D-Suite

WP1 Deliverable 1.3: Cost-Benefit Analysis

21/03/2024

Future Networks

ABOUT REPORT

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Created By	Joe Scott, Matthew Deakin, David Greenwood	
Reviewed By	Ritika Das	
Approved By	Andrew Moon	

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Executive Summary

This report undertakes a Cost-Benefit Analysis (CBA) for a set of six low voltage (LV) distribution networks across SP Energy Network's service territory to estimate the potential societal benefits of D-Suite devices used for increasing network capacity via congestion mitigation. Three networks from each of SP Manweb (SPM) and SP Distribution (SPD) service areas are analysed, with each representing a rural, suburban, or urban topology. The uptake of Low Carbon Technologies (LCTs) is modelled to 2040 for customers using sociodemographic data from EVUP and HEATUP databases, enabling modelling with a high-level of granularity. The proposed D-Suite solutions are compared against Business-as-Usual (BaU) reinforcement as the CBA's reference case. The CBA informs and is complemented by the results of the Beta phase CBA, whose method is compared against this detailed network-level CBA.

Full unbalanced modelling of the network enables the analysis of voltage congestion, substation or feeder thermal congestion, and voltage unbalance. All six networks have congestion by 2040 following LCT forecasts derived from the Leading The Way (LTW) Future Energy Scenario, and so the six networks are good candidates to explore potential benefits of D-Suite. Four reinforcement actions are considered for congestion: transformer uprating, feeder reinforcement (via cable overlay or a split feeder), or installation of a new substation. Validation of findings related to phase unbalance are enabled via analysis of half-hourly monitoring data, obtained from 103 data streams across 20 monitored LV sites. Under peak load conditions, it is found that phase unbalance is a significant factor, with typical values of the Phase Current Balance Factor (PCBF) being 85% or lower (ideally the PCBF should be 100% at peak loading to fully utilise the assets).

Table 1: CBA summary for present and future PED costs. Negative NPVs indicate costs.

Ntwk. ID	Scenario							Investments for congestion mitigation compared	
	Reference case	D-Suite central case (£250/kVA for D-Suite costs)			D-Suite, future PED cost (£63/kVA D-Suite costs)			Reference case	D-Suite case
	NPV, £k	NPV, £k	ΔNPV, £k	(%)	NPV, £k	ΔNPV, £k	(%)		
SPM Urban	-147.3	-152.0	-4.7	-3%	-109.9	37.4	25%	New substation	2 D-STATCOMs, 180 kVA total capacity
SPD Urban	-98.5	-66.6	31.9	32%	-44.2	54.3	55%	Split feeder	D-ST
SPM Sburbn.	-100.0	-159.9	-59.9	-60%	-101.2	-1.2	-1%	Feeder overlay	2 D-STATCOMs, 240 kVA total capacity
SPD Sburbn.	-99.9	-154.7	-54.8	-55%	-93.3	6.6	7%	Split feeder & Tx uprate	2 D-SOPs, 120 kVA total capacity
SPM Rural	-72.5	-79.2	-6.7	-9%	-64.1	8.4	12%	Feeder overlay	D-STATCOM 60 kVA
SPD Rural	-11.0	-18.9	-7.9	-72%	-13.1	-2.1	-19%	Tx uprate	D-STATCOM, 24 kVA

Table 1 summarises the findings of the CBA for the central scenario, considering present D-Suite device costs (£250/kVA) and in a future cost scenario (£63/kVA). In today's system, D-Suite provides has good benefits in one of six cases and has a marginal negative in one case. Considering realistic future cost reductions of PEDs, the benefits are improved, with half of cases having improved NPV of 12% of greater and only case with a strong negative NPV. Overall, in the future scenario, across all six networks the costs of reinforcement are reduced by 20%.

This CBA report has resulted in four Alpha-phase learnings to be considered in the Beta stage.

1. The relatively high cost of D-Suite devices today highlights the need for installations which have good utilization of the D-Suite devices' capacity. Devices with lower capacity will typically have higher utilization. D-STs are designed to be partially rated for voltage control, and D-SOPs can be partially rated in terms of installation of smaller capacity than the feeder to which they are connected. This capacity reduction can also reduce the size and weight of the D-Suite PEDs, improving practicality.

Beta recommendation: Demonstrate the potential for partial rating in D-SOP and D-ST devices in network trials.

2. Present placement of D-Suite devices for D-STATCOM and D-SOPs has been completed via manual approaches that do not consider all possible locations for these devices (for example, D-SOP placement has been limited to placement at normally open link boxes). However, new street furniture can be placed in a flexible way – for example, D-SOPs can be placed across nearby feeders even if there were no existing link boxes. Systematic optimization of D-Suite placement could further improve D-Suite benefits and reduce their investment costs.

Beta recommendation: Develop optimized placement of D-Suite devices to further minimize investment costs for D-SOP and D-STATCOMs considering the wider HV-LV system.

3. As with other smart assets which enable deferred reinforcement, the greatest value provided is when the cost of reinforcement is high and there is a good opportunity to defer investment. The case studies demonstrate how low-cost transformer uprating is unlikely to be cost-effective even under optimistic PED cost reduction cases. Feeder reinforcement and major new substation investments are more costly, and therefore are a better candidate reinforcement action to be targeted by D-Suite trials.

Beta recommendation: Focus network trials on locations that could avoid high-cost reinforcement actions such as feeder reinforcement or major new substation works.

4. Network model outputs and monitoring data highlight the importance of network unbalance in assessing thermal congestion, as demonstrated through the estimate of median Phase Balance Factor (PBF) of 0.85 at peak loading, potentially enabling 18% capacity uplift across a wide range of assets through a D-STATCOM. For networks interconnected through a D-SOP, the level of unbalance that can be exploited in practise should also be explored.

Beta recommendation: Leverage monitoring data through smart meters and LV monitoring to assess the additional benefits via D-Suite active balancing of phases and feeders.

Contents

Glossary

CBA	Cost-benefit analysis
CLNR	Customer-Led Network Revolution
CT	Consumer Transformation FES scenario
DFES	Distribution Future Energy Scenario
DNO	Distribution Network Operator
D-SOP	D-Suite Soft Open Point
D-ST	D-Suite Smart Transformer
D-STATCOM	D-Suite Static compensator
FES	Future Energy Scenario
FS	Falling Short FES scenario
GIS	Geographic information system
HV	High voltage
LCT	Low carbon technology
LTW	Leading The Way FES scenario
LV	Low voltage
NPV	Net present value
OHL	Overhead line
PED	Power electronic device
PF	Power factor
PV	Present value
SIF	Strategic Innovation Fund
SPD	SP Distribution (service area)
SPM	SP Manweb (service area)
ST	System Transformation FES scenario
Th-F	Thermal congestion - feeder level
Th-SS	Thermal congestion - substation level
Tx	Transformer
UGC	Underground cable
VM	Voltage magnitude congestion
VUB	Voltage unbalance congestion

1. Introduction

As energy systems transition towards net zero, distribution network operators (DNOs) must maintain adequate network capacity to supply demand whilst maintaining power quality and appropriate levels of service. Capacity constraints limit the power transfer capabilities of power distribution networks. This includes maintaining thermal constraints of assets (e.g., transformers, cables, or overhead lines), maintaining safe operating voltages for both customers and assets, and also ensuring a high level of power quality (e.g., low levels of voltage unbalance) to enable high utilization of sensitive loads. Should uptake of low carbon technologies (LCTs, such as electric vehicles and heat pumps) follow projections necessary to meet the UK government's carbon budgets, it has been estimated that up to £64 bn will need to be invested by 2050 to reinforce LV distribution networks alone.

The D-Suite project aims to provide a suite of power electronic device (PED)-based solutions that can be installed by a DNO at low voltage to address congestion. Such an approach maximises the utilization of existing network assets, removing or deferring the need for upgrades. For example, if the demand across the two sides of a normally open link box (i.e., a normally open point, NOP) varies with time, then the utilization of both sides of the feeder can be increased by transferring power through a PED-based Soft Open Point, or D-SOP.

In this report, we undertake a detailed cost-benefit analysis (CBA) for six networks across SPEN's SPD and SPM service areas to assess the potential societal benefit of making use of D-Suite solutions between now and 2040. There are three steps to undertake the CBA, as shown in Figure 1. Firstly, the business case for D-Suite must be articulated. The proposed CBA is chosen to be based on the Common Evaluation Methodology (CEM) [1], itself building on OFGEM's CBA planning tool [2] thereby following standard practise for DNOs in the UK, enabling the key value stream of reinforcement deferral to be estimated for D-Suite solutions. Secondly, a data collection step collates all of the parameters required to estimate the costs of both the reference, Business-as-Usual (BaU) for comparison against D-Suite. Finally, highly granular modelling of both low carbon technologies (LCTs) uptake and full unbalanced network power flows, enables time-series analysis of each network in both present and future conditions.

