The University of Manchester

*Title:* **Deliverable 3.4.3 "Report on the Carbon Impact Implications of the Smart Street Method at ENWL and Great Britain Scale"**

*Synopsis:* This is the Final Report for the carbon accounting task in WP3 of the Smart Street project. The University of Manchester has applied a comprehensive life cycle assessment method to determine the net carbon impact of Smart Street interventions. The methodology for the assessment, including goal and scope, is provided for the purpose of framing the interpretation of results. The study covers changes in greenhouse gas emissions associated with the operation of electricity networks (network assets and energy losses) and reducing customer energy consumption through Smart Street. Findings that highlight the effect of Smart Street interventions for carbon emissions savings on the HV and LV trial networks in the study are reported. The effects of energy system scenario assumptions are assessed. The results from the carbon impact assessments of the HV and LV networks are scaled to Electricity North West distribution network area and Great Britain as a whole to determine the potential macro implications of the Smart Street Method.

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# Executive Summary

This document is the final report on the carbon impact of the Smart Street (SS) methods project and corresponds to Deliverable D3.4.3 of Work Package (WP) 3 “Cost Benefit Analysis and Business Case” of the SS project run by Electricity North West Limited (ENWL).

This report presents findings on the potential carbon savings of the SS method relative to a business as usual (BAU) counterfactual. This includes how SS interventions effect traditional network reinforcement and operation in response to the uptake of low carbon technologies (LCTs) and how customer energy consumption is reduced through the method. The analysis is based on modelling outputs from the techno-economic assessment of the SS method on representative HV and LV trial networks. The results of the carbon impact assessment for the trial networks are used to inform understanding of the implications of SS methods for reducing greenhouse gas (GHG) emissions (referred to here also as carbon reduction) at distribution network operator (DNO) regional level and for Great Britain (GB) as a whole.

This report presents the life cycle assessment (LCA) methodology applied for the carbon impact assessment. The scope of the study includes life cycle GHG emissions relating to operating the networks over a 2016 to 2060 timeframe, including change in network assets, energy losses and customer energy use. The goal and scope of the study and relevant system boundaries are presented, as is an overview of the life cycle GHG emissions data that is used. This report follows the Second Interim Report on Carbon Accounting for SS, which provides more detailed system boundary definitions and full life cycle inventory (LCI) data. This report does however provide updated assumptions on maintenance and reuse of network assets and summary contribution analysis of the assets and LCI and impact assessment for capacitors. The results of the carbon impact assessment for the trial networks under a range of LCT uptake scenarios based on National Grid Future Energy System scenarios are presented. These results are used to determine the potential carbon saving potential for rural, urban and dense urban network types and for HV or LV focused SS method application. Three SS methods are assessed; the use of on-load tap changers (OLTC); OLTC combined with capacitor banks; OLTC, capacitor banks and meshed interconnection between networks. The emissions savings for representative networks are then used to inform an assessment of the potential carbon impact implications of SS solutions at DNO and GB scale.

The report finds that SS methods deliver net reductions in life cycle GHG emissions for the HV and LV trial networks. Absolute GHG reductions, compared to the baseline no-SS method case, in each of the demand and grid emissions scenarios are primarily attributed to reduced customer energy consumption and, to a lesser extent, by reduced energy losses. The trial results show minimal deferred or avoided traditional network reinforcement between SS method and BAU cases, therefore they are not a significant contributor to network carbon impacts.

In terms of the carbon impacts of the electricity networks themselves (network assets and operational losses), OLTC and meshing provide emissions savings at HV and LV level. Emissions saved through reduced network losses offset the emissions associated with installing the OLTC at HV and LV and the WEEZAP and Lynx devices for LV network meshing. Capacitor banks, as they perform in the SS model, do not provide savings through network energy loss reduction that are sufficient to offset the upstream carbon emissions of the assets. In some of the trial networks capacitor banks contribute to net increase in network carbon emissions compared to the non-SS counterfactual.

At the wider system level, the carbon emissions savings from reduced consumer energy consumption are substantial, and for no trial network or scenario are asset carbon emissions >3% of the carbon savings from reduced consumption. As customer energy reduction is achieved principally through the OLTC, there is minimal variation between the SS inventions in terms of overall net carbon impact. The SS solutions therefore reduced emissions at the HV level by between 4% and 5 %, depending on the network type and energy scenario. With SS implemented at the LV level instead of the HV, emissions savings in the range of 7% to 10% across the trial networks are seen.

By taking the proportional greenhouse gas emissions savings for the trial networks as indicative of ENW or GB networks as a whole, and assuming immediate SS role out across every network, it is possible to

infer the potential carbon impact of SS solutions at the DNO and national scale. For HV level SS solutions within the ENWL DNO area emissions savings of between 5 $MtCO_2e$ to 8 $MtCO_2e$ over the 2016 to 2060 timeframe may be possible under varying rates of electricity grid decarbonisation and LCT uptake, translating to between 64 $MtCO_2e$ and 101 $MtCO_2e$ at GB scale. For the LV interventions, assuming high and low cases to account for the range in proportional savings, as much as 17 $MtCO_2e$ may be avoided within ENW's region and 214 $MtCO_2e$ at GB, assuming some level of grid decarbonisation. These figures are illustrative, and there is increasing uncertainty as the scaling of the trial networks up to ENW and GB introduces greater heterogeneity in network topographies, customer numbers and type. However they do highlight that energy savings through SS solutions can offer significant carbon savings compared to the business as usual case.

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# Abbreviations

| Acronym | Full Name |
|---|---|
| BAU | Business as Usual |
| CLCA | Consequential Life Cycle Assessment |
| $CO_2$ | Carbon Dioxide |
| $CO_2e$ | Carbon Dioxide Equivalent |
| CVR | Conservative Voltage Reduction |
| DNO | Distribution Network Operator |
| ENWL | Electricity North West Limited |
| EV | Electric Vehicle |
| GHG | Greenhouse Gas |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LTC | Low Carbon Technology |
| OLTC | On-Load Tap-Changer |
| PV | Photovoltaics |
| SS | Smart Street |
| WP | Work Package |

# 1 Introduction

Smart Street (SS) provides a new way to enable electricity distribution networks to operate reliably and safely in the context of significant changes in electricity loads (from electric vehicles and heaters), and distributed generation, (such as PV). SS also aims to implement new measures that will reduce the overall carbon impact of operating networks. Business as usual operation (BAU) of networks in this changing environment implies traditional network reinforcement options (e.g. cable and transformer replacement) and increased operational energy losses in lines and transformers. Reinforcement and energy losses have associated greenhouse gas (GHG) impacts that should be considered when evaluating the overall GHG savings of energy provision at a network level. Smart Street (SS) aims to reduce these impacts by enabling the same expanded network provision as traditional reinforcement with lower GHG impact network assets. The application of Conservation Voltage Reduction (CVR) and optimisation techniques introduce new assets to the network including on load tap changers (OLTCs), switching capacitors and switching tie lines. Both SS and traditional reinforcement will affect network GHG emissions through the assets that are added to the network and changes in energy losses and potentially over energy consumption. Carbon accounting is a process for GHG emissions so that projects, products, nations and organisations can compare, manage and reduce their contribution to climate change. The carbon accounting approach used in this study applies the methods of consequential life cycle assessment (LCA) to compare the net change in GHG emissions for the network between traditional network management and SS approaches. Ultimately it will allow a comprehensive evaluation of the net carbon savings from SS when additional network assets and operation network emissions are accounted for.

The report presents the findings from the life cycle assessment (LCA), showing the net GHG emissions ($CO_2e$) savings for the trial networks with SS and BAU operation of the network. This analysis is applied to three variations of the SS method, combining on-load tap changers, existing capacitors and network meshing. These solutions are applied to rural, urban and dense urban HV and LV network types and in four energy scenario contexts. The analysis is based on modelling of the trial networks for each SS and BAU assumption under the varying scenario conditions over the 2016 to 2060 timeframe are documented in the WP3 techno-economics report. Comprehensive assessments of the net carbon impact of the SS methods in the trial networks, under the different scenario, are presented. Extrapolations of these results to inform an understanding of the carbon impact of SS methods across the ENW network and GB as a whole are discussed.

The report is structured as follows:

- Section 2 provides an overview of the LCA approach being employed in the SS carbon accounting. It reiterates the key goal and scope considerations and the consequential methodological approach that is being utilised. The assessment for capacitors included in the analysis is presented. It also reviews changes to the scope since the Second Interim Report on Carbon Accounting for SS.

- Section 3 presents the results from the SS carbon impact assessment. The results for the HV trial networks are given, followed by the results for SS applied to LV networks. Scaling to ENW area and GB is discussed, limitations of the study and areas of future work.

- Section 4 gives the conclusions from the analysis.

# 2 Methodology

This section describes the methodology applied to calculate the carbon impact of the SS network trials. The framework for the method is provided to facilitate clear interpretation of the results. It explains the LCA approach and sets out the goal, scope and system boundary descriptions that inform the study. A more detailed discussion of the methodology is available in "Deliverable 3.4.1: Interim Report on Carbon Accounting". This section also includes the life cycle GHG emission values used in the analysis to calculate the carbon impacts of network assets, energy losses and reduced customer energy use. The impact assessment results and composition analysis of the sources of emissions are reported here as they are relevant to the interpretation of the carbon impact assessment. This is includes data used to calculate the upstream emissions of capacitor banks. Further information on how the impact assessment was carried out for the network assets and GHG emissions associate with electricity losses is provided in "Deliverable 3.4.2: Second Interim Report on Carbon Accounting". The assumptions pertaining to exogenous factors (electricity demand, LCT uptake and electricity grid mix) are described in the scenario outline sections. Relevant information of the trial networks and how they are referenced in the results section of the report are also provided.

