of the three feeders that form the example LV urban distribution network. These levels of headroom and legroom are attained for the most overloaded network circuits in a specific half hour time period during winter.



(a) Thermal headroom **(b) Voltage legroom**

Figure 8 Effect of domestic customers' peak reduction in LV network performance

It can be seen in Figure 8a that the energy efficiency interventions from domestic customers leads to a reduction of the peak load of their daily electricity consumption increases the level of thermal headroom of cables and of the transformer at the substation under consideration. In spite of the headroom released for the three peak reduction cases, it is observed that the magnitude of the headroom increase with respect to the no peak reduction case is relatively small. For instance, the thermal headroom of cables increases from 16% in 0% peak reduction to 20% in 15% peak reduction. The magnitude of thermal headroom released in 'main' cables (i.e. feeders) and substation transformers is broadly driven by the total number of individual domestic customers participating in energy efficiency measures and their ability to reduce load during peak load periods. The magnitude of voltage legroom released also depends on the location of the deployment of energy efficiency measures with respect to the location of voltage drop issues.

Figure 8b shows that customers' energy efficiency interventions manifesting in peak load reduction support the network operation and management by releasing voltage legroom. The magnitude of voltage legroom ranges from 22% without peak reduction to 28% for 15% peak reduction.

The uptake of energy efficiency measures by domestic customers can support network constraint management by relieving congestion in distribution substations as well as relieving thermal and/or voltage constrained power transfer problems.

Energy time-shifting

The impact of customers' energy efficiency interventions that lead to time-shifting load are analysed for different levels of power and energy shifts within a day, i.e. 5%, 10% and 15% shift. For example, in the analysis, 5% power and energy shift indicates that the maximum power that can be moved in a particular time period (i.e. half hour) is 5% of the customer's load in that same period and the maximum amount of energy that can be shifted is 5% of the overall daily energy of a particular domestic customer. It is highlighted that these magnitudes of load change (i.e. power and energy) have been selected for illustrative purposes only. Figure 9 depicts the effect of domestic customers' energy efficiency interventions in their respective daily load profile through energy time-shifting.

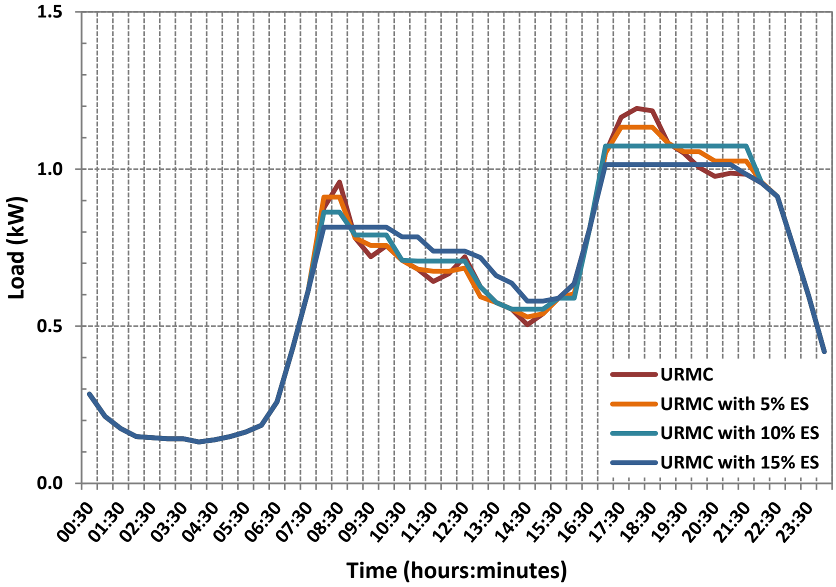
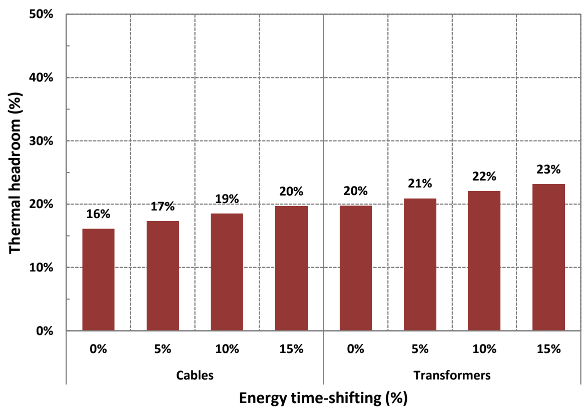