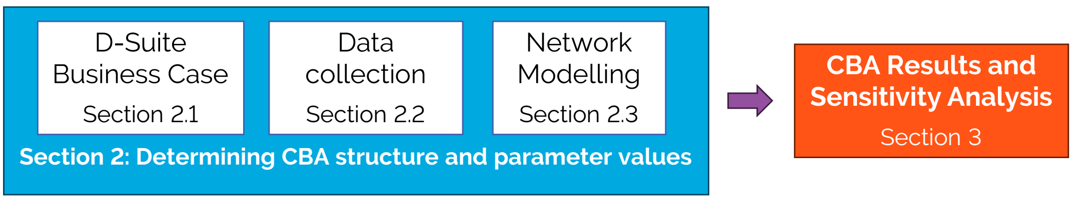


Figure 1: Structure of this report. Section 2 describes in detail the CBA structure and highlights the data collection and network modelling approaches used for each network. Results and sensitivity analysis for each network are then reported in Section 3.

This three-stage analysis approach enables load duration curves (LDCs) of each type of congestion to highlight the evolution of network constraints as LCTs increase loading. This allows the CBA results for the six networks to be determined, and sensitivity analysis to be conducted to consider the robustness of the results, and the conditions under which D-Suite will be most effective at providing societal value.

1.1. The D-Suite Solution

The three D-Suite devices considered in this report (D-ST, D-STATCOM, D-SOP) can address some or all of: voltage magnitude (VM) congestion, thermal congestion on feeders (Th-F), thermal congestion in substation transformers (Th-SS), and voltage unbalance (VUB). Therefore, they have potential to mitigate congestion caused by low carbon technologies. In this section, we briefly introduce these technologies to highlight the main congestion issues they can address.

1.1.1. D-STATCOM

A D-STATCOM is a PED that consists of a three- or four-leg power converter connected in shunt to the individual phases of the LV distribution system (Figure 2). By controlling the currents injections from each leg of the D-STATCOM, the power flowing in each phase of the network can be adjusted. A D-STATCOM can also inject balanced reactive power to adjust voltages. In contrast to transmission-connected STATCOM devices, the D-STATCOM is primarily envisioned as a device for providing steady-state congestion mitigation, rather than dynamic voltage control. This is because dynamic voltage stability is not a major concern in distribution networks, and because phase unbalance is much more likely in distribution (as the aggregation effects seen at higher voltages are not as applicable at LV).

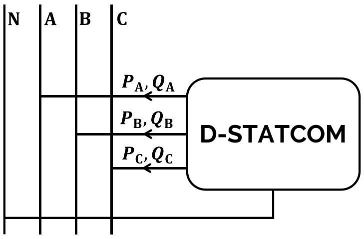


Figure 2: The D-STATCOM can inject active and reactive power into a network subject to current and power balance constraints within the device. Both balanced and unbalance current injections are possible, with the neutral wire enabling injection of zero sequence current.

1.1.2. D-SOP

A D-SOP is a PED constructed of back-to-back converters (Figure 3) and is conventionally installed in-place of a normally open link box. As compared to a STATCOM, it has increased flexibility as it can allow active power to be transferred between feeders. As with the STATCOM, the neutral connection enables increased flexibility for the converter when injecting unbalanced powers into the active phase legs A, B, C.

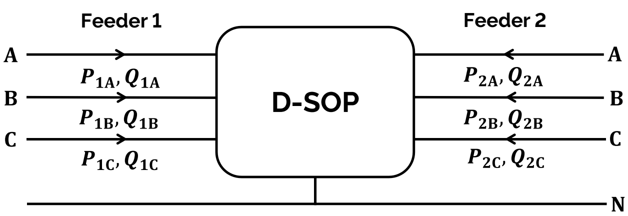


Figure 3: Distributed Soft Open Point (D-SOP). As with the D-STATCOM, the D-SOP can inject arbitrary active and reactive powers into the phases of each feeder.

1.1.3. D-ST

The D-ST is the most complex of the D-Suite devices. As with the D-SOP, the power electronics are constructed of a back-to-back PED. In contrast, however, these devices are connected in a shunt-series configuration, as shown in Figure 4, with a series transformer enabling a partially rated PED to inject a voltage V which can be used to adjust the voltages and currents on the secondary side of a distribution transformer. The active and reactive power P, Q is required to inject the voltage from the series converter.

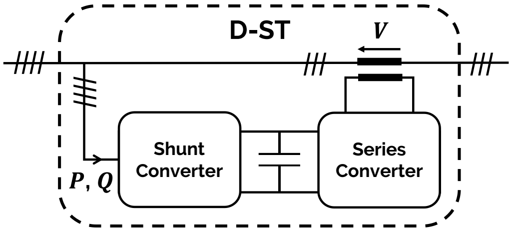


Figure 4: Distributed Smart Transformer (D-ST) has a shunt-series connection to enable a voltage injection (V) across a series transformer, enabling voltage magnitudes to be controlled. Active and reactive powers (P, Q) are drawn to enable the voltage injection. As with the D-SOP and D-STATCOM, the voltage and power injections can be unbalanced (not shown for simplicity).

2. D-Suite Business Case and Cost-Benefit Analysis Methodology

The CBA methodology used in this report is based on OFGEM's CBA Guidance [2] as used by all DNOs in the UK, extended through the ENA's Common Evaluation Methodology (CEM) [1]. At a high level, the aim for the CBA is to evaluate all benefits of both the proposed D-Suite device and a reference case, monetize those benefits, and then compare each solution. The societal benefit for the D-Suite solution is the difference between the reference and D-Suite NPVs – if the benefit is positive, this indicates a cost-effective solution.

In general, there are many factors that affect the CBA, including the D-Suite capacity required to install, its utilization rate, the uplift in capacity that can be provided by the device and therefore the duration of deferral benefit that can be realised. In this section, we summarise the value this reinforcement deferral provides, present the data collected to develop this business case, then summarise the network modelling approach required to undertake the granular network-level CBA.

2.1. D-Suite Business Case

Figure 5 presents a high-level summary of the business case proposal for D-Suite devices. The driver of investment is demand growth caused by, for example, growth in LCTs or new connections. When the demand reaches the nominal capacity of the network, new capacity must be released in the network. In the reference case, reinforcement is installed at the point demand reaches network capacity, enabling demand to continue to grow. (This is required as, in the absence of investment, a DNO will not be meeting their licence conditions.). In the D-Suite case, a D-Suite device is installed instead, which releases (typically) a smaller amount of capacity than the full reinforcement case. This will also enable demand growth, as in the reference case. As demand growth reaches the new capacity released by the D-Suite device, the conventional reinforcement will then be triggered.

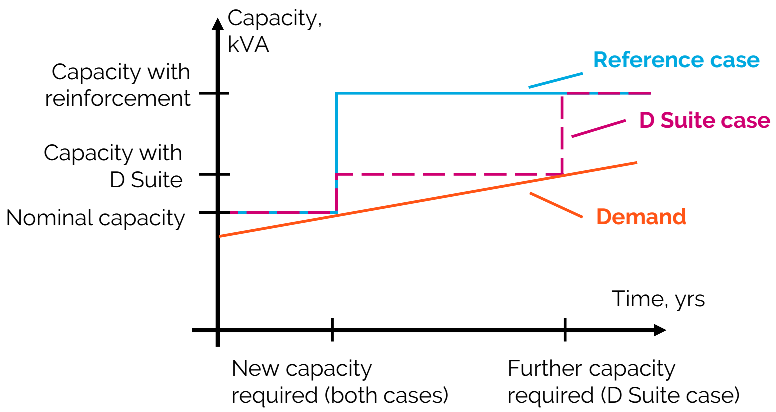


Figure 5: Deferment benefit under D-Suite case versus the Reference case.

The D-Suite solution can therefore be considered as a DNO-owned flexible investment approach that enables the deferral (or, in the case of low demand growth) avoidance of costly reinforcement actions. For a device to be cost-effective, it must be able to release an appropriate amount of capacity to enable a reasonable deferral of reinforcement at a cost which is sufficiently low to enable the deferral to be realised.

2.1.1. Network Congestion Mitigation from D-Suite Devices

D-Suite devices can address network congestion caused by voltage rise or voltage drop, thermal congestion at substations, thermal congestion at feeder level, and power quality issues such as voltage unbalance. D-Suite devices do not inject significant fault current as compared to conventional electrical machines, and so typically are not effective at addressing fault level constraints, except where they can enable network de-meshing.

Voltage and thermal constraints are active on a per-phase basis, so if there is congestion on any one phase, mitigation must be provided. D-Suite devices can control voltage and power on a per-phase basis, so can provide mitigation without replacing an asset due to loading on just one phase. This motivates unbalanced network analysis, so that congestion issues can be identified with greater precision. For example, unbalanced loading results in a reduction in network capacity as compared to balanced loading, as powers are limited on a per-phase basis. The Phase Current Balance Factor (PCBF) can be used to study this issue (Appendix C).