## 2.1 Life Cycle Assessment

The carbon impact assessment approach is based on LCA methods, which are formalised in the International Organisation of Standardization ISO14040 [1] and ISO14044[2] guidelines and principles. LCA is a holistic method for determining the environmental impact of a product or process. It quantifies the totality of environmental burdens and benefits of a given unit of analysis, accounting for transactions to and from the environment associated with the provision of the unit, from the extraction of raw material inputs, through manufacture, operational usage to final disposal. The holistic nature of LCA makes it a suitable tool for comparing low carbon interventions that may result in diverse impacts across the product or process life cycle. In the case of SS there are three potential sources of GHG impacts on the electricity distribution network from different life cycle stages to account for; the embodied $CO_2$ in network assets (including cables, transformers and SS assets) from their manufacture through to deployment, essential operation and maintenance requirements; changes in operational energy losses from the network; changes in customer energy demand. To assess the net impact of SS on the network a LCA method suitable for accounting for consequential changes in the electricity system, specifically changes to network distribution losses and customer demand, is required. In a typical 'attributional' form of LCA, the boundary of analysis is limited to direct impacts from the product being studied [3]. Therefore a consequential LCA that enables system expansion to incorporate relevant direct and indirect changes in adjacent products or process arising from the addition of a new product or function is needed [4]. The key implication of the CLCA approach is that the results of the impacts assessment represent the net change in GHG emissions for the networks compared to a baseline reference case with no SS interventions. This is important for the interpretation of results as it means they are contingent upon scenario assumptions about changes in the system (in this case, the electricity distribution network and grid system) [5]. The method does however allow for a comprehensive assessment, accounting for net change in network GHG emissions to inform an understanding of the carbon impact of SS interventions.

## 2.2 Goal and Scope

The goal of the LCA for the SS carbon impact assessment is to facilitate comprehensive carbon accounting of the SS method so that uncertain and potentially rapid LCT uptake can be managed in a low carbon way. As a consequential assessment the results are relative to a baseline, BAU case for the given network, rather than an absolute, stand-alone projection for the given network. There are multiple GHGs responsible for anthropogenic global warming including; carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), halocarbons (CFCs and HCFCs), methane ($CH_4$) and sulphur hexafluoride ($SF_6$). These gases have different heat trapping properties, lifespans in the atmosphere, and interactions with other atmospheric components. $CO_2$ is the dominant driver of climate change [6] to which the effects of other gases are compared and quantified as $CO_2$ equivalent ($CO_2e$) within carbon accounting frameworks. The LCA includes all GHG emissions identified in the impact assessment stage in terms of carbon dioxide equivalent ($CO_2e$) from sources based on the 100 year global warming impact approach in IPCC [7]. Although included in some earlier GHG assessments of electricity network assets, leakage of the high warming impact $SF_6$ (an insulator in electrical switch gear and transformers) is not included in the scope, as it is now managed through EU F-gas directives.The functional unit for the LCA study is the kg$CO_2e$ emissions per electricity network over the time frame of analysis. The timeframe of the analysis is 2016 to 2060.

The scope for the SS CLCA includes traditional reinforcement assets (underground electricity cable, transformers), assets required for SS method interventions (on-load tap changers (OLTC), capacitor banks and switches (WEEZAP, LYNX, Gateway)) and the life cycle $CO_2e$ emissions associated with energy savings from reduced network energy losses and/or reduced customer energy demand through voltage control operation of the distribution network. The study boundary therefore includes energy savings by distribution network customers, and therefore instead of assessing the change in the operational emissions of the network, the wider emissions savings for the electricity system are considered. The scope is restricted to first order impacts. It is presumed that customers receive the same energy services through the network, and perhaps will see reduced electricity bills as a consequence of reduced energy inputs to provide these services. Rebounds from these financial savings have not been studied and are not included in this assessment.

The LCA is performed on the three HV distribution networks in the SS trial and a select nine LV networks. This is based on the SS trial networks as modelled in other WPs. Due to the modelling data available HV and LV trial results are not combined to give a single aggregate value within an HV network area. Instead the results show potential emissions savings at HV and LV level and this is used in extrapolations that inform an assessment of overall potential saving at distribution network operator level and GB as a whole.

## 2.3 Smart Street Methods and Scenarios

The three SS interventions are included in this impact assessment are defined as:

a. Installing and operating an OLTC on the network

b. Installing and operating an OLTC and capacitors on the network

c. Installing and operating an OLTC and capacitors on the network and meshing networks together. In the case of LV networks this entails adding Weezap, Lynx and Gateway devices to the network to benefit interconnected networks through meshing.

These assets and their operation enable the SS method to provide a network with increased capacity in response to LCT uptake, lower energy losses in the network and the energy required for electricity services provision through better voltage management. The future impact of SS is likely influenced by assumptions about changes in network load, whether through energy efficiency measures or new distributed generators (such as PV) lowering demand, or LCTs such as heat pumps and electric vehicles increasing overall demand and peak loads. Therefore four scenarios have applied to characterize different potential future outcomes in electricity loads. These scenarios are based on the Future Energy Scenarios produced by National Grid, which have varying outcomes in terms of new electricity loads and generation out to 2050. The assumptions of these scenarios inform the load growth modelling in the WP3 network analysis on which the carbon impact assessment is based.

| Reference | Name | Characteristics |
|---|---|---|
| S1 | Two Degrees | $CO_2$ emissions stay within the Committee on Climate Change's budget for the UK's target to contribute to avoiding >2°C global warming. Electrification of heat and transport increases overall electricity demand by ~10%, but user engagement in demand management mitigates underlying peak demand growth. |
| S2 | Slow Progress | Not compliant with avoiding 2°C of global warming, but with a slow increase in electric vehicles and heating by 2040. Slight increase in underlying peak demand compared with 2016 by 2040. |
| S3 | Steady State | Grid $CO_2$ emissions stay fairly constant from 2015 values, making this the high grid $CO_2$ scenario, with minimal LCT uptake and the change in electricity demand primarily driven by population growth. |
| S4 | Consumer Power | Not compliant with avoiding 2°C of global warming, but with falling grid emissions and a rapid uptake of electric vehicles and heating after 2020 increasing annual demand by 25%. Significant increase in underlying peak demand compared with 2016 primarily due to electric vehicle usage without effective demand management. |

**Table 1: Future Electricity System Scenarios for SS, based on National Grid [8]**

Full information on the scenarios can be found at National Grid [8], and the translation of the scenario assumptions to the trial networks is described in the WP3.3 reports.

The SS methods were applied to HV and LV trial networks that represent dense urban, rural and urban network types.

| Type | Classification | Name | Customers | LV Networks |
|---|---|---|---|---|
| HV | Dense Urban | HV_DU | 10,303 | 49 |
| | Rural | HV_R | 10,214 | 258 |
| | Urban | HV_U | 17,068 | 109 |
| LV | Dense Urban | LV_DU_1 | 149 | 1 |
| | Dense Urban | LV_DU_2 | 116 | 1 |
| | Dense Urban | LV_DU_3 | 382 | 1 |
| | Rural | LV_R_1 | 168 | 1 |
| | Rural | LV_R_2 | 255 | 1 |
| | Rural | LV_R_3 | 340 | 1 |
| | Urban | LV_U_1 | 366 | 1 |
| | Urban | LV_U_2 | 220 | 1 |
| | Urban | LV_U_3 | 301 | 1 |

**Table 2: SS Trial Networks for Carbon Impact Assessment**

The carbon impact assessment LCA was applied to the trial results for the networks in Table 2 for the four future electricity demand scenarios (Table 1) with the SS method interventions applied and with a baseline BAU case.

### 2.3.1 System Boundary

This subsection classifies the system boundaries for the LCA of network assets and the GHG emissions associated with the change in energy losses and demand in the SS trials. The system boundary for the CLCA has two discrete elements. Firstly, the attributional assessment of $CO_2e$ emissions associated with network assets. This includes upstream emissions (raw material extraction through to installation), and maintenance or replacement requirements. Operational phase emissions as a result of energy losses from the assets as part of the network infrastructure are included in the operational network losses provided by the trial results.

Maintenance of additional transformers and the OLTC is included through the reconditioning of oil in the units. It is assumed, following discussion with the network operator that the disposal phase of a product's life cycle is also not included, as is practiced in LCA projects where it is assumed to have minimal impact on the analysis [9]. There is potentially an environmental credit if materials such as metals are recycled from transformers as this often has lower impacts than virgin materials. Such an assumption can be problematic for long lived products such as those in electricity networks, requiring further assumptions about metal production and manufacturing in coming decades. Therefore the disposal phase is not currently included in system boundary of this study. The same boundary is being applied to the traditional reinforcements and the SS intervention cases to ensure consistency.

To value the GHG emissions from energy losses and demand reduced by SS a system boundary comparable to that of the network assets is applied to electricity grid emissions. A system boundary for electricity generated by the grid, as proposed in [10] will be used to account for non-UK territorial GHG emissions associated with electricity generation, including upstream emissions from plant construction and fuel cycle of thermal and renewable generators. In doing so, a more compressive emissions accounting for operational network losses and demand reduction is provided (Figure 1).