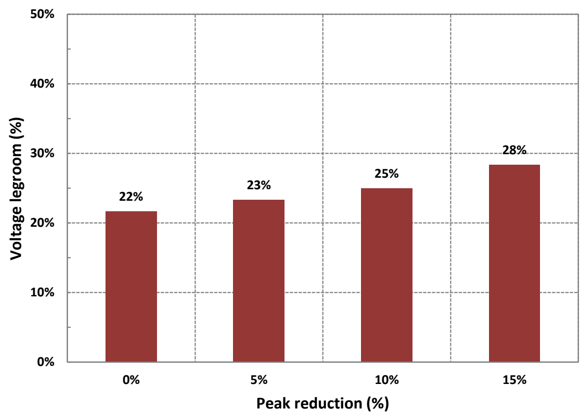
Figure 9 Energy time-shifting (ES) in domestic customers' load

It can be seen in Figure 9 that energy efficiency interventions resulting in time-shifting load tend to flatten the load shape throughout the day by decreasing load during peak time periods and increasing load during off peak time periods.

Figure 10 presents the minimum levels of headroom and legroom available across the various circuits of the three feeders that form the example LV urban distribution network. These levels of headroom and legroom are attained for the most overloaded network circuits in a specific half hour time period during winter.



(a) Thermal headroom



(b) Voltage legroom

Figure 10 Effect of domestic customers' energy time-shifting in LV network performance

It can be observed in Figure 10a that domestic customers' energy efficiency interventions resulting in time-shifting load support network management by releasing thermal headroom in the network assets. The thermal headroom of cables is estimated to increase by 4% from a 0% energy shift to a 15% energy shit. Similarly, Figure 10b indicates that energy efficiency interventions by domestic customers can contribute to decrease the levels of voltage drop in the distribution network.

Energy reduction

The impact of customers' energy efficiency interventions are considered to result in lower levels of daily electricity consumption. The analysis assumes a reduction of the overall electricity consumption requirements by 5%, 10% and 15%. Figure 11 displays the effect of domestic customers' energy efficiency interventions in their respective daily load profile through energy reduction.

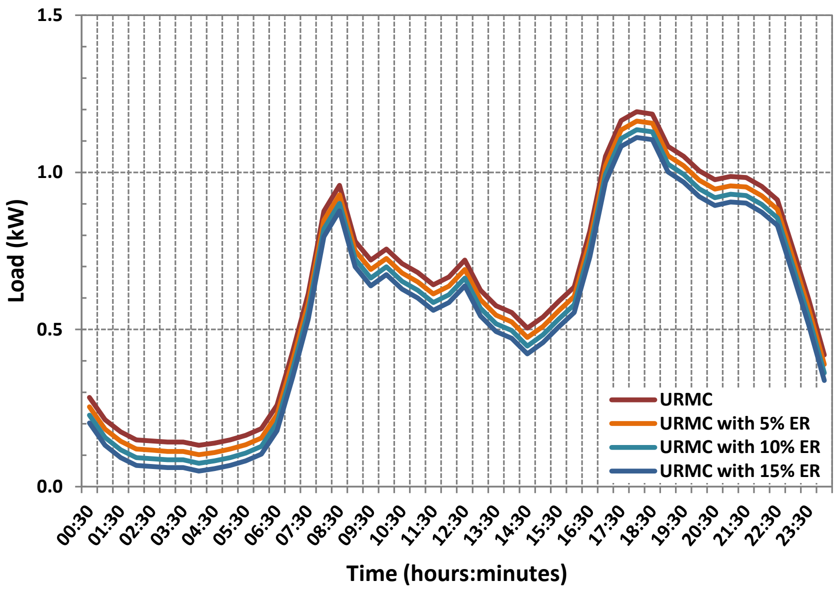
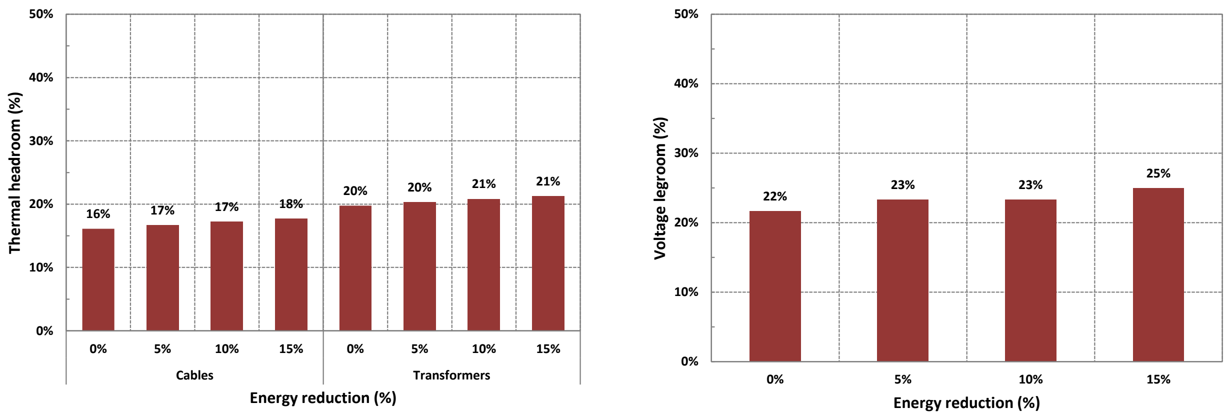