2.2. CBA Data Collection

2.2.1. Reference case

BaU Interventions include a range of options: transformer upgrade, feeder reinforcement (cable overlay or split LV feeder), or installation of a new substation to serve the network. To estimate the costs of these reinforcement actions accurately, data from SPEN's RIIO-ED2 planning data are incorporated into the CBA, as shown in Table 2. LV cable provision and install are derived from this data assuming feeder lengths for split cable and cable overlay are for lengths that match the lengths seen in the six networks modelled in this report.

Table 2: CBA parameters for conventional reinforcement activities used in the reference case.

CBA Parameter	Value	Source
New UGC-based substation	£20,000	SPEN ED2 CBA
Tx replacement and install (overhead)	£11,000	SPEN ED2 CBA
Tx replacement and install (ground mounted)	£20,000	SPEN ED2 CBA
LV cable provision and install	£500/m	SPEN ED2 CBA (derived)
LV customer connection (for cable overlay)	£500/service	SPEN ED2 CBA (derived)
UGC split feeder additional installation costs	£10,000/feeder	SPEN ED2 CBA
Discount rate (≤30 yrs)	3.5%	RIIO ED2 guidance
Discount rate (>30 yrs)	3%	RIIO ED2 guidance

CBA Parameter	Value	Source
CBA duration	45 years	RIIO ED2 guidance
Cost of losses	£58.22/MWh	RIIO ED2 guidance
O&M cost	2% of asset capex	BaU cost assumptions

Several of the parameters in OFGEM's CBA guidance are neglected in the analysis. This includes changes in customer interruptions and customer minutes lost, or changes in major injuries due to D-Suite, as these are not expected to change. Within the CBA, if an asset is a replacement (e.g., a transformer uprating), it is assumed that O&M costs for the new asset are not substantially different from the existing asset.

2.2.2. D-Suite case

The parameters affecting the CBA from the perspective of the D-Suite device are summarised in Table 3. The capacity required to install is determined by the capacity required to install (in kVA), the per-kVA PED cost, any further auxiliary device costs (e.g., installation of a link box or series transformer), the D-Suite lifetime (itself affecting device depreciation). The capacity of D-Suite device that is required is determined in this report. A 20 year PED lifetime is considered.

Table 3: CBA parameters for calculating the NPV of the D-Suite case.

Parameter	Value	Source
D-Suite PED capacity cost	£250/kVA	Data from suppliers
Fixed costs, D-SOP and D-STATCOM (civil works)	£3,500	BaU cost assumptions
Fixed costs, D-ST (civil works)	£7,000	BaU cost assumptions
Fixed costs, D-ST (series transformer)	£15,000	Data from supplier
D-Suite device efficiency	95%	D-Suite Alpha WP2 Report
Operational utilization	10%	See note below

The operational utilization of the device is used to calculate the device losses. As the D-Suite device is typically used to provide network capacity, it is assumed it will be used during peak hours. An operational utilization of 10% is equivalent to 6 hrs/day over 40% of the year. To estimate the future PED costs, a capacity cost today of £250/kVA is assumed based on costs from suppliers. This is a higher cost than other PEDs on the market today such as solar inverters, and it is expected that increased volumes will enable a good reduction in costs in future. Therefore, a lower capacity cost is considered a critical sensitivity analysis, as considered in Section 3.2.

2.3. Network Modelling

Six network models are explored for the detailed CBA analysis, as shown in Table 4. Between them, there are three networks from SP Manweb and three networks from SP Distribution, with one rural, urban, and suburban network from each service area. A range of customer numbers are covered, from just 24 customers to more than 1,200. Similarly, there are a range of average peak demands by 2040 from 1.8 to 3.3 kW per customer under the Leading The Way (LTW) scenario. This is due to variation in the propensity for take-up of LCTs (e.g., it is assumed that off-gas properties are most likely to be incentivised transition to heat pumps early due to the high cost and carbon intensity of alternatives). The D-Suite candidate locations are presented in Appendix A (Section 5.1).

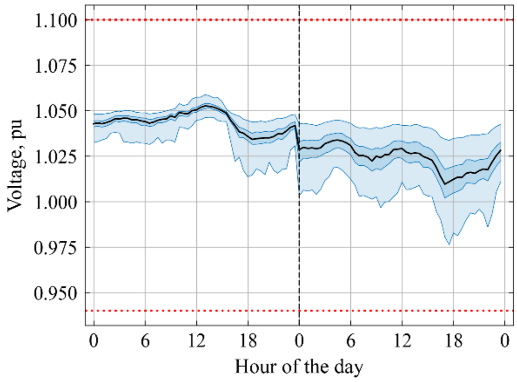
*Table 4: Summary of basic properties of the six networks studied in detail. The network ID is the service area (as SP Manweb, SPM or SP Distribution, SPD) and the type of network (as urban, U; suburban, S; or rural, R). *For interconnected (Intrcntcd.) networks, only the rating of a single transformer is given.*

Ntwk. id	No. customers	No. feeders	Topology	Tx Rating, kVA	Per customer 2040 demand (LTW), kW	First congestion year (LTW scnro.)
SPM-U	283	4	Intrcntcd.	500*	2..37	2040
SPD-U	1260	6	Radial	1000	2.03	2023
SPM-S	1125	5	Intrcntcd.	500*	1.83	2040
SPD-S	453	5	Radial	750	2.20	2032
SPM-R	36	3	Radial	200	3.01	2040
SPD-R	24	2	Radial	50	3.33	2025

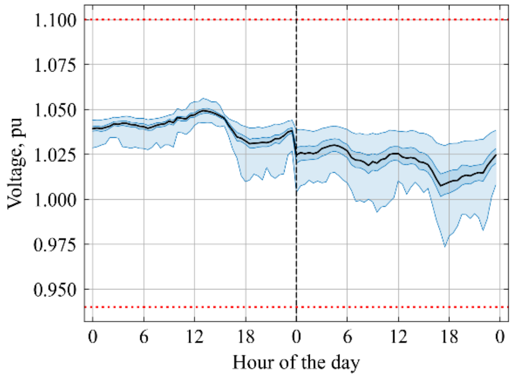
2.3.1. Network model extraction and power flow analysis method

Network models are obtained from SPEN's NAVI tool in the form of Opendss ".dss" files. These models have information about the substation, cable or OHL type and their connectivity, link boxes, and location and phase of loads. Loads are linked to customers' unique property reference numbers (UPRNs) using a nearest-neighbour approach from geographic information system (GIS)-based location. Some of this information is assumed and requires validation, such as transformer impedances and capacities, and customer phase. Results are therefore indicative for long-term planning consideration; where networks are identified for reinforcement due to congestion from modelling, this congestion should be validated via LV monitoring or analysis of smart meter power flows and voltages where possible.

To enable fast load flow, a Jacobian-based linear power flow (LPF) model is built. This model returns unbalanced voltage, currents and powers as required for congestion analysis (and has also been used for optimal control scheduling in other D-Suite work package tasks). The LPF method has very good accuracy as compared to the full non-linear power flow analysis, with a comparison of the results of the full non-linear power method and results from OpenDSS shown in Figure 6.



(A) METHOD: OPENDSS



(B) METHOD: LINEAR POWER FLOW

Figure 6: Comparison between OpenDSS and LPF power flow results for SPM-S. Plotted are the 0, 25, 50, 75 and 100% quantiles of the voltages across the network for a cold winter day (21/12) and a summer day (23/7) for LTW scenario in 2035. It can be observed that voltages for the LPF method very closely match the voltages obtained using the OpenDSS (the exact, non-linear method).

HV Voltage Assumptions

LV monitoring is present at one of the six networks. It is therefore not widespread enough to assess the voltage at the HV side of the secondary substation, an important parameter when modelling potential issues due to voltage constraints. Therefore, congestion analysis is carried out considering an HV voltage at two points, at a nominal voltage of 1.01 pu, or a lower voltage case of 0.98 pu. These voltages are well within HV operational limits of 0.94 pu and 1.06 pu.

2.3.2. LCT allocation and load growth

The method used to model the LCTs and their usage across each network was based on forecasting LCT uptake on a per-customer basis, combined with annual load profiles to create demand forecasts from the present up to 2040. The data required to undertake this analysis came from a range of sources.

- Knowledge of the per-customer information in each network is based on SPEN's HEATUP [3] and EVUP databases [4]. This was verified (if there were any ambiguities) by viewing satellite imagery or through Streetview software.

- LCT uptake is modelled using National Grid ESO's 2023 Future Energy Scenario (FES). The FES models a range of scenarios [5], and we use the series directly to determine uptake curves for heat pumps and electric vehicles across four scenarios. To forecast solar photovoltaic uptakes, we use Northern PowerGrid's DFES [6]. For this study all uptakes were normalised to their peak and used as a relative uptake (or percentage). referenced are given in

- Table 19. For each of these LCT types, a set of profiles were gathered from smart-grid trials. These were processed, where needed, to create year-long profiles at half-hourly resolution.

The datasets which formed the LCT profiles was collected from a variety of sources, as summarized in Table 5. They were each chosen as they are open licensed, have a suitable temporal resolution, and a good level of diversity amongst the profiles.