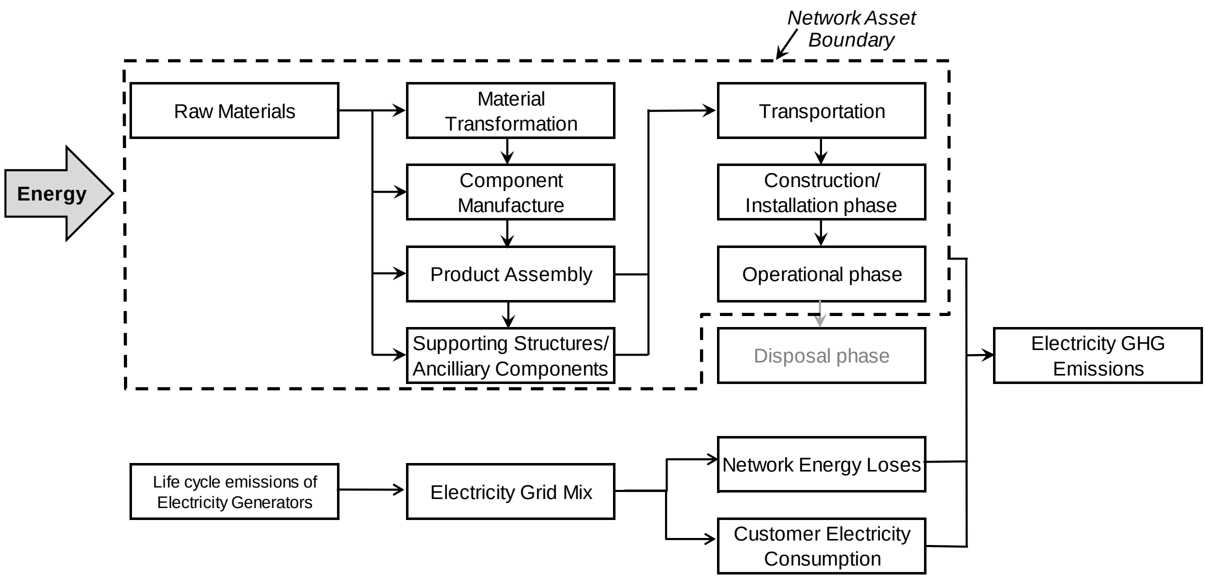


**Figure 1: Representation of Smart Street LCA System Boundary**

The allocation of emissions over time is a key methodological concern for the assessment of long lived assets in ongoing systems such as electricity distribution networks [5; 11]. Without an appropriate approach to the allocation of emissions within the timeframe of analysis, an endlessly recursive time horizon on network change overlapping asset lifetimes [5] is implied. To deal with this issue a temporal allocation approach as demonstrated in [5] is applied to the LCA. As shown in Figure 2, when asset lifetimes exceed the timeframe of analysis, only a proportion of the assets total life cycle GHG emissions are accounted for in the assessment. This enables the LCA to account for different asset life times and investment dates. This approach averages the total emissions of the product over the full assumed lifetime, then proportionally allocates these emissions relative to the period within the timeframe of analysis [5]. For example a hypothetical transformer with a 30year lifespan installed six years prior to the end of the network modelling period, would have 20% of its total lifetime fixed emissions allocated to reflect the period for which it provides a network service within the analysis timeframe.

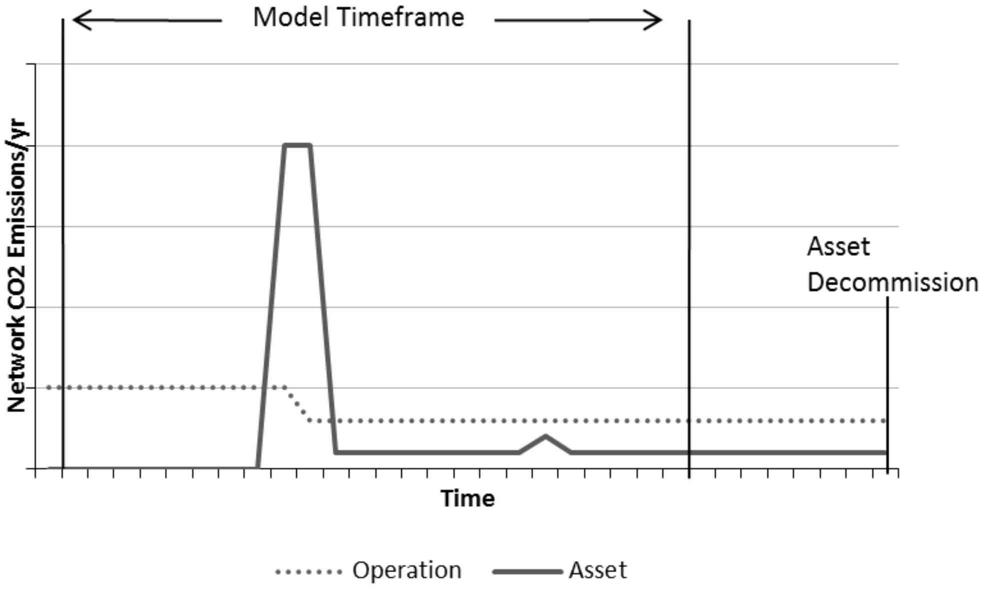


**Figure 2: Graphical Display of Temporal Allocation: For static allocation, asset $CO_2$e emission are averaged over the typical lifespan for the unit then proportionately**

## 2.4 Life Cycle Values

This section provides data on the life cycle GHG emission values used for the network assets and for electricity grid GHG emissions. Further details on the life cycle inventories used can be found in the "Deliverable 3.4.2: Second Interim Report on Carbon Accounting". This includes the material and energy flows into transformer, cable, OLTC, capacitors, Weezap, Lynx and Gateway products and the method for determining life cycle electricity grid emissions.

### 2.4.1 Capacitors

Three types of capacitor bank are considered in the SS trials; HV ground mounded units with switchgears, HV pole mounted units for rural networks and LV ground mounted units. Life cycle inventory data for distribution network capacitor banks is scarce in the literature. The best available data was taken from an LV metal enclosed capacitor environmental performance assessment [12], which provided a mass contribution for this analysis. This data was scaled to the capacitor sizes used in the SS trials. The LV capacitor includes a metal enclosure and is scaled to the ABB 100var 700 series LV capacitor bank. The ground mounted HV capacitor is also metal enclosed and based on the ABB ABBACUS capacitor bank. An exact weight for this capacitor back was identified in available documentation for the product; therefore an estimated value based on the key components in to the unit, of 4,000kg is used. For the HV pole mounted capacitor, the specification of the ABB QPole device is used as the scaling value. It is assumed that the pole mounted capacitor is installed on an existing network pole. Emissions factors used in this study are detailed in "Deliverable 3.4.2: Second Interim Report on Carbon Accounting". Manufacture is assumed to be in Bad Honnef, Germany. A 30 year life span is assumed for the capacitor banks. Replacements of components such as filters might be expected over this period, depending on the utilisation of the capacitor banks, but not included in this assessment.

**Table 3: Summary of cradle to site life cycle GHG emissions for capacitor banks**

| $kgCO_2e$ | LV | HV Ground Mounted | HV Pole Mounted |
|---|---|---|---|
| Energy | 574 | 8,669 | 1,315 |
| Steel | 414 | 6,247 | 948 |
| Aluminium | 109 | 1,640 | 249 |
| Stainless Steel | 8 | 127 | 213 |
| Cables | 46 | 687 | 104 |
| Copper | 23 | 347 | 53 |
| Polypropylene | 11 | 173 | 26 |
| Transport | 3 | 45 | 7 |
| Wood | 2 | 30 | 5 |
| Paper | 1 | 8 | 1 |
| Total | 1,191 | 17,974 | 2,922 |

It is also assumed that the ground mounted HV capacitor banks are deployed with a switchgear. A Lucy VRN2a type switchgear is assumed. A general mass balance for a primary distribution switchgear provided in [13] and scaled to the size of the Lucy switchgear. The assumed lifespan of the switchgear is 15 years.

**Table 4: Summary of cradle to site life cycle GHG emissions for switchgear**

| kgCO2e | Switchgear |
|---|---|
| Energy | 852 |
| Electronics | 746 |
| Steel | 469 |
| Epoxy Resin | 198 |
| Copper | 64 |
| Aluminium | 57 |
| PVC | 13 |
| Transport | 4 |
| Total | 2,403 |

### 2.4.2 Transformers

The LCA value for the transformers is based on inventory data from Turconi et al [14], based on the ABB 50/10 kV (14MVA) transformer and an ABB 10/0.4 kV (335kVA) transformer. A slight variation from the inventory presented in “Deliverable 3.4.2: Second Interim Report on Carbon Accounting” is that re-conditioning/recycling of transformer oil is more fully included. Analysis of the emissions data provided by [15] for transformer oil showed that electricity required to reprocess the oil every five years is included in the life cycle $CO_2e$ value for the product. Additionally transport to and from the ENW oil reprocessing plant in Blackburn from Manchester (as a reference location) by truck was included in the LCA. Overall this had a <0.0001% increase in life cycle emissions for both transformers.

New concrete and steel support pads for the transformers are assumed after ENW advised that new transformers are installed alongside existing assets on new support pads to ensure continuity of supply. This assumption has a significant effect on the emissions assumed for the transformers.