Figure 11 Energy reduction (ER) in domestic customers' load

Figure 12 provides the minimum levels of headroom and legroom available across the various circuits of the three feeders that form the LV urban distribution network. These levels of headroom and legroom are attained for the most overloaded network circuits in a specific half hour time period during winter.



(a) Thermal headroom **(b) Voltage legroom**

Figure 12 Effect of domestic customers' energy reduction in LV network performance

Figure 12a indicates that domestic customers' energy efficiency interventions resulting in an overall energy reduction, marginally increase the level of thermal headroom of cables and of the transformer at the substation under consideration. It is observed a 2% release of the thermal headroom of cables and a 1% release of the thermal headroom of transformers. This marginal improvement in thermal headroom is driven by the limited reduction in peak demand achieved through an overall energy reduction as demonstrated in Figure 11. Correspondingly, Figure 12b suggests a limited increase of voltage legroom of the order of 3% for the 15% energy reduction case.

Summary of the impact domestic energy efficiency interventions in LV network performance

This subsection establishes a comparison of the impact of the of different domestic energy efficiency interventions in the operation and management of the example LV urban distribution network. The comparison presents the net effect of the domestic energy efficiency interventions on the thermal headroom of assets and on voltage legroom. The net effect of the energy efficiency interventions on the distribution network performance corresponds to the difference observed in headroom or legroom with and without energy efficiency interventions. As a result, a positive net headroom or legroom indicates that energy efficiency interventions release headroom whilst a negative net headroom or legroom specifies that energy efficiency interventions increase the loading of the assets. Table 6 presents the comparison of the impact of the different domestic energy efficiency interventions in the operation and management of the LV urban distribution network.

Table 6 Net circuit headroom and legroom for the LV network

Case	Intervention	Net thermal headroom		Net voltage legroom
		Cables	Transformers	
5%	Peak reduction	1%	1%	1%
	Energy shift	1%	1%	1%
	Energy reduction	1%	0%	1%
10%	Peak reduction	2%	2%	3%
	Energy shift	3%	2%	3%
	Energy reduction	1%	1%	1%
15%	Peak reduction	4%	3%	6%
	Energy shift	4%	3%	6%
	Energy reduction	2%	1%	3%

It can be seen in Table 6 that domestic customer driven energy efficiency interventions result in positive net thermal headroom and voltage legroom. Consequently, the uptake of energy efficiency measures supports network constraint management and operation by decreasing the thermal utilisation of circuits and decreasing the voltage drop. It can also be seen in Table 6 that the energy efficiency interventions have a greater impact in decreasing voltage drop compared to decreasing the thermal utilisation of circuits. In LV radial distribution networks, voltage drop is a localised issue generally occurring in the load consumptions points further away from the network substation. Thus, decreasing domestic load consumption at these localised points generally improves the voltage drop. In contrast, the thermal utilisation of circuits (e.g. main feeders) is usually a wider network issue. In order to decrease the overall utilisation of the feeder, in particular closer to the substation, it requires a greater number of domestic customers to take on energy efficiency measures. If the uptake of energy efficiency measures by domestic customers is at the 30% level then the overall effect on main feeder utilisation will be marginal. For instance, for 15% peak reduction, energy efficiency measures by domestic consumers increases the thermal headroom of cables by 4% whilst the voltage legroom increases by 6%.