- Smart meter profiles (without LCTs) are based on data from the Customer Led Network Revolution (CLNR) smart meter trail. This was chosen due to wide geography of smart meters, with Logica subset chosen due to its low degree of missing values.
- The Electric Nation (EN) dataset provides a larger number of charging demand data at fixed addresses. It has an open license and provides high resolution suitable for our usage [7].
- Solar PV and electric heating demand data is based on weather-based models, with the RenewablesNinja tool chosen due to the ability to choose weather years, and because of consistency between the outputs it produces.

The resulting sets of profiles were sampled according to the uptakes and model decisions to determine appropriate application of LCT profiles. For a in depth description see Appendix B: LCT Allocation Software Model.

Table 5: Listing of datasets providing profiles. Additional tables are used for the parameters of models or in the case of studies the parts of the studies used.

Name	Citation	Remark
CLNR- TC1a (Logica subset)	[8]	Sample of 900 split based on quantiles, see Table 19.
Electric Nation	[7]	All ~300 profiles split on quantiles. Shifted 5 hours to produce smart-charging variants. Repeated 10-week period for a year, see Table 18.
Renewables Ninja: Heat Pumps and Photovoltaic	[9]	Year for 2010, for Wrexham and Glasgow. Heating Thermostats at 15, 17 and 19 degrees Celsius. For parameters see: Table 16 and Table 17.
2023 NGESO FES & 2022 NPG DFES	[5], [6]	See Table 20 for a listing of the how FES data was used from the scenarios.

Selecting a weather year for modelling of electric heating

Electric heating demand is closely related to temperatures, and it is well-known that temperatures can be subject to extreme swings from year-to-year. Therefore, to ensure that the peak demand from electrified heating is well-modelled, a 1-in-20 peak demand is considered, following practises used in gas network peak demand modelling [10]. The year chosen to model such cold weather is the 2010 winter, which had very cold temperatures across the UK through December. By cross-checking against historic weather data from 1950 for SPD and SPM regions [11], it was confirmed that this winter had return periods close or at the 1-in-20-year cold weather rate.

3. Results

In this Section, the results of network analysis and the CBA for each of the six networks is reported. To do so, for each congestion type, a load duration curve (LDC) has been developed using the LCT forecast and LCT profiles, with uptake considered to 2040. Figure 7 shows an example of such an LDC for the SPD-R network, highlighting how growth of LCTs leads first to partial congestion in 2025, before congestion is clearly visible from 2030.

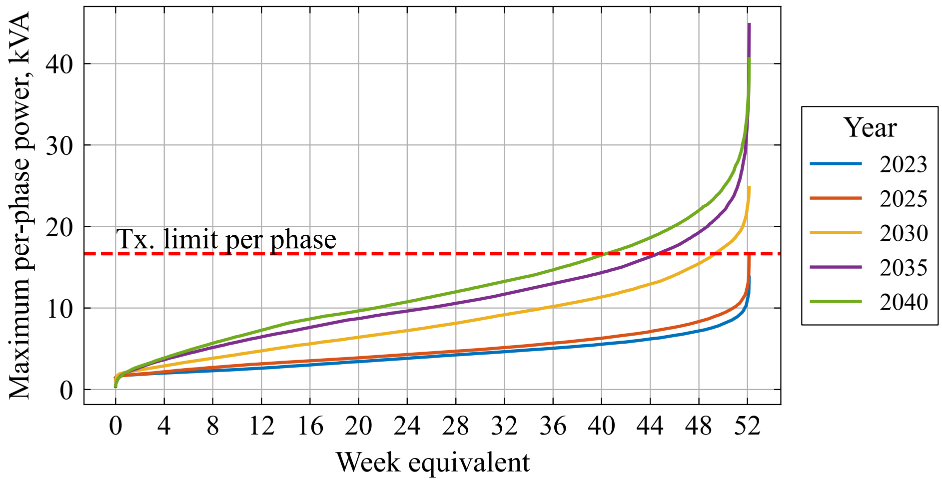


Figure 7: Load duration curve (LDC) for transformer loading for each of the modelled years from 2023 to 2040 (for Leading The Way scenario) for SPD-R, demonstrating increased congestion. A low level of congestion is observed in 2025 as compared to the transformer per-phase power, with clear congestion shown in years 2030 to 2040.

Table 6 summarises the types of congestion for each of the six networks. It can be seen that all six networks have some congestion by 2040. Two networks (SPD-U, SPD-R) show congestion soon, where other networks having congestion only starting by the end of the modelled period of 2040. Under the low voltage scenario (with HV at 0.98 pu), all networks have some level of voltage issues. The other four constraints each have at least one network with issues, with SPD-U showing the highest levels of congestion.

Table 6: Summary of network congestion for each of the six networks for the five congestion types considered.

Network ID	Constraint type					Congestion Start
	Thermal		Voltage		Voltage unbalance	
	Substation	Feeder	HV:1.01 pu	HV: 0.98 pu		
SPM-U	N	N	(Y)	Y	N	2040
SPD-U	Y	Y	Y	Y	Y	2023
SPM-S	N	(Y)	(Y)	Y	N	2040
SPD-S	Y	Y	(Y)	Y	N	2032

Network ID	Constraint type					Congestion Start
	Thermal		Voltage		Voltage unbalance	
	Substation	Feeder	HV:1.01 pu	HV: 0.98 pu		
SPM-R	N	N	(Y)	Y	(Y)	2040
SPD-R	Y	N	N	(Y)	Y	2025

Given there is congestion in each network, there is a potential benefit in the use of D-Suite across all six networks. Therefore, for all six networks, both the Reference case and D-Suite are defined, as given in Table 7. In some cases, multiple reinforcement actions or D-Suite reinforcements are required to address all congestion in each network. For conciseness just one or two D-Suite devices have been selected to compare against one or two reinforcement actions, as shown in the final column of Table 7, analysed in Section 3.1. Finally, in this section, we consider both today's PED costs (from suppliers, these have value of £250/kVA) and future PED costs (£63/kVA) with re-use of PED, if they do not enabled deferral of the PED lifetime of 20 years. Section 3.2 considers these and other sensitivity analyses in further detail.

Table 7: Summary of investments required for D-Suite and the reference case to provide congestion mitigation.

Network ID	Reference case	D-Suite case	D-Suite CBA comparison
SPM-U	Two feeder reinforcements (e.g., 400m split feeder & 200m split feeder), or, new 500 kVA substation	30 kVA D-STATCOM and 150 kVA D-STATCOM for voltage control.	Full reference case reinforcement deferral (new substn.)
SPD-U	New link box, new LV substation (or reinforcement of adjacent substation) for new capacity, two feeder reinforcements (400m and 200m split feeder).	D-ST at the substation for voltage control to avoid one cable reinforcement (D-STATCOM and D-SOP much more expansive). Two 100 kVA D-SOPs for substation and feeder reinforcement deferral.	Feeder reinforcement deferral using D-ST
SPM-S	Either, new 500 kVA substation near voltage congestion, or feeder reinforcement (350m cable overlay, 25 connections)	Two D-STATCOMs, each of 120 kVA to provide voltage control on a feeder with high R/X ratio.	Feeder reinforcement deferral (lower cost option)
SPD-S	Feeder reinforcement (split feeders of 100m and 150m), plus Tx reinforcement (500 kVA to 1000 kVA) after 4 years.	Two SOPs of 60 kVA each, connected to two congested feeders; also mitigates Tx congestion.	Full reference case reinforcement deferral
SPM-R	Feeder reinforcement, (cable overlay 250m and 20 customers)	60 kVA D-STATCOM for voltage congestion mitigation	Full reference case reinforcement deferral
SPD-R	Transformers uprate (50 kVA to 100 kVA)	24 kVA D-STATCOM for phase current unbalance mitigation.	Full reference case reinforcement deferral

Each network has a different potential reinforcement deferral duration, depending on the solution and the additional headroom that is released. Table 8 collects the number of years reinforcement deferral for low, central, or high load growth estimates. The rates of load growth are considered by considering a five-year moving average of load growth rates across all four FES scenarios and vary between 1% and 12% depending on the network (see Appendix B, Section 5.2.1). The number of years of deferral is then determined by calculating the number of years before the capacity released by the D-Suite device has been met by the load growth.

Table 8: Number of years of reinforcement deferral per network as a benefit of D-Suite installation, considering low, central, and high load growth rates.