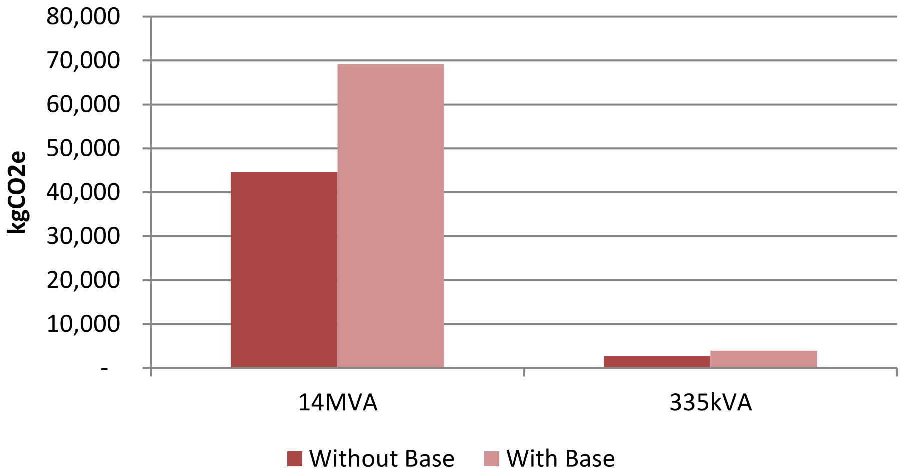


**Figure 3: Comparison of total GHG emissions for transformer types with and without support bases**

The 14MVA transformer is used as a proxy for the transformer upgrade specified in SS WP3 model outputs, for HV requirements. Similarly the 335kV transformer will be used as a proxy for LV network requirements. A 30year lifespan is assumed for each transformer. Key assumptions in the LCI include assembly and shipping from Bad Honnef, Germany with aluminum sourced from Norway, copper from China, oil, steel and pressboard from within Germany. Overall emission data and contribution analysis for the transformers is presented in Figure 4 and Figure 5.

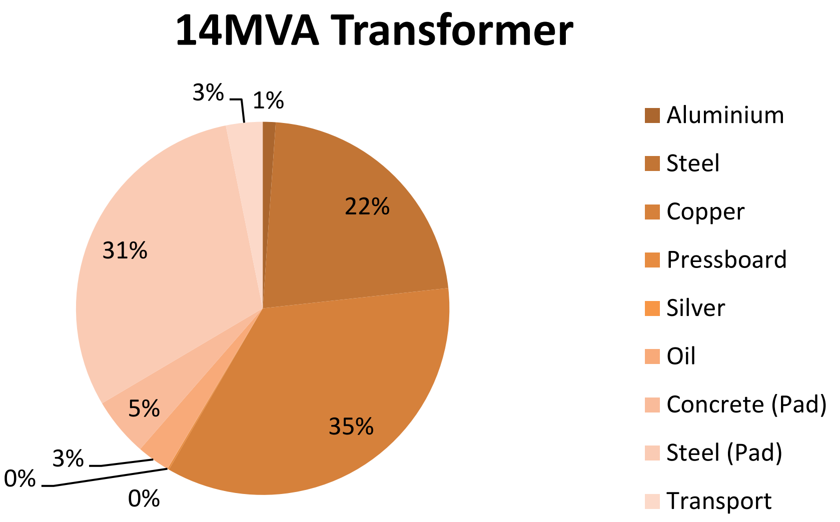


**Figure 4: Contribution Analysis for 14MVA Transformer. Total life cycle GHG emissions of 69,147kgCO₂e**

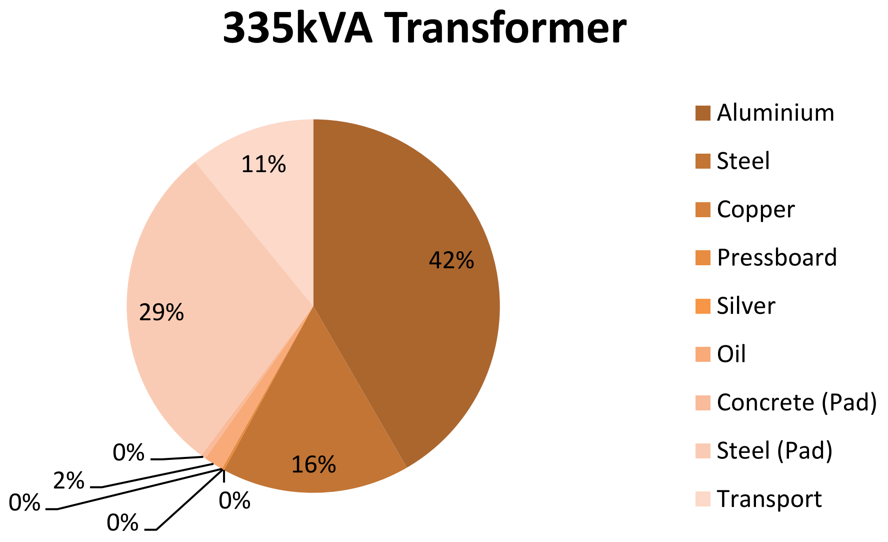


**Figure 5: Contribution Analysis for 335kVA Transformer. Total life cycle GHG emissions of 3,938 kgCO₂e**

### 2.4.3 Cable

The life cycle GHG emission factor for network cables is derived from a bottom up inventory assessment based on the technical cable specification available from cable supplier Nexans [16]. This impact assessment is fully documented in "Deliverable 3.4.2: Second Interim Report on Carbon Accounting". The assessment was carried out for a three core copper 300mm$^2$ cable and a three core copper 175mm$^2$ cable, which reflect the cable types specified in network trial results. The life cycle values are relative to 1km of cable to align with outputs from the SS network modeling work. Emission factors for underground installation are based on previously reported values in the Low Carbon Networks Fund C2C [17] project. Life spans of 80years and 90years for underground and overhead cables respectively are assumed based on Jones and McManus [10].

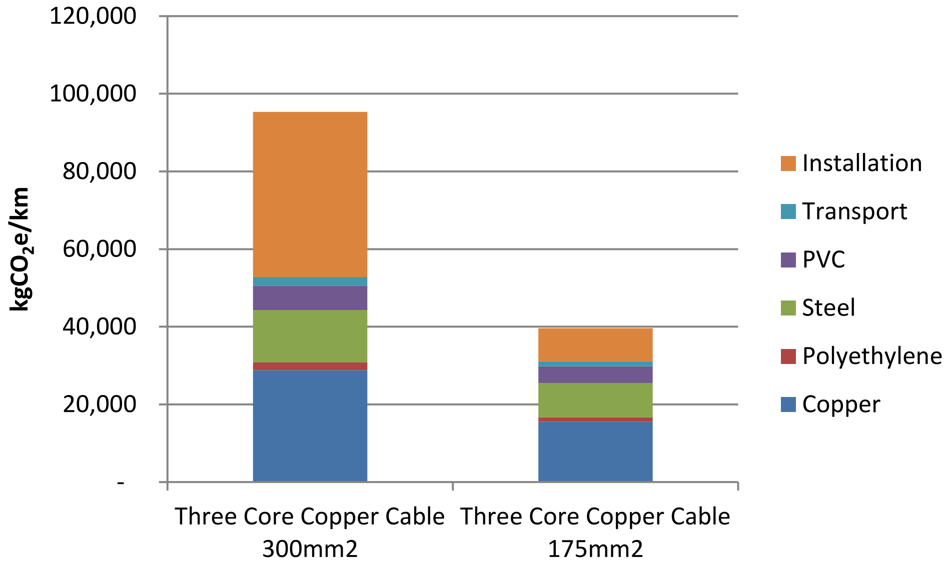


**Figure 6: Composition Analysis for Network Cables. Installation includes excavation, backfill and restoration of subsurface and resurfacing**

### 2.4.4 On-Load Tap-Changer

The life cycle impact assessment for the OLTC was the first such assessment for carbon impact assessments. It is based on the best inventory compiled for SS from the technical specification data for an OLTC model supplied by ABB [18]. The ABB vacuum OLTC VUBB model on which it is based is suitable for transformers up to 100MVA [18]. This value is used for HV level OLTC. For LV level the inventory was down scaled to the ABB VRLTC type. In both cases it is possible the OLTC is oversized for the applications being considered in SS, however equivalent data for smaller OLTC if they are available was not found. Therefore the values in relation to SS carbon impact accounting may be considered a conservative estimate. Full details of the LCI and impact assessment are provided in "Deliverable 3.4.2: Second Interim Report on Carbon Accounting", however as with the transformers the assumptions for oil reprocessing at the ENW Blackburn facility were improved to include transport of the oil to and from Manchester as a reference location. It is assumed that the OLTC is manufactured and shipped to the UK from the ABB facility at Bad Honnef in Germany. Aluminum is sourced from Norway, copper from China, glass products, steel and plastics from within Germany. The life span of the OLTC is assumed to be 30 years.