It can be observed in Table 6 that the impacts of energy efficiency interventions that result in peak reduction and energy shift have the same impact. For example, for 15% peak reduction and 15% energy shift cases the thermal legroom of cables increases by 4% in both cases while the voltage legroom increases by 6% also in both cases. These impacts are mostly driven by the magnitude of peak load that has been reduced through the energy efficiency interventions applied. Based on the levels of peak reduction and energy shift assumed for this analysis, Figure 7 and Figure 8 show that the impact in reducing peak load is similar which in turn translates in a similar impact in thermal headroom and voltage legroom under the different cases of Table 6. The NMT is aligned with the UK distribution network planning and design standards that consider conditions of peak demand to evaluate the need for headroom in distribution networks rather than energy demand requirements. Hence the ability to reduce peak load drives the levels of distribution network headroom and leg room.

Furthermore, Table 6 shows that the headroom and legroom benefits associated with energy reduction interventions are lower than those achieved through peak reduction and energy shift. For instance, for a 15% energy reduction the thermal headroom of cables increases by 2% whist for the 15% peak reduction and 15% energy shift interventions the thermal headroom of cables increases by 4%. Similar behaviour is observed for voltage legroom. This is driven by the more limited ability of the energy reduction intervention in reducing peak load (i.e. Figure 11) when compared with the peak reduction and energy shift interventions as demonstrated in Figure 7 and Figure 8.

The uptake of energy efficiency measures by domestic customers was observed to support the LV network by releasing thermal headroom of circuits and simultaneously releasing voltage legroom. The effect of these energy efficiency interventions can assist network operators in: managing network constraints in operational timescales by relieving congestion in distribution substations as well as relieve thermal and/or voltage constrained power transfer problems; and facilitate outage management and enhance quality and security of supply to critical load customers. Potentially it can also support network planners in avoiding or deferring network investment.

4.3.3 Energy efficiency interventions to manage distribution network constraints

This subsection investigates the effectiveness of domestic energy efficiency interventions in managing thermal and voltage constraints in the example LV urban distribution network. Here, we simulate a network constraint by scaling up customer demands. As in the previous section, the effectiveness of the interventions is quantified by establishing a comparison between the levels of thermal headroom and voltage legroom achieved in cases with energy efficiency measures against cases without energy efficiency. The assessment considers that domestic energy efficiency interventions are deployed to support network constraint management in three distinct ways: (i) relieve thermal constraints in the transformer of the substation; (ii) relieve thermal constrained power transfer problems in circuits; and (iii) relieve voltage constrained power transfer problems. The assessment assumes that the uptake of energy efficiency measures from domestic customers shapes their load curve by reducing peak load only.

Thermal constraint management of substation transformers

In order to create a network thermal constraint on the substation transformer, the annual electricity consumption of all domestic customers of URMC type was increased by 40% from its original value. Under these conditions, the substation transformer becomes overloaded with a loading 3% above of its nominal rating. Subsequently, domestic customers' energy efficiency interventions are deployed with the intent of relieving this thermal constraint. In agreement with Subsection 4.3.2, the analysis assumes that 30% of the total number of domestic customers present in the network engage in energy efficiency interventions. These customers have been distributed accordingly across the three feeders in the example LV network.

Figure 13 shows the levels thermal of headroom available on the transformer of the substation under different levels of domestic energy efficiency resulting in peak load reduction.