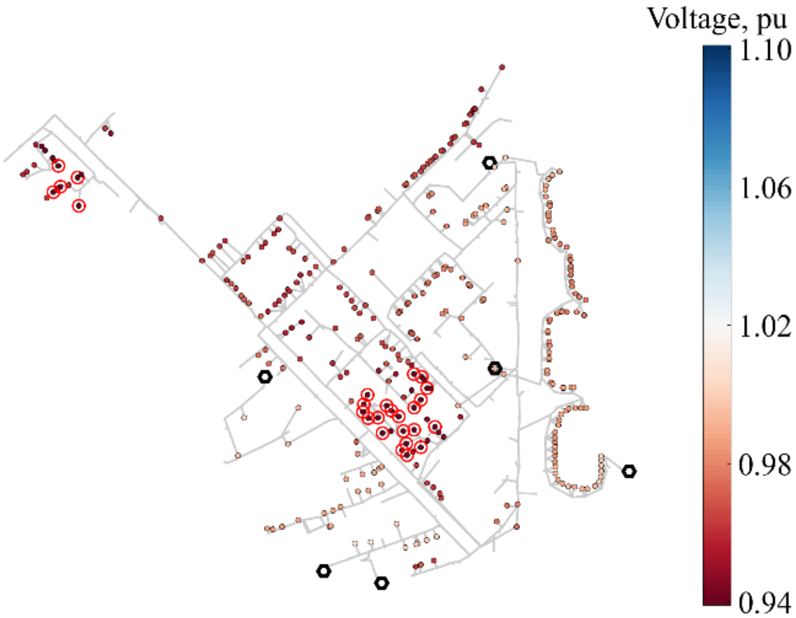
Ntwk. ID	No. years reinforcement deferral		
	Low load growth	Central load growth	High load growth
SPM-U	20.0	16.6	11.1
SPD-U	20.0	20.0	20.0
SPM-S	9.3	4.7	3.1
SPD-S	18.1	9.1	4.5
SPM-R	20.0	6.7	2.8
SPD-R	20.0	7.2	3.0

3.1. Network-level comparison of BaU and D-Suite solutions

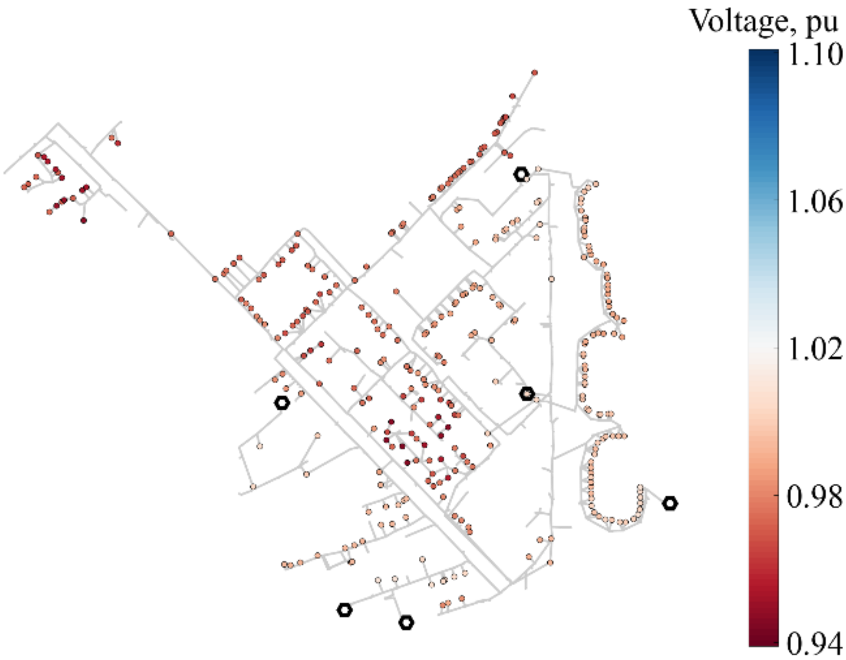
3.1.1. SPM-U Network

The SPM-U network has undervoltage issues, particularly in the case of low voltages on the HV system at peak. For the nominal HV voltage of 1.01 pu, voltage drops are only observed in one small area, and so can be resolved using a single 30 kVA D-STATCOM. Under the lower HV voltage of 0.98 pu, voltage issues are spread across two areas of the network, and so two D-STATCOMs are required of capacity 30, 150 kVA respectively. This enables an estimated reinforcement deferral of 16.6 years (this lengthy reinforcement deferral period is due to this network having a low median growth rate estimate of just 2%). Congestion before and after the latter case are shown in Figure 8.

Each of the CBA cost categories for SPM-U are summarised in Table 9. A total of 180 kVA of D-STATCOM capacity has been installed at two locations. In this case, although D-Suite enables a good deferral benefit, achieving almost its full lifetime usage, the investment required for the additional substation is not great enough. Therefore, in this case, the D-Suite device will not be cost-effective, with the NPV reduced by 3.3% compared to the reference case. Given the NPV for D-Suite is slightly negative, this case is classified as a 'marginal' case for D-Suite. In contrast, as the D-Suite PED costs are reduced in the future case, the cost-effectiveness is increased considerably, with an increase in NPV of 25% and £37,420 difference between the two cases, indicating a strong case for the D-Suite solution.



(A): VOLTAGE CONGESTION BEFORE MITIGATION



(B): AFTER D-SUITE CONGESTION MITIGATION

Figure 8: Voltage magnitude violations before and after mitigation using D-Suite congestion management (using two D-STATCOMs, with rating 30 kVA and 150 kVA respectively, located at the points of congestion in the network). Voltage violations below 0.94 pu are highlighted with red circles (these red circles are only visible in (A); all congestion is cleared in (B)). Voltage violations are determined by considering the minimum voltage over the full year's simulation.

Table 9: CBA outputs for SPM-U considering the reference and D-Suite cases. The D-Suite case enables a deferral duration of 16.6 years. PV refers to the present value (of a cost), and is always negative as there are no revenues associated with either D-Suite or reference cases. A project with a less negative NPV should be preferred. If D-Suite is cost-effective, it is highlighted in green; if it is not cost-effective, it is highlighted in orange.

	Reference case		D-Suite case	
	Cost	PV	Cost	PV
Capital costs	£100,000	-£100,000	£52,000	-£52,000
Additional O&M	£2,000/yr.	-£47,291	£900/yr.	-£11,206
Additional losses	-	-	£459/yr.	-£5715
Rnfcmnt, deferred	-	-	£147,291	-£83,104
NPV:	-	- £147,291	-	- £152,025
D-Suite benefit, PV:	-	-	-£4734	(-3.25%)
NPV (future PED)	-	-£147,291	-	-£109,871
D-Suite benefit (future OED costs), PV	-	-	£37,420	(+25%)

3.1.2. SPD-U Network

The SPD-U network has the most severe congestion issues, and so requires several reinforcement actions to mitigate both thermal and voltage issues in the network. For the D-Suite case, we consider the use of a D-ST for voltage control. This enables an almost complete decoupling of voltages in the network, and so the deferral due to the voltage congestion is the length of the PED (20 years).

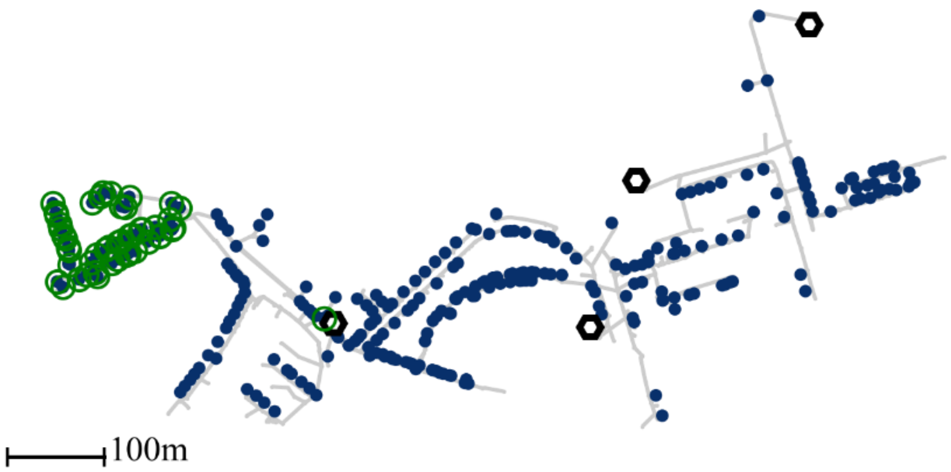


Figure 9: the feeder that needs to be reinforced for the SPD-U network extends to be several hundred metres from the western-most substation (loads connected to the feeder requiring reinforcement are highlighted in green).

The loads on the feeder which would be reinforced are shown in Figure 9. The CBA breakdown and results for D-Suite and reference case are shown in

Table 10. The reinforcement considered is a split LV feeder, with a 350m cable installed to the point where there are several loads. By contrast, the D-ST solution requires a capex of only £37,000.

Note that, in this case study, as compared to others, it is assumed that at the end of life of the PED, a new PED will be installed, and this will last the same time as the BaU asset (up to 45 years). In this case, as the asset installation can be avoided, the benefit is increased-the PV of a second PED device is only £23,148. As a result, there is a more positive NPV for the D-Suite case, resulting in a good business case for the D-ST. There is, however, a potential ambiguity here or other options that might be more appropriate. For example, if the cable has reached the end of its useful life, then it may be more appropriate to reinforce the cable at the end of the D-Suite device lifetime. At the detailed planning stage, such considerations would be required to be validated to ensure the robustness of the decision-making at the end of life of the D-ST.