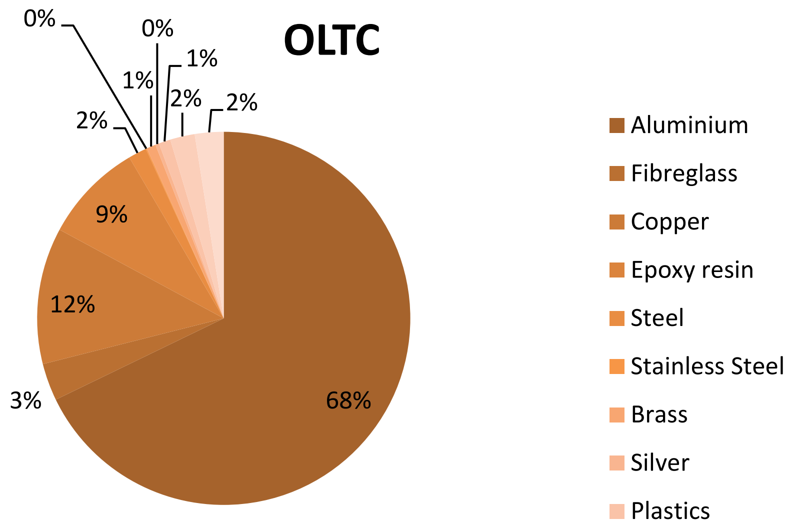


**Figure 7: Contribution analysis for OLTC based on [18]. Total life cycle GHG emissions of 2,394 kg$CO_2$e**

### 2.4.5 WEEZAP, LYNX and Gateway

The LCA data for the WEEZAP circuit breaker, Lynx low voltage switch unit and Gateway remote terminal unit are based on LCI data provided by ENWL. It is assumed that these devices are assembled in Northern Ireland with UK derived steel and plastics, Chinese origin copper and Norwegian aluminium.

After discussion with manufacturer Kelvatec, it is assumed that after ten years the PCB electronics are replaced in the Lynx and WEEZAP devices and after 20years the whole unit is replaced. The Gateway, which is primarily a PCB electronic device, is assumed to be replaced after 10years. The following contribution analysis figures show the life cycle value for an initial 10 year use phase.

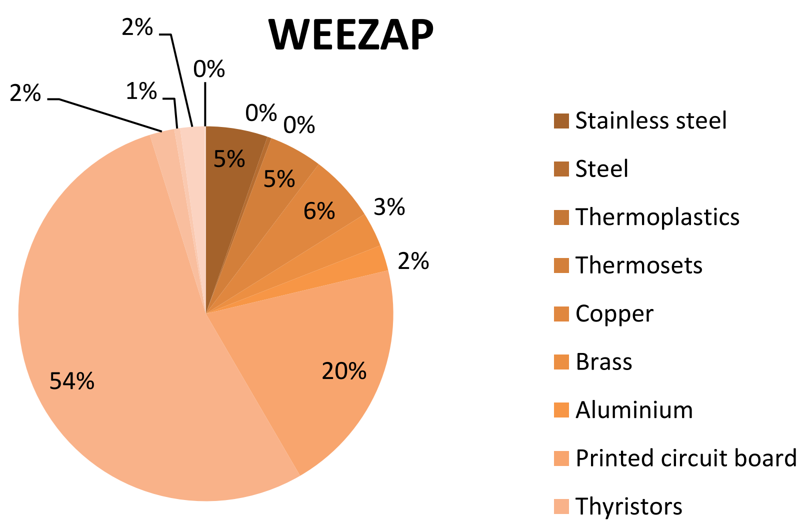

**Figure 8: Contribution analysis for WEEZAP. Total life cycle GHG emissions of 63 $kgCO_2e$**

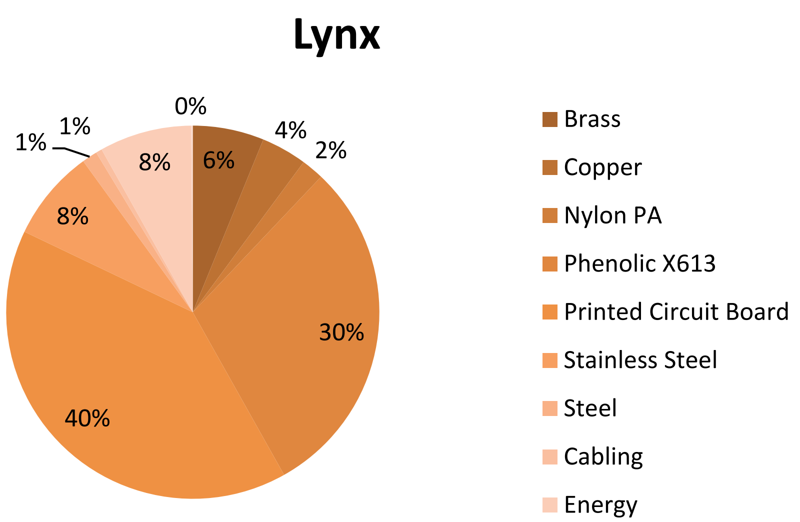


**Figure 9: Contribution analysis for Lynx. Total life cycle GHG emissions of 19 kgCO2e**

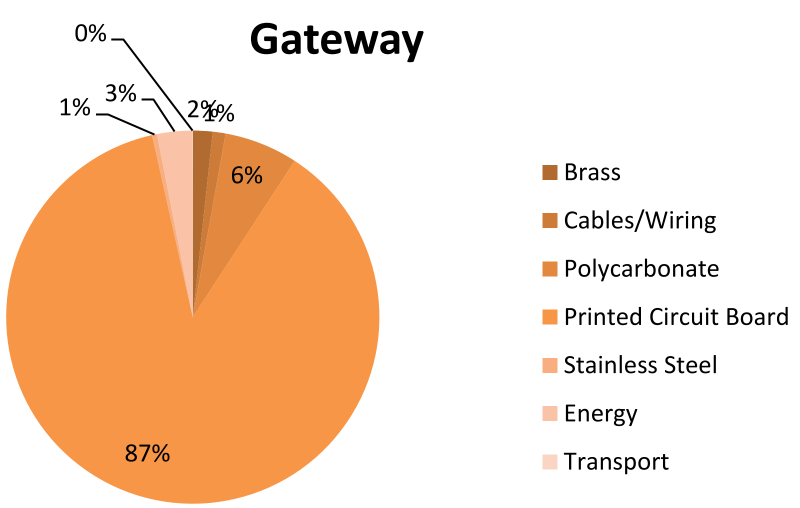


**Figure 10: Contribution analysis for Gateway. Total life cycle GHG emissions of 20 $kgCO_2e$**

## 2.5 Electricity Grid Emissions

The GHG emissions values for changes in network energy losses and customer electricity consumption as a result of SS method interventions are based on an assessment of the emissions associated with electricity provision within the 2016 to 2060 timeframe. These values are established by combining National grid projections of electricity generation mix in the four future energy system scenarios (see Table 1) with life cycle emission data for generation technologies. This provides a different set of outcomes from grid $CO_2$ emission intensities based on UK direct territorial emissions (i.e. fossil fuel combustion for electricity within UK power stations) only. The expansion of the system boundary to include upstream life cycle emissions from generators such as nuclear and wind is consistent with the approach of studies such as [10]. In such a way, a consistent system boundary is applied to the network assets and the operational changes in energy associated with the networks.

Electricity grid mix assumptions are provided by National Grid [8]. These assumptions are annualized figure for electricity generation by technology type from 2016 to 2050. For the purpose of this study the operation of the grid is assumed to remain static for the 2050 to 2060 period of the SS timeframe. Life cycle emission values for the grid mix were derived from the literature on reviewing and harmonizing LCA values for different electricity generator technologies as discussed in [19]. This enables a projection of annual average grid $gCO_2e$ /kWh for the four underlying scenarios used in SS. These scenario based projections are used in conjunction with the network load growth scenarios in the trial network analysis in WP3.

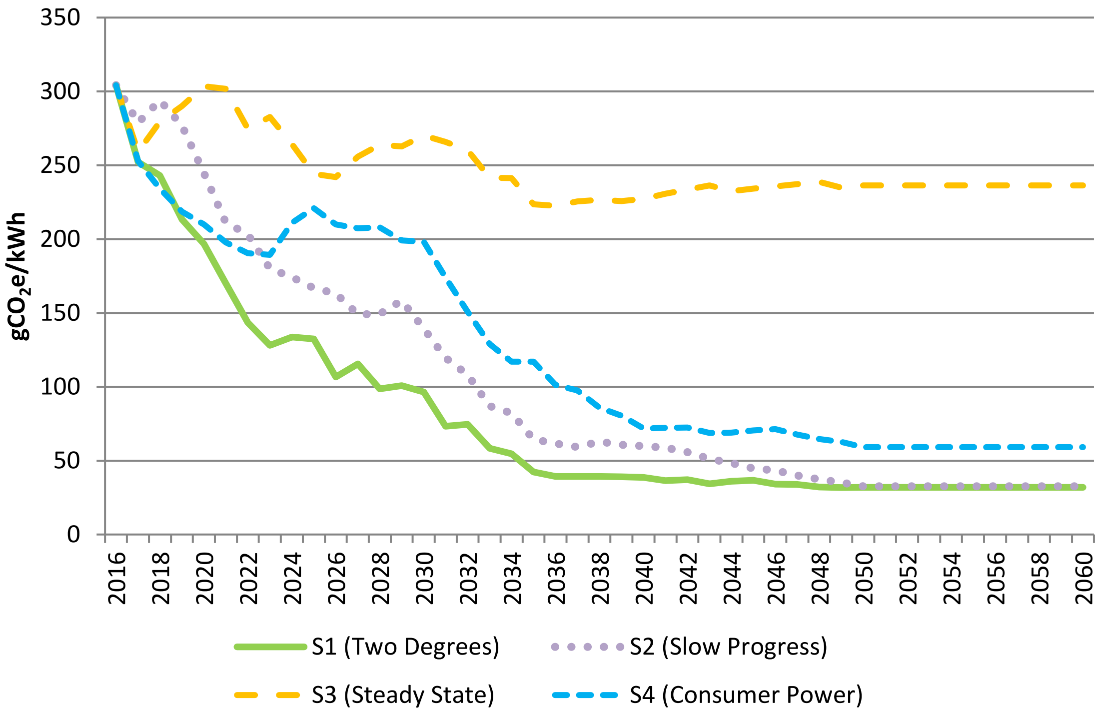


**Figure 11: Projections for life cycle emissions of UK grid electricity ($gCO_2e$/kWh Value) by Scenario**

# 3 Results

This section presents the results of the life cycle assessment method applied to the SS trial networks outputs from WP3. The change in GHG emissions between the Baseline case, with no SS interventions, and the SS intervention cases allocated to the 45year timeframe of the assessment are reported. The analysis is presented in three stages, in each case three SS interventions are assessed; SS application with OLTC; SS application with OLTC and existing capacitor banks; SS application with OLTC, capacitor banks and network meshing. Firstly the impact of SS interventions on the operational emissions of the trial HV and LV networks are presented. This includes the change in emissions associated with network energy losses, new assets deployed on the network. Secondly the combined net impact of SS on the trial networks as a whole system, including reduced customer electricity consumption is presented. Finally the results for net system savings in the trial networks are scaled up to the ENW and GB scale.