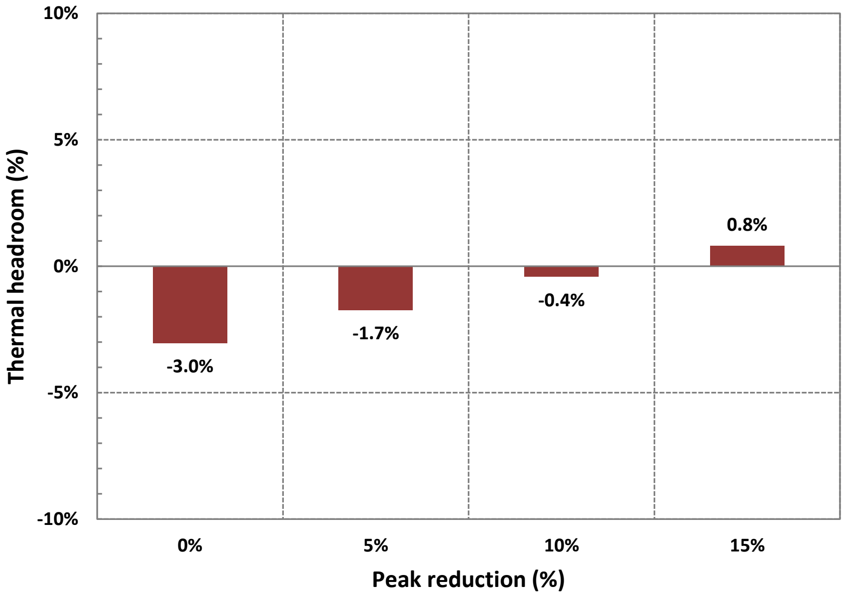


Figure 13 Thermal headroom of the substation transformer

It can be seen in Figure 13 that without energy efficiency interventions from the domestic customers the transformer at the substation is overloaded and therefore represented by a negative thermal headroom of 3%. It can be observed that the deployment of energy efficiency interventions from domestic customers leading to a reduction of the peak load of their daily electricity consumption increases the level of thermal headroom of the transformer at the substation. The thermal headroom ranges from a negative level of 1.7% (i.e. overloaded) for 5% peak reduction to a positive level of 0.8% (i.e. loaded below the nominal rating) for 15% peak reduction.

Figure 13 indicates that energy efficiency interventions from the domestic customers may be an efficient way to managing network thermal constraints in operational timescales by relieving congestion in distribution substations.

Thermal constraint management of network feeders

A network thermal constraint was created in the network cable with the highest utilisation by increasing the annual electricity consumption of all domestic customers of URMC type present in the particular feeder under consideration. The most utilised cable was located in feeder 3 (see Figure 6) connecting the substation to immediately adjacent load points (Circuit 6 in Table 4). As a consequence of this thermal constraint, the cable becomes overloaded with a loading 1% above of its nominal rating.

Figure 14 depicts the levels thermal of headroom available on this particular cable of feeder 3 under different levels of domestic energy efficiency leading to peak load reduction.

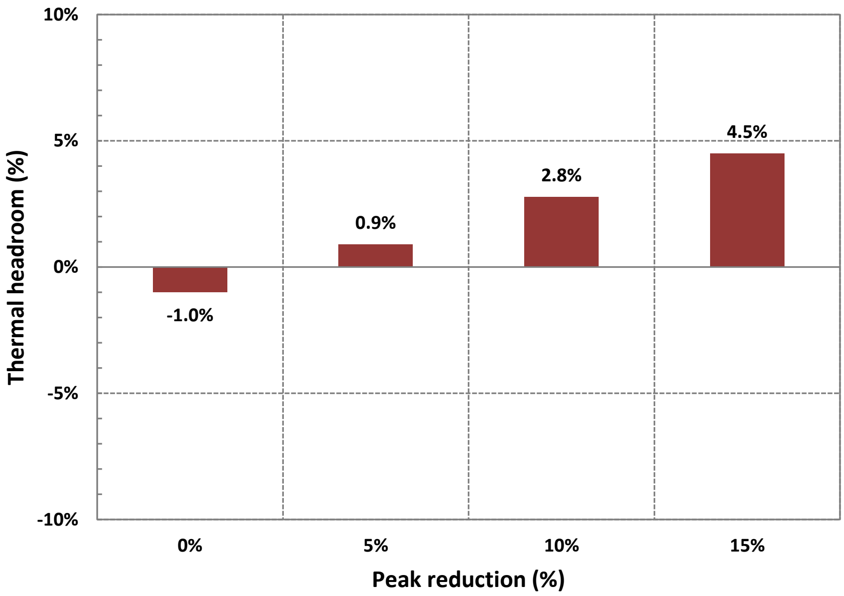


Figure 14 Thermal headroom of network feeders

It can be seen in Figure 14 that without energy efficiency interventions from the domestic customers the network circuit under consideration is overloaded and therefore represented by a negative thermal headroom of 1%. Domestic customers' energy efficiency interventions are observed to relieve thermal constrained power transfer in the circuit under analysis by increasing the level of thermal headroom available. Figure 14 shows the thermal headroom of the circuit becomes positive and equal to a 0.9% (i.e. loaded below the nominal rating) for a relatively small level of 5% peak reduction. Additional gains in thermal headroom are seen to occur as domestic customers become more engaged in energy efficiency activities.