Table 10: CBA outputs for SPD-U considering the reference and D-Suite case.

	Reference case		D-Suite case	
	Cost	PV	Cost	PV
Capital costs	£98,500	-£98,500	£37,000	-£37,000
Additional O&M	-	-	£300/yr.	-£4,264
Additional losses	-	-	£415/yr.	-£5,898
Rnfcmnt, deferred	-	-	£46,060	-£23,148
NPV:	-	-£98,500	-	-£66,586
D-Suite benefit, PV:	-	-	+£31,913	(+32.4%)
NPV (future PED costs)	-	-£98,500	-	-£44,223
D-Suite benefit (future OED costs), PV	-	-	+£54,277	(+55%)

3.1.3. SPM-S Network

The SPM-S network has a relatively low amount of congestion by 2040, with the main issue in the network undervoltage under a low HV network sensitivity. Conventional reinforcement via a new substation could resolve these issues, however, the streets around the congested area do not show an obvious candidate location for a substation. Therefore, under the reference scenario, a cable overlay is proposed to address the congestion, as the location with voltage congestion has a conductor of relatively low ampacity (250 A) which can be uprated to a larger conductor 400 A to reduce the voltage drop (due to the reduced cable impedance).

For the D-Suite case, the amount of capacity that can be installed is limited by the ampacity of the cables. With two D-STATCOMs, the voltage issues can be mitigated, however, it could result in thermal issues on the cable if there is further load growth, as 120 kVA must be installed on the two feeders. With this intervention, investment can be deferred, but only by 3.7 years. As a result, for the central case the CBA shows a highly negative value, as the D-Suite solution requires quite a substantial investment. In contrast, with future PED costs, there is a marginal negative NPV. Therefore, although the D-Suite solution may not be installed in practise, in future it could be a preferred option, for example, if the reinforcement solution has other costs that are not monetized in this CBA framework (e.g., varying levels of disruption for the two solutions, or uncertainty in load growth rates).

Table 11: CBA outputs for SPM-S considering the reference and D-Suite case.

	Reference case		D-Suite case	
	Cost	PV	Cost	PV
Capital costs	£100,000	-£100,000	£67,000	-£67,000
Additional O&M	-	-	£1,200/yr.	-£4,126
Additional losses	-	-	£699/yr.	-£2,405
Rnfcmnt, deferred	-	-	£99,700	-£87,701
NPV:	-	-£100,000	-	-£159,857
D-Suite benefit:	-	-	-£59,857	(-59.9%)
NPV (future PED costs)	-	-£100,000	-	-£101,248
D-Suite benefit (future OED costs), PV	-	-	-£1,248	(-1%)

3.1.4. SPD-S Network

The SPD-S network has a mix of both thermal overloads at the substation and on two of the feeders. As a result, by addressing the feeder overloads, the substation reinforcement can also be deferred. For this case, two 60 kVA D-SOPs can be installed at the link boxes on the two feeders, as shown in Figure 10. These capacities were chosen as they are around 25% of the capacity of the feeders they are connected to, and it is assumed there will not be sufficient headroom on the interconnected feeder to enable greater capacity than this. (If the interconnected networks have a higher capacity that they can achieve, or normally open points can be moved, the reinforcement deferral could be extended further; the Beta phase should explore this in more detail.) These D-SOPs enable the deferral of the feeder reinforcements by 9.1 years.

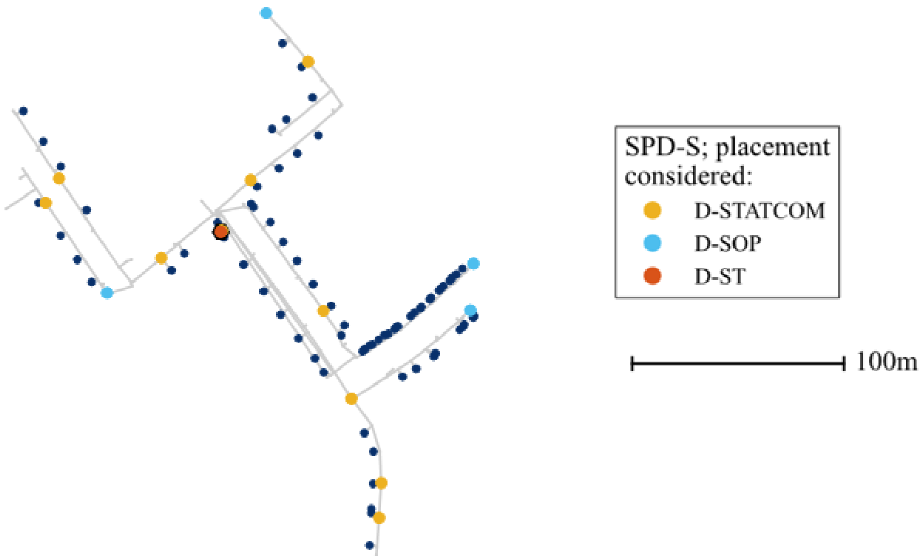


Figure 10: The two locations for the D-SOPs in the SPD-S network that can address both feeder-level congestion and congestion at the secondary substation.

For the CBA calculation, this case is more complex as the Reference case includes an uprated transformer after four years after feeder congestion starts. The costs of D-Suite are high (note that a 60 kVA D-SOP requires two 60 kVA modules, and so costs double that of a 60 kVA D-STATCOM). As a result, even though there can be a good level of reinforcement deferral (9.1 years), the high cost of the PEDs for current devices means the deferred reinforcement benefit of almost £30,000 cannot be captured under present costs of D-Suite devices. Considering future costs of PEDs, however, the D-Suite device becomes cost-effective, with 7% improvement in NPV with a benefit of £6,619.

Table 12: CBA outputs for SPD-S considering the reference and D-Suite case.

	Reference case		D-Suite case	
	Cost	PV	Cost	PV
Capital costs	£102,500	-£99,929	£67,000	-£67,000
Additional O&M	-	-	£1,200/yr	-£9,179
Additional losses	-	-	£612/yr	-£4,682
Rnfcmnt, deferred	-	-	£102,500	-£73,715
NPV:	-	-£99,929	-	-£154,704
D-Suite benefit, PV:	-	-	-£54,775	(-54.8%)
NPV (future PED costs)	-	-£99,929	-	-£93,310
D-Suite benefit (future OED costs), PV	-	-	+£6,619	(+7%)

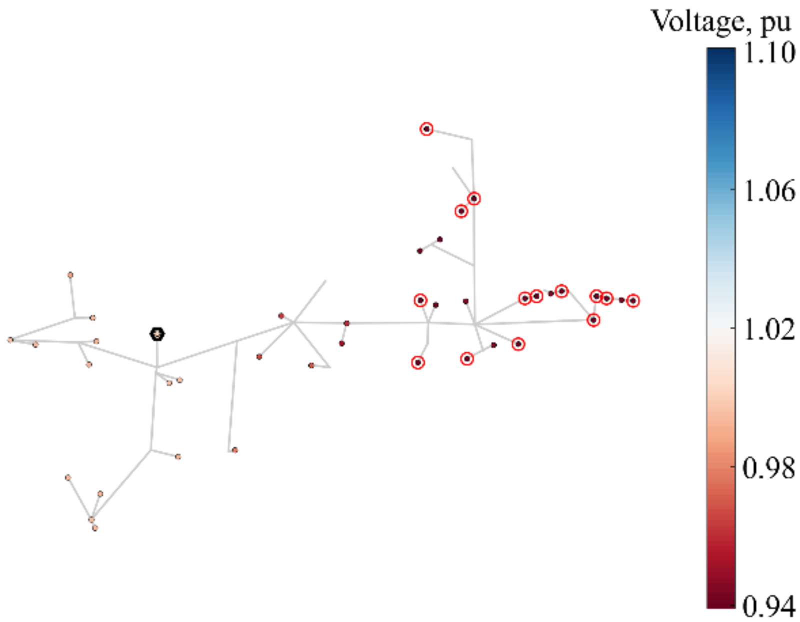
3.1.5. SPM-R

The SPM-R network shows the least congestion of the six networks, with only modest voltage congestion by 2040, despite large load growth. This is in part due to the relatively large substation transformer for the number of customers in the network. The only significant congestion seen in this network are undervoltage constraints, as shown in Figure 11.