## 3.1 Impact of SS HV Network Solutions on Network Greenhouse Gas Emissions

The carbon impact assessment method is applied to SS HV trial networks representing rural, urban and dense urban network types. Network trial results for the three HV networks provided yearly changes in network energy losses and network assets, varying by demand scenario (Table 1) and the type of SS intervention (Section 2.3) applied. Figures 12 to 14 show how for each of the four demand scenarios, assets and energy losses vary between the baseline and the three alternatives with SS interventions. The figures show the change in $CO_2e$ emissions associated with the network over the 2016 to 2060 timeframe, whether due to new assets or change in operational energy losses. They also present the net change in emissions against the baseline BAU case, showing whether a reduction or increase in $CO_2e$ is achieved by the SS intervention over the period. For the HV networks no WEEZAP, Lynx or Gateway devices are assumed to be required for the SS meshing function.

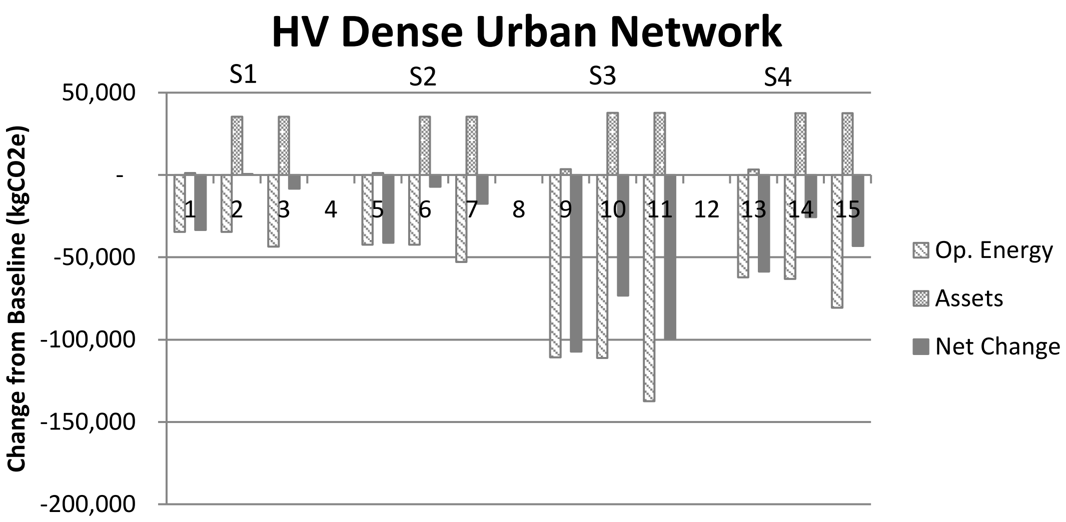


**Figure 12: Change in Network Related Life Cycle $CO_2e$ Emissions against Baseline varied by Four Scenarios and SS Solution; (a) OLTC, (b) OLTC and Capacitor, (c) OLTC, Capacitor and Meshing**

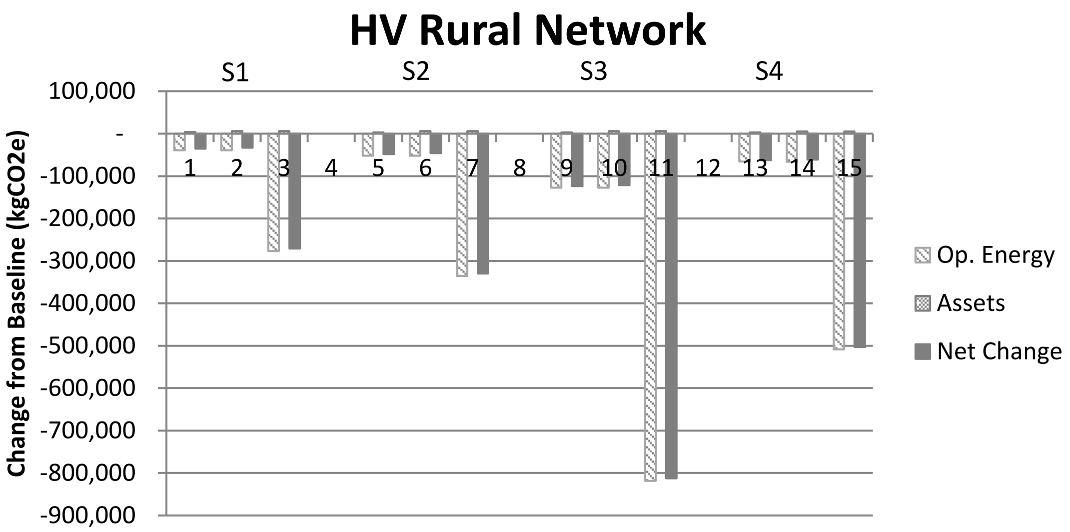


**Figure 13: Change in Network Related Life Cycle $CO_2$e Emissions against Baseline varied by Four Scenarios and SS Solution; (a) OLTC, (b) OLTC and Capacitor, (c) OLTC, Capacitor and Meshing. Note, different Axis scales compared to Fig.12 and Fig.14.**

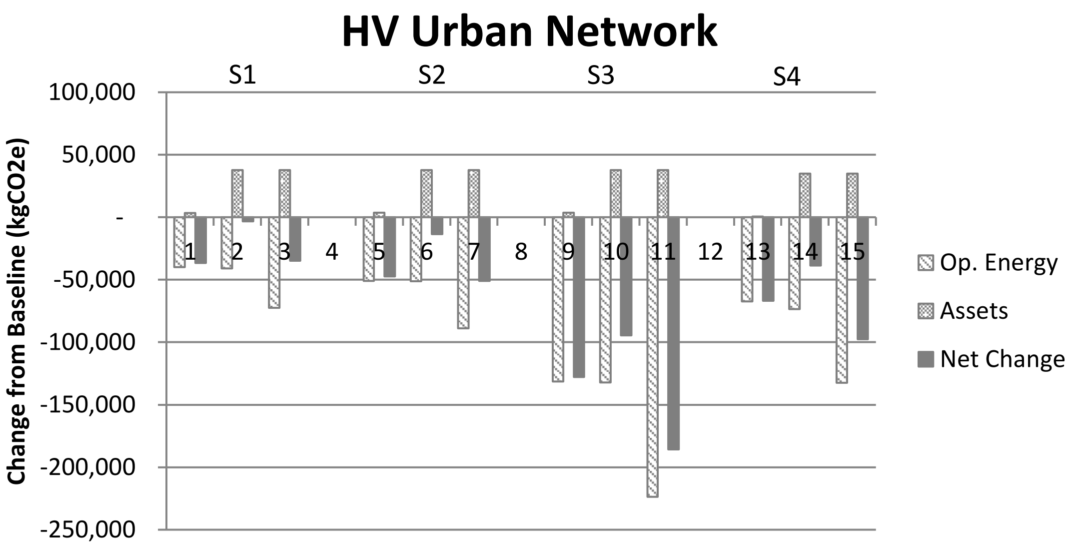


**Figure 14: Change in Network Related Life Cycle $CO_2$e Emissions against Baseline Case varied by Four Scenarios and SS Solution; (a) OLTC, (b) OLTC and Capacitor, (c) OLTC, Capacitor and Meshing**

The results highlight the significance of emissions associated with the capacitor banks. When capacitors are included in SS they increase the asset emissions of the network but do not effect a significant increased reduction in operational energy in comparison with the OLTC only intervention. Network meshing provides sufficient operational energy savings to offset the emissions of the capacitor assets. In the rural network, the lower upstream emissions of the pole mounted capacitor and the relatively high network energy loss reduction from SS means that capacitors have little impact on net network emissions. Meshing is also shown to be particularly effective in reducing network losses and therefore overall carbon in the rural network area.

The results also highlight the significance of underlying scenario assumptions on the GHG emissions saving potential of the SS methods. As anticipated the greatest savings in emissions is achieved under the assumptions of the steady state scenario (S3) for the electricity grid, which has the highest $gCO_2e/kWh$ value for electricity usage reduction by the network. The second highest savings are realised in the consumer power (S4) scenario results. Despite the average emissions of S4 being only 18% greater than the average emissions intensity of the slow and steady scenario (S2) over the 2016 to 2060 period, the overall emissions savings from SS interventions are 31% to 64% greater in S4 compared to S2 (varying by network type and SS intervention). This is most likely attributed to a much faster uptake of LCT such as EVs in S4 compared to S2. Similarly, the average life cycle $gCO_2e/kWh$ value for electricity losses in S1 are 36% lower than the average emissions intensity in S4, yet the net reductions in S4 are 74% to 124% greater in S4 than for equivalent SS interventions in S1. Both S1 and S4 have similarly high uptake rates of LCTs, however in S4 there is no demand management assumed, therefore potential demand peaks are higher. This suggests that SS is particularly significant for reducing network related GHG emissions where LCT uptake is high without demand management measures.