Voltage constraint management

The section of the LV network with the highest voltage drop was identified and the annual electricity consumption of the local cluster of domestic customers was increased. This procedure creates a network constraint characterised by a voltage drop over the 6% design limit. The network circuit with the highest voltage drop is located feeder 1 (see Figure 6) and is the furthest circuit (Circuit 16 in Table 5) away from the substation (i.e. ≈520m) for the LV network under analysis.

Figure 15 displays the voltage headroom available on this particular circuit of feeder 1 under different levels of domestic energy efficiency causing peak load reduction.

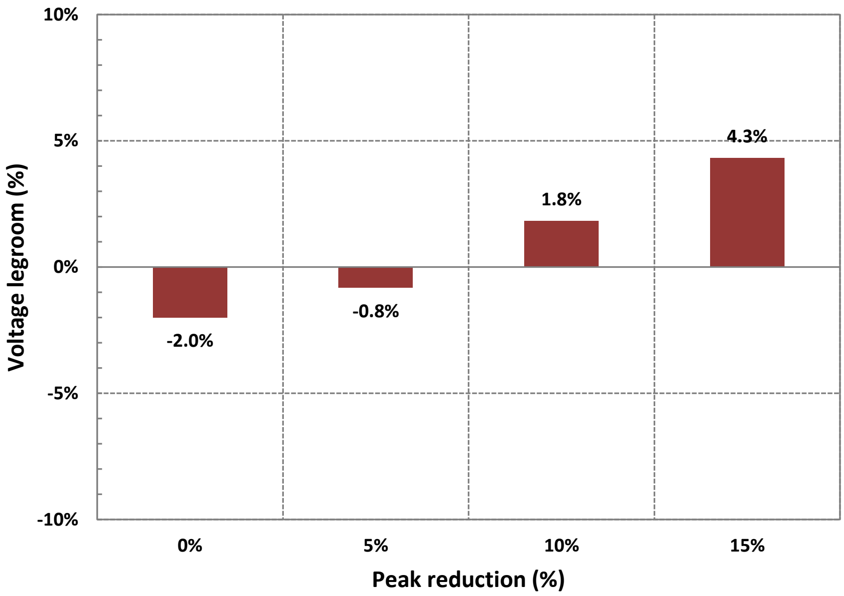


Figure 15 **Voltage legroom of network feeders**

It is observed in Figure 14 that without energy efficiency interventions from the domestic customers the voltage drops over the design limit results in a negative voltage legroom of 2%. Domestic customers' energy efficiency interventions are observed to reduce the voltage drop. The uptake of energy efficiency interventions from domestic customers contributes to maintain network voltage within the limits as the voltage legroom rises from -0.8% for 5% peak reduction to 4.3% for 15% peak reduction.

Energy efficiency interventions from the domestic customers may be an efficient way to manage network voltage constraints in operational timescales by reducing the level of voltage drop in distribution networks.

4.4 Low Voltage Rural Electricity Distribution Network

This subsection applies the NMT to an example LV rural electricity distribution network in the SEPD licence area, providing a high level assessment of the impact of different domestic energy efficiency interventions in network operation and management. The analysis assumes that the uptake of energy efficiency measures from domestic customers shapes their load curve in one of the three possible ways: (i) peak reduction; (ii) energy time-shifting; and (iii) energy reduction. The subsection will demonstrate some of the technical functional features of the NMT and their respective application to real electricity distribution networks.

4.4.1 Overview of the LV network characteristics and structure

The example LV network is a 3 phase, overhead rural network. It is supplied through an 11/0.4kV, 100kVA pole mounted transformer serving approximately 28 domestic customers through a single main outgoing feeder. This feeder is subsequently split in two main circuits. One of the circuits has a total length of 343m serving 22 customers whilst the other circuit has a total length of 181m supplying 6 customers. The load curve of customers' electricity consumption used in the analysis is extracted from ACE Report No. 49 standard for design of LV radial distribution networks and, is representative of an average domestic customer of URMC type. Figure 16 displays the schematic representation of the LV rural electricity distribution network used in the application of NMT and associated analysis.

Figure 16 Schematic representation of the LV rural electricity distribution network

4.4.2 Overview of the LV network performance

This subsection illustrates the impact of the different domestic energy efficiency interventions in the operation and management of the example LV rural distribution network. The impact is measured through the changes observed in the levels of thermal headroom of assets and on voltage legroom created by the introduction of energy efficiency measures. The analysis assumes that 30% of the total number of domestic customers present in the network engage in energy efficiency interventions. These customers have been distributed accordingly across the main outgoing feeder in the example LV network. Table 7 presents the impact of the different domestic energy efficiency interventions in the operation and management of the LV urban distribution network. The minimum levels of headroom and legroom available across the circuits of the single feeder of the LV rural distribution network are presented for the purpose of this analysis.