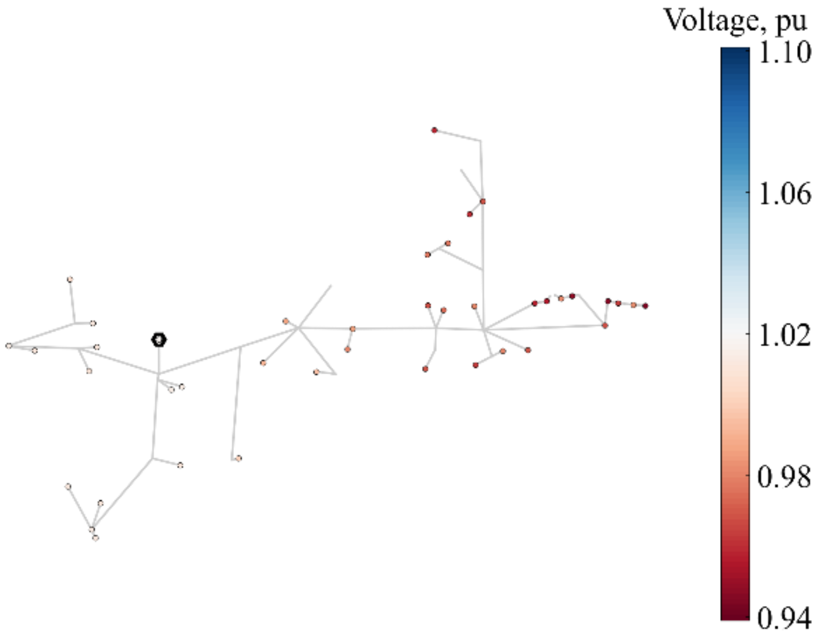
A split feeder can be used to reduce the voltage drop in this network to mitigate this issue. A comparison between the D-Suite and Reference case in Table 13 highlights that there is some potential for reinforcement deferral in this case, but again the relatively high cost of the D-Suite device today results in a negative NPV for D-Suite as compared to the reference case. As PED costs drop, the situation reverses, with a deficit of -9.2% being replaced with a benefit of +12%.

Table 13: CBA outputs for SPM-R considering the reference and D-Suite case.

	Reference case		D-Suite case	
	Cost	PV	Cost	PV
Capital costs	£72,500	-£72,500	£18,500	-£18,500
Additional O&M	-	-	£300/yr.	-£1,443
Additional losses	-	-	£244/yr.	-£1,776
Rnfcmnt, deferred	-	-	£82,500	-£65,410
NPV:	-	-£72,500		-£79,200
D-Suite benefit, PV:			-£6,700	(-9.2%)
NPV (future PED costs)	-	-£72,500	-	-£64,111
D-Suite benefit (future OED costs), PV	-	-	+£8,389	(+12%)



(A): VOLTAGE CONGESTION IN 2040



(B) AFTER D-SUITE CONGESTION MITIGATION

Figure 11: The SPM-R network under a low HV voltage of 0.98, showing undervoltage by 2040 in parts of the network farthest from the substation (subfigure (A), with undervoltage highlighted by red circles). By introducing a 60 kVA D-STATCOM, these undervoltage can be avoided (subfigure (B), with no red circles, highlighting congestion has been cleared).

3.1.6. SPD-R

The SPD-R LV network is off-gas, and the transition to electrified heat (heat pumps) is fast. This results in a fast load growth initially. Furthermore, a high level of households with multiple car-parking spaces leads to higher EV demand. As a result, there are thermal overloads at the substation in this network quickly, has been shown previously in Figure 7.

As the network is in a rural location, there are no potential locations for D-SOPs to relieve the substation transformer at peak loading. As a result, D-Suite can only support this network via active phase balancing from a D-STATCOM. A 24 kVA can increase the capacity in this way, with the relatively small number of customers means that the fraction of the capacity that can be released via PCBF improvement is greater than substations on other networks with larger transformers.

Table 14: Summary of central scenario NPV calculation for the SPD-R case.

	Reference case		D-Suite case	
	Cost	PV	Cost	PV
Capital costs	£11,000	-£11,000	£9,500	-£9,500
Additional O&M	-	-	£120/yr.	-£752
Additional losses	-	-	£12.24/yr.	-£77
Rnfcmnt, deferred	-	-	£11,000	-£8,587
NPV:	-	-£11,000	-	-£18,916
D-Suite benefit, PV:	-	-	-£7,916	-72.0%
NPV (future PED costs)	-	-£11,000	-	-£13,102
D-Suite benefit (future OED costs), PV	-	-	-£2,102	(-19%)

The results of this network are summarised in Table 14. For this case, as the transformer is relatively small, a larger D-Suite capacity can be installed for PCBF improvement than in larger networks (24 kVA, as compared to the transformer rating of 50 kVA). This enables deferral of the reinforcement of more than six years. In this case, however, as the reinforcement action is quite low-cost, there is no significant benefit of D-Suite in this case - this result also holds even for the future PED cost. This result is not unexpected, as in this case the uprating of the transformer much lower cost than other solutions (the next smallest reinforcement action is six times more expensive for SPM-R, at £72,500).

3.2. Sensitivity Analysis

As D-Suite is a new solution, there are several CBA parameters which are uncertain which can have a significant impact on results, and so are considered as part of sensitivity analysis, as follows.

- The cost of capacity of the D-Suite devices are high, at £250/kVA, and it is assumed there is no salvage value of the device. In the sensitivity analysis, we consider a potential reduction in cost of 75% to £62.5/kVA, and, with the PED available for redeployment at the end of its useful life. This is considered an optimistic but realistic future cost in the next 5-10 years, based on a comparison against LV three-phase solar inverters or AC drives which typically cost from £40/kVA to £135/kVA (depending on manufacturer, capacity, and device capabilities). Redeployment of PEDs would require suitable designs and training to enable extraction from its housing (and so is not envisioned for the Beta phase).

- Assuming linear depreciation and a 20-year PED life, redeployment could be particularly effective in cases installation costs can be minimized and deferral is for only a small number of years, or, where there is the risk of fast load growth, this would mitigate the risk of stranded assets.

  In many cases, this rate of load growth in the network is not well-known, as the installation rates of LCTs are determined by customers. This means that the duration of reinforcement deferral will not be known at the time at which the D-Suite device is installed (so, load growth at installation could potentially follow any of the values of Table 8). Therefore, there will likely be significant uncertainty as to load growth potential. Although they are not explored here, formally 'real option' analysis can be used to quantify these benefits. Here, we consider the benefits if load growth is small to consider the potential increase in potential benefits; future work could explore those formal techniques for assessment of the benefits.

Table 15: Result of sensitivity analysis for cases of cost-effective PEDs, and for a low load growth. Lower cost PEDs will make D-Suite a much more attractive solution, with half of networks having a good level of benefit as compared to the BaU reference case (more than 10% benefit). The term 'ΔNPV' refers to the change in NPV between D-Suite and reference cases.

Ntwk. ID	Scenario									
	Reference case	D-Suite central case			D-Suite, cost-effective and reusable PEDs			D-Suite, low load growth scenario		
	NPV, £	NPV, £	ΔNPV, £	(%)	NPV, £	ΔNPD, £	(%)	NPV, £	ΔNPV, £	(%)
SPM-U	-147,291	-152,025	-4,734	-3%	-109,871	37,420	25%	-145,338	1,953	1%
SPD-U	-98,500	-66,586	31,914	32%	-44,223	54,277	55%	-66,586	31,914	32%
SPM-S	-100,000	-159,857	-59,857	-60%	-101,248	-1,248	-1%	-153,773	-53,773	-54%
SPD-S	-99,929	-154,704	-54,775	-55%	-93,310	6,619	7%	-142,252	-42,323	-42%
SPM-R	-72,500	-79,200	-6,700	-9%	-64,111	8,389	12%	-61,374	11,126	15%
SPD-R	-11,000	-18,916	-7,916	-72%	-13,102	-2,102	-19%	-16,908	-5,908	-54%

Table 15 reports the values of this analysis for the six networks and these two sensitivities. A number of key points can be drawn from this table. Firstly, it can be seen that a reduction the cost of PEDs for D-Suite applications would result in the business case being improved in all cases, as can be expected. For example, in the central case, PEDs are cost-effective in one network (SPD-U) and have marginal negative NPV (less than 10% reduction) in two cases. In contrast, for a low-cost D-suite case, only one network will have poor cost-effectiveness (SPD-R), with three of the six cases having an improvement of more than 12%.

It is also interesting to note the cases with the strongest positive and negative NPVs remain strongly viable and strongly non-viable even considering the two sensitivity analyses. The favourable load growth sensitivity (resulting in longer deferral periods for D-Suite in cases where the deferral benefit is less than 20 years) has a smaller impact on the cost-effectiveness of D-Suite devices in many cases, but it does have a strong impact on the SPM-R case. This is because SPM-R has up to 2040 some periods where load growth is very low (1%), enabling the deferral to be increased up to 20 years to make full use of the D-STATCOM in that case.

3.3. Comparison Against Beta Phase Proposal CBA

The activities carried out in this report have been conducted in parallel with the GB-wide CBA developed for the Beta Phase proposal, with the latter's analysis having been carried out by SPEN. Outputs from this CBA have informed their analysis; likewise, the CBA of this report also has utilized known reinforcement costs obtained from SPEN's ED2 planning processes obtained for the GB-wide CBA.

Note that the detailed methodology and results of the GB-wide CBA are not presented in this report. Nevertheless, a short comparison between the methods is given to highlight how the results of this analysis have been leveraged to support the extrapolation to the GB-wide CBA.