## 3.2 Impact of SS HV Network Solutions on Network Greenhouse Gas Emissions

As with the HV trial networks, the carbon impact assessment method is applied to SS LV trial networks representing rural, urban and dense urban network types. The SS trial included several LV network. Three LV networks for each network type were selected (Table 2), varying in customer number per network. For each type at least one network was selected that was suitable for all SS interventions (OLTC, capacitors and interconnection potential for meshing). The LV network trial results for these networks provided yearly changes in network energy losses and network assets, varying by demand scenario (Table 1) and the type of SS intervention (Section 2.3) applied. For Figures 15 to 17 the three LV networks representing dense urban, rural and urban network types suitable for all SS interventions are presented. These figures show how for each of the four demand scenarios, assets and energy losses vary between the baseline and the different SS interventions. The figures show the change in net network life cycle $CO_2e$ emissions over the 2016 to 2060 timeframe delivered by SS interventions. For the SS intervention with OLTC, Capacitor and Meshing (c), WEEZAP, Lynx and Gateway devices are utilised, adding to the asset emissions of the 'c' variant in the results.

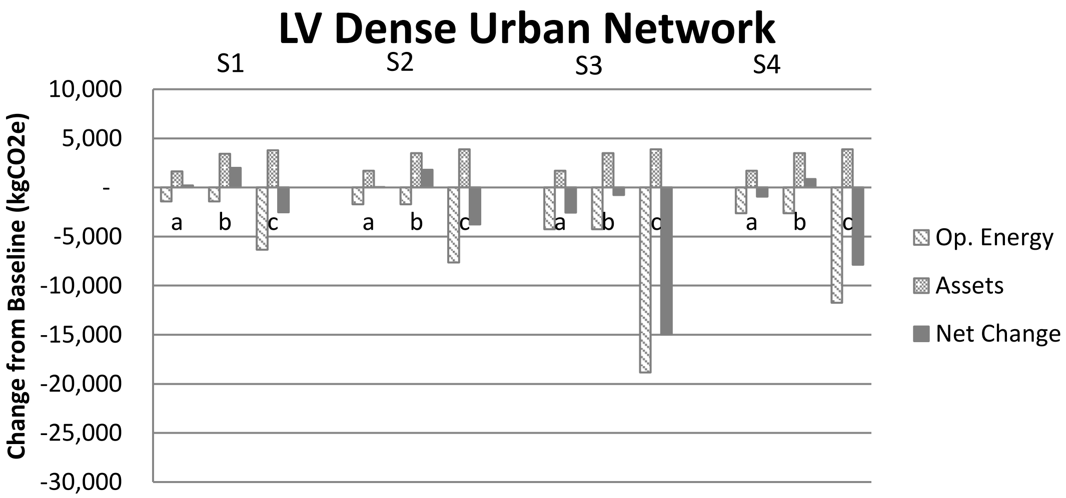

**Figure 15: Change in Network Related Life Cycle $CO_2$e Emissions against Baseline Case varied by Four Scenarios and SS Solution; (a) OLTC, (b) OLTC and Capacitor, (c) OLTC, Capacitor and Meshing**

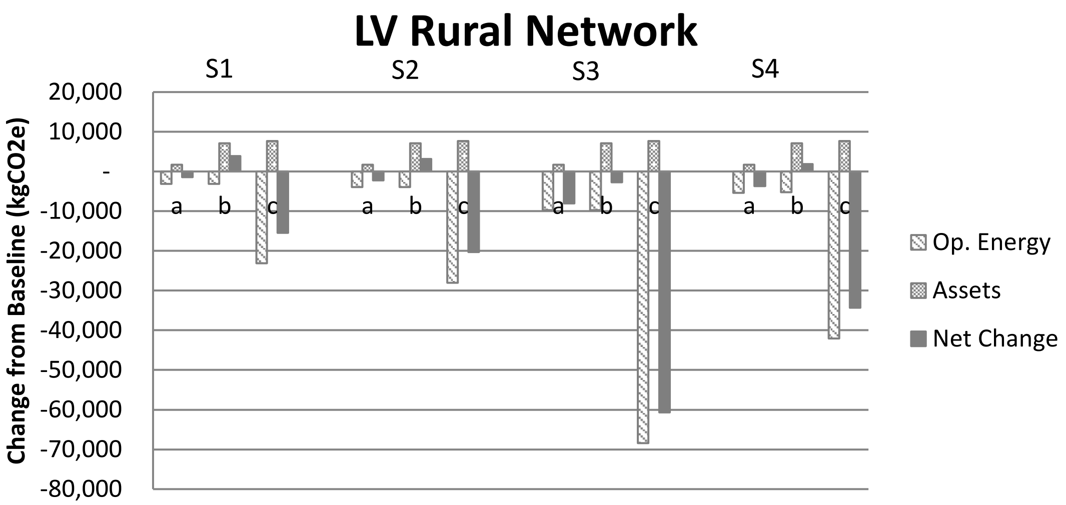


**Figure 16: Change in Network Related Life Cycle $CO_2$e Emissions against Baseline Case varied by Four Scenarios and SS Solution; (a) OLTC, (b) OLTC and Capacitor, (c) OLTC, Capacitor and Meshing**

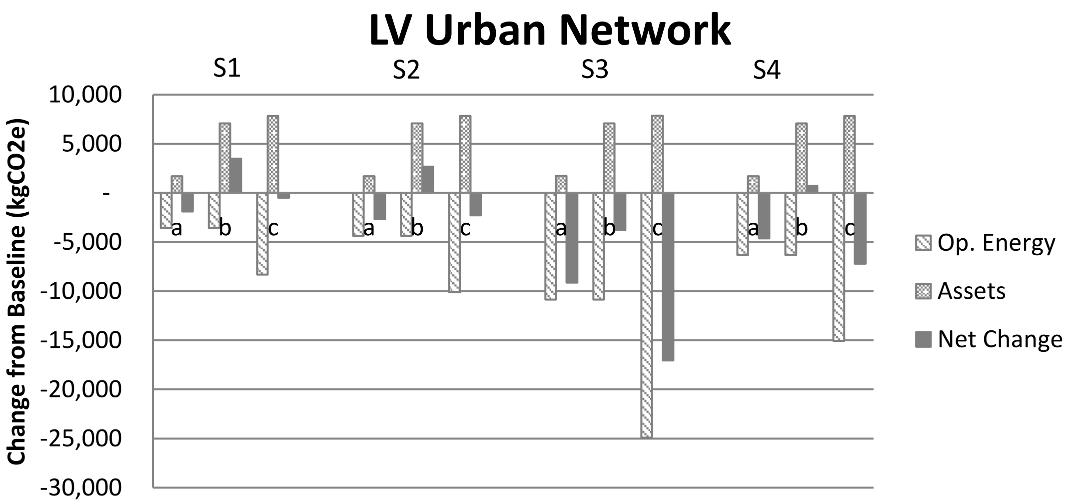


**Figure 17: Change in Network Related Life Cycle $CO_2$e Emissions against Baseline Case varied by Four Scenarios and SS Solution; (a) OLTC, (b) OLTC and Capacitor, (c) OLTC, Capacitor and Meshing**

As with the HV networks, where steady state emissions intensity for the electricity grid are assumed (S3), the reduction in energy losses in the network from SS interventions are sufficient to result in GHG reductions that lead to net reductions against the baseline case. In the other scenarios, which assume some rate of grid decarbonisation, emissions saving from energy savings are largely offset by the life cycle emissions associated with additional network assets for SS in many cases. Where capacitors are added there is a net increase in life cycle GHG attributed to the network if grid emissions are assumed to decrease over time. The addition of meshing through the installation of WEEZAP, Lynx and Gateway devices, despite higher asset emissions, results in net carbon savings on the networks. This highlights that as grid $gCO_2e/kWh$ factors reduce, the efficacy of network interventions to yield overall savings need greater examination. The results also show the particular effectiveness of the SS method using the functions of the WEEZAP and Lynx configurations in rural networks.

## 3.3 Wider System Impacts through Customer Energy Demand Reduction

The SS method offers the potential for wider system benefits than reducing network carbon emissions through lower energy losses and avoided asset reinforcement, by reducing electricity consumed by customers. The voltage management allows the possibility to save customers electricity while providing the same end use energy services. This reduction in overall electricity consumption is SS greatest contribution to emissions reduction at the system level.