Table 7 Effect of domestic customers' energy efficiency interventions in thermal headroom and voltage legroom for the LV network

Intervention	Case	Thermal headroom		Voltage legroom
		Lines	Transformers	
Peak reduction	0%	80.3%	61.9%	76.7%
	5%	80.5%	62.5%	78.3%
	10%	80.7%	63.0%	78.3%
	15%	81.0%	63.5%	78.3%
Energy shift	0%	80.3%	61.9%	76.7%
	5%	80.5%	62.5%	78.3%
	10%	80.7%	63.0%	78.3%
	15%	81.0%	63.5%	78.3%
Energy reduction	0%	80.3%	61.9%	76.7%
	5%	80.4%	62.2%	78.3%
	10%	80.5%	62.4%	78.3%
	15%	80.7%	62.7%	78.3%

It can be seen in Table 7 that domestic customer driven energy efficiency interventions have a positive, however, limited impact in releasing thermal headroom and voltage legroom of network circuits. For example, it is seen in Table 7 that as domestic customers become more engaged in energy efficiency activities that lead to peak reduction, the thermal headroom of the substation transformer increases from 61.9% without energy efficiency interventions to 63.5% with energy efficiency interventions that result in a 15% peak reduction. A similar trend is observed for interventions leading to energy shift and energy reduction.

It can be observed in Table 7 the thermal headroom and voltage legroom available in this LV rural network are relatively high. Without energy efficiency interventions the 80.3% and 61.9% thermal headroom of overhead lines and transformers respectively, translate in relatively low circuit utilisations. Regarding voltage, the level of legroom is estimated to be 76.7% resulting in a low voltage drop of the magnitude of 1.4%. In this context, the deployment of domestic customers' energy efficiency innervations in an already non-constrained network will have a limited impact in further releasing network headroom.

4.5 Conclusions

This section applied the preliminary version of the NMT to quantify and assess the impact of different domestic customers' energy efficiency interventions in the operation and management of two example (i.e. urban and rural) electricity distribution networks in the SEPD licence area. Furthermore, the section demonstrated some of the technical functional features of the NMT and their respective application to real distribution networks.

The analyses performed assumed that the uptake of energy efficiency measures from domestic customers shapes their load curve in one of the three possible ways: (i) peak reduction; (ii) energy time-shifting; and (iii) energy reduction. The analyses then demonstrated the effectiveness of the energy efficiency interventions in relieving thermal constraints in the transformer of the substation, relieving thermal constrained power transfer problems in network circuits and relieving voltage constrained power transfer problems. The key findings of the illustrative analyses can be summarised as follows:

- The effect of domestic customers' energy efficiency interventions in the operation and management of distribution networks can be captured in a consistent manner through the concept of 'headroom' (e.g. thermal, voltage, fault level, power quality).

- In the example LV urban distribution network without energy efficiency interventions, the thermal headroom of feeders and transformers and voltage legroom are relatively low (i.e. around 15% to 20%) but are within the nominal rating limits of the assets was within the voltage statutory limits respectively.

- The network circuits with the lowest levels of thermal headroom (i.e. highest loading) correspond to ‘main’ circuit cables whilst the lowest levels of voltage legroom (i.e. highest levels of voltage drop) are present in the ‘tapered’ circuit cables.

- Energy efficiency interventions from domestic customers leading to: reduction of customers’ peak load, time-shifting of customers’ load (i.e. from peak to off-peak) and energy reduction customers’ load (i.e. overall daily load reduction), contribute to increase the level of thermal headroom of cables and substation transformers and the level of voltage legroom.

- The magnitude of thermal headroom released in ‘main’ circuit cables (i.e. feeders) and substation transformers is broadly driven by the total number of individual domestic customers engaged in up taking energy efficiency measures and their ability to reduce load during peak load periods. The magnitude of voltage legroom released also depends on the location of the deployment of energy efficiency measures with respect to the location of voltage drop issues.

- Energy efficiency interventions that shape the use of electricity consumption of domestic customers can reduce the utilisation of the network assets and the magnitude of the voltage drop in circuits, benefiting network operation and network investment planning.

- The distribution network constraint analysis indicated that the uptake of energy efficiency measures by domestic customers can assist network operators in: managing network constraints in operational timescales by relieving congestion in distribution substations as well as relieve thermal and/or voltage constrained power transfer problems; and facilitate outage management and enhance quality and security of supply to critical load customers.

- In the LV rural distribution network without energy efficiency interventions, the thermal headroom of feeders and transformers and voltage legroom are relatively high (i.e. around 60% to 80%) resulting in low circuit utilisation and voltage drops. In this context, domestic customers’ energy efficiency innervations are observed to have a limited impact in further releasing network headroom.

4.6 Further work

The NMT will be developed throughout the SAVE project lifecycle. The timing of the formal deliverables is as follows:

- **SDRC 7.2:** Produce updated report, December 2016; and
- **SDRC 7.3:** Produce final report and host a workshop demonstrating the tool, June 2018.

5. Conclusions

A number of real-world customer field trials will be completed as part of the SAVE project to assess the effectiveness of four specific energy efficiency interventions in reducing and/or time-shifting demand for electricity in domestic households, i.e. (i) LED installation; (ii) data-informed engagement campaign; (iii) DNO price signals direct to customers plus data-informed engagement; and (iv) community coaching. Since the trials are currently being set up, customer and/or community behaviour data in response to energy efficiency intervention is not presently available. Accordingly, and for illustrative purposes only, this report assumes that domestic energy efficiency interventions will shape customers' load in in one of the three possible ways: (i) peak reduction; (ii) energy time-shifting; and (iii) energy reduction.

Network analyses were completed to demonstrate the effectiveness of the energy efficiency interventions in relieving thermal constraints in the substation transformers, relieving thermal constrained power transfer problems in network circuits and relieving voltage constrained power transfer problems. The network analyses were performed with the preliminary version of the NMT on two example (i.e. urban and rural) real electricity distribution network of the SEPD licence area. The network analyses were also used to demonstrate some of the technical functional features of the NMT and their respective application to real distribution networks.

The key findings of the analyses can be summarised as follows:

C1. The effect of domestic customers' energy efficiency interventions in the operation and management of distribution networks can be captured in a consistent manner through the concept of 'headroom' (e.g. thermal, voltage, fault level, power quality, etc.).

C2. In the LV urban distribution network without energy efficiency interventions, the thermal headroom of feeders and transformers and voltage legroom are relatively low (i.e. around 15% to 20%) but are within the nominal rating limits of the assets and within the voltage statutory limits respectively.

C3. The network circuits with the lowest levels of thermal headroom (i.e. highest loading) correspond to 'main' circuit cables whilst the lowest levels of voltage legroom (i.e. highest levels of voltage drop) are present in the 'tapered' circuit cables.

C4. Energy efficiency interventions from domestic customers leading to: reduction of customers' peak load, time-shifting of customers' load (i.e. from peak to off-peak) and energy reduction of customers' load (i.e. overall daily load reduction), contribute to increase the level of thermal headroom of cables and substation transformers and the level of voltage legroom.

C5. The magnitude of thermal headroom released in 'main' circuit cables (i.e. feeders) and substation transformers is broadly driven by the total number of individual domestic customers engaged in up taking energy efficiency measures and their ability to reduce load during peak load periods. The magnitude of voltage legroom released also depends on the location of the deployment of energy efficiency measures with respect to the location of voltage drop issues.

C6. Energy efficiency interventions that shape the use of electricity consumption of domestic customers can reduce the utilisation of the network assets and the magnitude of the voltage drop in circuits, benefiting network operation and network investment planning.

C7. The distribution network constraint analysis indicated that the uptake of energy efficiency measures by domestic customers can assist network operators in: managing network constraints in operational timescales by relieving congestion in distribution substations as well as relief thermal and/or voltage constrained power transfer problems; and facilitate outage management and enhance quality and security of supply to critical load customers.

C8. In the LV rural distribution network without energy efficiency interventions, the thermal headroom of feeders and transformers and voltage legroom are relatively high (i.e. around 60% to 80%) resulting in low circuit utilisation and voltage drops. In this context, domestic customers' energy efficiency innervations are observed to have a limited impact in further releasing network headroom.

C9. The functional requirements for and associated outputs from the initial NMT meet the requirements for SDRC deliverable 7.1 as outlined in the Project Direction for the SAVE project.