By assigning an emissions value to the electricity demand avoided by SS solutions compared to a BAU baseline for each scenario, combined with changes in operational energy losses and additional network assets the overall carbon impact of SS on the trial networks can be determined. The change in electricity consumption by customers accounts for ~99% of the change in the emissions between the SS interventions and the BAU case over the 2016 to 2060 timeframe. Table 5 and Table 6 show the overall emissions reduction from SS when reduced customer electricity demand is accounted for:

**Table 5: Change in GHG emissions for SS HV trial networks compared to BAU baseline**

| Type | Scenario | tCO2e | | |
|---|---|---|---|---|
| | | OLTC | OLTC+Cap | OLTC+Cap+Mesh |
| DU | 1 | - 8,427 | - 8,403 | - 8,247 |
| | 2 | - 10,536 | - 10,509 | - 10,318 |
| | 3 | - 25,729 | - 25,745 | - 25,259 |
| | 4 | - 13,963 | - 14,044 | - 13,807 |
| U | 1 | - 12,322 | - 12,308 | - 12,379 |
| | 2 | - 15,261 | - 15,371 | - 15,490 |
| | 3 | - 37,213 | - 37,600 | - 37,903 |
| | 4 | - 19,122 | - 19,195 | - 19,336 |
| R | 1 | - 8,286 | - 8,284 | - 8,316 |
| | 2 | - 10,559 | - 10,556 | - 10,560 |
| | 3 | - 25,678 | - 25,675 | - 25,728 |
| | 4 | - 13,073 | - 13,197 | - 13,264 |

**Table 6: Change in GHG emissions for SS LV trial networks compared to BAU baseline**

| Type | Scenario | tCO2e | | |
|---|---|---|---|---|
| | | OLTC | OLTC+Cap | OLTC+Cap+Mesh |
| DU | 1 | - 367 | - 366 | - 365 |
| | 2 | - 458 | - 456 | - 456 |
| | 3 | - 1,118 | - 1,116 | - 1,116 |
| | 4 | - 626 | - 624 | - 623 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| U | 1 | - | 496 | - | 490 | - | 500 |
| | 2 | - | 625 | - | 619 | - | 630 |
| | 3 | - | 1,516 | - | 1,511 | - | 1,538 |
| | 4 | - | 814 | - | 809 | - | 831 |
| R | 1 | - | 382 | - | 377 | - | 413 |
| | 2 | - | 490 | - | 484 | - | 524 |
| | 3 | - | 1,184 | - | 1,179 | - | 1,277 |
| | 4 | - | 604 | - | 597 | - | 674 |

Due to the energy savings of SS, GHG emissions are reduced in all the trial network scenarios. The OLTC alone is sufficient to produce these savings, although in most instances for HV and LV networks meshing provides additional savings. Additional SS assets – capacitors and mesh devices – have a <2% variation in the emissions saved by the OLTC alone in the dense urban and urban cases. In the rural network trial, meshing had a more significant impact, increasing the overall emissions saving by 10% compared to the OLTC only case in the S4 (consumer power) scenario.

## 3.4 Implications for a Distribution Network and Great Britain

The final stage of the SS carbon impact assessment was to investigate the potential savings that could be achieved if SS was deployed beyond the trial networks to the whole of the ENW network area and ultimately GB as a whole.

The SS trial results represent three broad network types (dense urban, urban and rural), at HV and LV level. Scaling of absolute values for carbon savings in these trial networks adds uncertainty to the analysis because of the heterogeneity of distribution networks. The results for the LV networks show how network topography, customer number and type may lead to differences in net absolute carbon savings. However proportional carbon savings per trial network are very broadly similar, with <1 percentage point difference in relative savings for HV networks and a 3 percentage point variation across the 9 LV networks studied. Therefore a proportional saving for ENW and GB in emissions associated with losses reduction and customer energy savings is applied.

As ~99% of the carbon savings associated with SS are associated with electricity savings, in the form of reduced network losses and customer energy consumption, SS solutions are primarily an energy efficiency saving for the electricity system. The carbon value of the electricity saved in delivering the same energy services more efficiently through SS is determined by the life cycle GHG emissions of the electricity saved by SS over the 2016 to 2060 timeframe. The analysis also includes additional network assets to enable SS, an adjustment is made based on the average proportional offset to net savings from increased network asset emissions, which varies by the type of Smart Street solution and the framing scenario. Due to the greater diversity of proportional emissions savings (7% to 10%) between the different LV networks a low and high case for potential savings is presented.

**Table 7: Summary of greenhouse gas emissions savings ($MtCO_2e$) potential with full Smart Street role out across ENW area over 2016-2060 period**

| Scenario | $MtCO_2e$ | HV | LV Low | LV High |
|---|---|---|---|---|
| S1 | OLTC | 5.13 | 7.24 | 10.84 |
| | OLTC+Cap | 5.11 | 7.07 | 10.81 |
| | OLTC+Cap+Mesh | 5.11 | 7.13 | 10.78 |
| S2 | OLTC | 6.30 | 8.91 | 13.33 |
| | OLTC+Cap | 6.28 | 8.74 | 13.26 |
| | OLTC+Cap+Mesh | 6.28 | 8.79 | 13.26 |
| S3 | OLTC | 15.14 | 21.45 | 32.06 |
| | OLTC+Cap | 15.11 | 21.28 | 31.99 |
| | OLTC+Cap+Mesh | 15.11 | 21.30 | 31.93 |
| S4 | OLTC | 8.09 | 11.43 | 17.12 |
| | OLTC+Cap | 8.08 | 11.28 | 17.05 |
| | OLTC+Cap+Mesh | 8.08 | 11.31 | 17.05 |

**Table 8: Summary of greenhouse gas emissions savings ($MtCO_2e$) potential with full Smart Street role out across GB over 2016-2060 period**

| Scenario | $MtCO_2e$ | HV | LV Low | LV High |
|---|---|---|---|---|
| S1 | OLTC | 64.17 | 90.51 | 135.54 |
| | OLTC+Cap | 63.94 | 88.42 | 135.13 |
| | OLTC+Cap+Mesh | 63.94 | 89.15 | 134.73 |
| S2 | OLTC | 78.81 | 111.39 | 166.63 |
| | OLTC+Cap | 78.52 | 109.26 | 165.80 |
| | OLTC+Cap+Mesh | 78.52 | 109.93 | 165.80 |
| S3 | OLTC | 189.20 | 268.15 | 400.73 |
| | OLTC+Cap | 188.84 | 266.00 | 399.93 |
| | OLTC+Cap+Mesh | 188.84 | 266.27 | 399.13 |
| S4 | OLTC | 101.15 | 142.92 | 214.02 |
| | OLTC+Cap | 100.95 | 141.05 | 213.16 |
| | OLTC+Cap+Mesh | 100.95 | 141.34 | 213.16 |

The results of the carbon impact assessment therefore show that overall electricity system emissions reductions of ~5% may be possible, assuming a full application of Smart Street with OLTCs at the HV level, and 7% to 10% savings maybe possible where applied at the LV level instead. These results are indicative and based on a comparison to BAU practices and the assumptions of the modelling work. The range in values between the high and low case for LV level interventions highlights the range of uncertainty of scaling up from the trial networks to the nation as a whole. Further work to scale up the potential impacts in a more accurate way would require more representative networks and clearer dataset on potential outlier networks such as those with a single customer. The scaling results do however point to way in which the potential reduction in customer energy consumption and network losses through Smart Street can reduce emissions, particularly when the life cycle values of the electricity generated is taken into account. Furthermore the results show SS has greatest salience in grid decarbonisation scenarios (S4) where LCT uptake increases without demand management.

# 4 Conclusions

The aim of this study was to evaluate the carbon impact of SS method interventions in comparison with BAU network management under different future energy scenarios. The assessment was applied to dense urban, urban and rural HV and LV network types. The analysis considered the role of different overarching energy demand and electricity grid emissions scenarios and three forms of SS interventions combining OLTC, capacitors and meshing. In addition to assessing to the specific trial networks considered by the rest of the SS project; this report investigated the implications of the carbon savings in the trial networks for the ENW area and GB as a whole. The results are based on consequential LCA methods, where by modelling data is used to characterise change in a system given certain assumptions. In this case the results of techno-economic assessments for the trial networks in WP3 of SS were used. By comparing the results of the system under assumptions of a BAU case and a specified alternative measure (i.e. the SS intervention), a change in life cycle GHG emissions associated with the alternative measure is determined. These features of the consequential LCA approach, although necessary to account for dynamic changes in the distribution network, as the system under assessment, mean that the results are contingent upon the assumptions of the scenarios and models used. Therefore the results do not provide absolute accounting values for the SS measures, but do enable a comprehensive and accurate assessment of the potential emissions savings that they can yield in the given scenario circumstances.

With these considerations in mind, the following conclusions can be drawn from the carbon impact assessment:

- The primary source of GHG emissions savings is from reducing customer energy consumption –in the form of lower energy required to deliver electricity services. The greatest savings were identified at the LV level interventions. Even without LCT uptake on the network, as in the S3 scenario, SS methods have value from a climate change mitigation perspective. For LV level interventions, with steady state grid emissions, savings in order of 400 $MtCO_2e$ may be possible (depending on the representativeness of the SS trial networks) over the 2016 to 2060 period for GB. Where climate change mitigation strategies are pursued most rigorously (S1), through reduced grid emissions and LCT uptake, LV level savings of 90 $MtCO_2e$ to 135 $MtCO_2e$ may be achieved.

- For HV and LV network levels, the greatest overall system savings are achieved through the application of the OLTC. The emissions associated with capacitors are in some instances not fully offset by reduced customer energy demand or network losses, meaning that little additional gain is achieved by capacitors and meshing for the system overall.

- For emissions associated with the operation of the LV electricity network (assets and operational losses), network meshing through WEEZAP, Lynx and Gateway devices asset emissions are offset by increased savings in avoided operational energy consumption on the network. Therefore meshing reduces lowers the net emissions of the DNO itself.

- The scaling of network results to wider geographic areas adds additional uncertainties to the results, given potential diversity in network types across GB. Further work to better characterise network types and expanded trial network types in future research may address this.

Overall SS interventions have wider system benefits for, enabling carbon reductions, particularly in a decarbonisation context where increased LCT demand on the network is unmanaged.

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