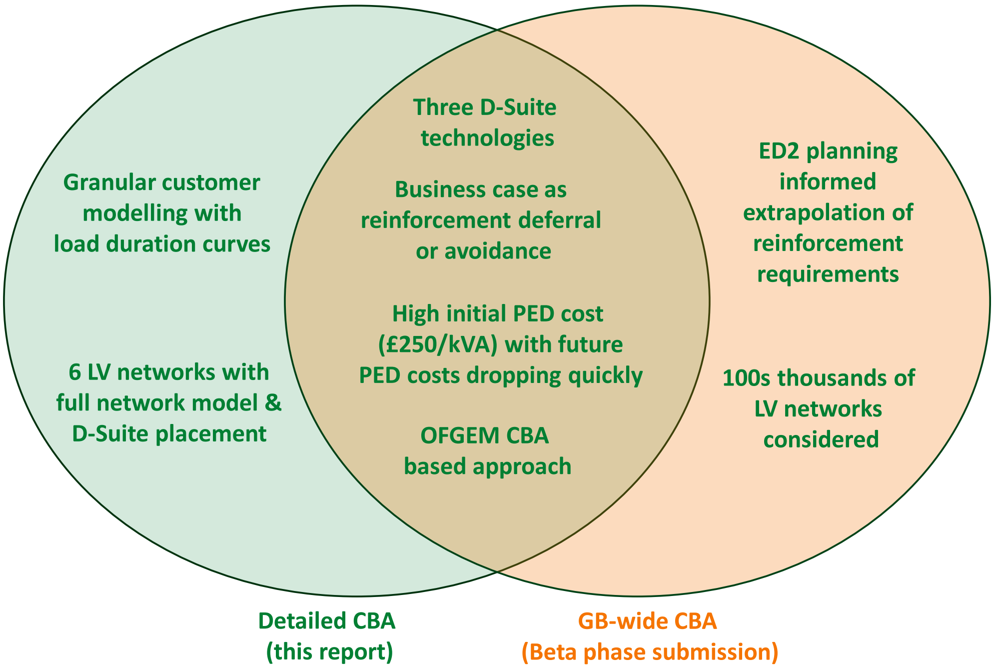


Figure 12: Venn diagram comparing the D-Suite CBA conducted in this report, as compared against the CBA carried out for the GB-wide CBA for the Beta phase submission. Naturally there are some differences in approach given the difference in scale, however there is a strong overlap between methods and strong cross-over of CBA parameters.

A comparison between the two approaches is summarised in Figure 12. The overlaps of the detailed network-level CBA (this report) and the GB-wide CBA (Beta phase proposal) include the following.

- OFGEM's CBA approach has been used for as the core analysis approach for the CBA to enable the approach to be considered in the context of ED planning and other innovation projects.
- Both analyses consider three D-Suite technologies (D-SOP, D-STATCOM, D-ST) for congestion mitigation, with the fraction of deployments of each technology in the GB-wide CBA derived from results of this report.
- Reinforcement deferral or reinforcement avoidance have been considered as the primary business case for these D-Suite devices, which ultimately enables societal benefit through a reduction in customer bills from reinforcement actions.
- The PED costs in both analyses consider a high initial cost for the Beta phase (£250/kVA), based on existing products available from current suppliers. However, both cases assume that PED costs will start to reduce as volumes of PEDs increase to match the material cost or costs of other comparable technologies (such as AC drives or solar inverters) more closely.

The main difference between the methods is in terms of the granularity of the detail that can be included within the analysis. The GB-wide CBA considers all LV networks within SPEN's service area using reinforcement forecasts for the ED2 period. The results are then extrapolated beyond the ED2 period to other service areas. Parameters from this CBA have been shared in the development of SPEN's CBA, including the specific technology used and their capacity (i.e., the fraction of devices which are D-ST, D-SOP or D-STATCOM and their capacities).

The CBA in this report complements this by considering a granular analysis across six networks. In addition to the provision of parameters required to consider D-Suite benefits in the GB-wide CBA, the high level of detail also enables consideration of technical aspects such as phase unbalance, LCT time series profiles for creating load duration curves, D-Suite placement, and detailed costing for specific reinforcement actions. It also enables illustration of the mechanism by which D-Suite provides societal benefits.

The benefits calculated in this report (Table 15) show potential improvements in NPV of tens of thousands of pounds per each LV reinforcement trigger, results of which are mirrored in the Beta phase D-Suite calculations (results of the GB-wide CBA not presented here). Similarly, this report highlights that although D-Suite will not be cost-effective in all scenarios, that a significant number of reinforcements can be deferred (one in six for present PED costs; four in six for future PED costs), with benefits across each of urban, suburban, and rural networks and each of the three D-Suite devices. Consequently, it can be considered that D-Suite has strong potential to be a cost-effective solution to enable growth of LCTs to support the Net Zero transition for DNOs.

4. Conclusions

D-Suite devices can provide a wide range of services that can support the uptake of LCTs in distribution networks across the UK. This report has developed a CBA methodology for assessing the potential benefits of deploying these devices on six networks in the SPD and SPM service areas. Customer-level LCT deployments highlight potential congestion on all six of these networks, particularly as heat pumps and electric vehicles are deployed.

The CBA approach is based on OFGEM's RIIO-ED2 framework and the Common Evaluation Methodology, enabling the societal benefits of reinforcement deferral to be evaluated. The CBA calculations use Business-as-Usual reinforcement as the reference case, with D-Suite device costs based on costs from potential suppliers of D-Suite solutions for the Beta phase.

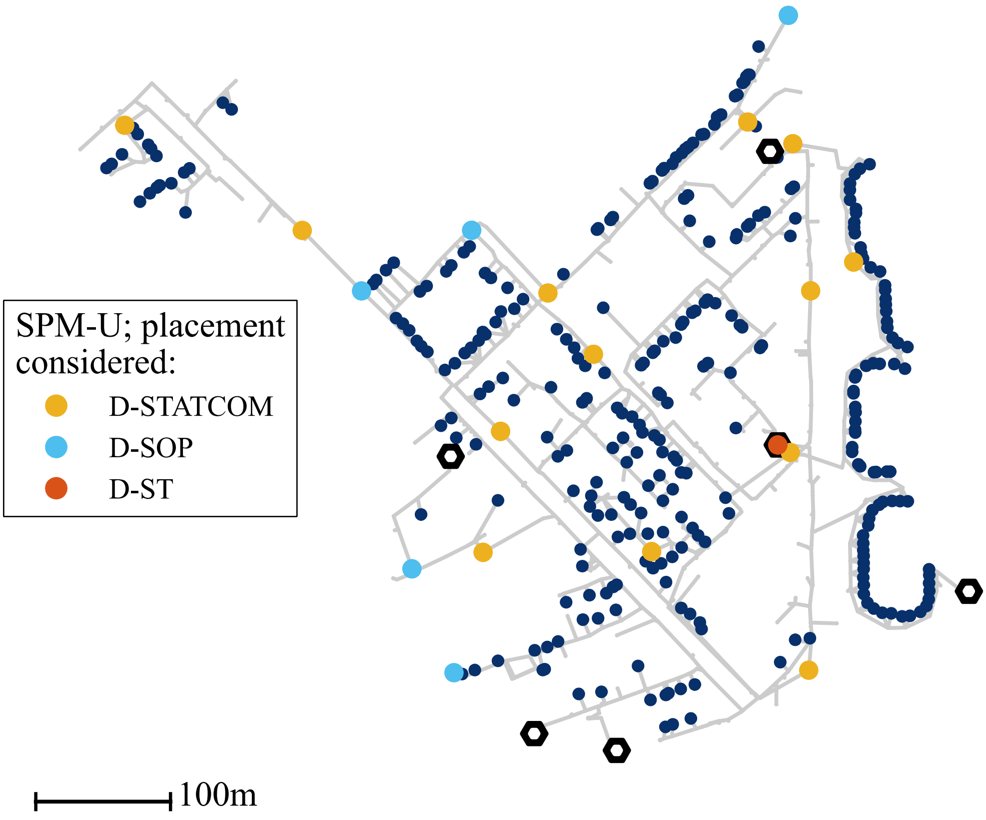
This detailed network-level CBA methodology has been developed in parallel with a GB-wide CBA (results not presented in this report) developed for the Beta phase proposal. Whilst the methods differ, there is strong overlap between the approaches and the scale of the potential savings are mirrored from the two methods (in terms of NPV improvement, and fraction of places where D-Suite is cost-effective).

Results of the CBA show that present costs of D-Suite devices lead to positive NPV in one of the six cases, with marginal negative NPVs in two of the six networks. Under a situation whereby D-Suite PEDs achieves costs closer to present solar inverter costs (on a per-kVA basis), D-Suite devices are much more cost-effective, with only one of the six networks showing a strongly negative NPV. It is concluded that, if D-Suite devices can exploit cost reductions in similar power electronic technologies to realise these cost reductions, that D-Suite could become an attractive option for LV distribution network reinforcement deferral across the UK.

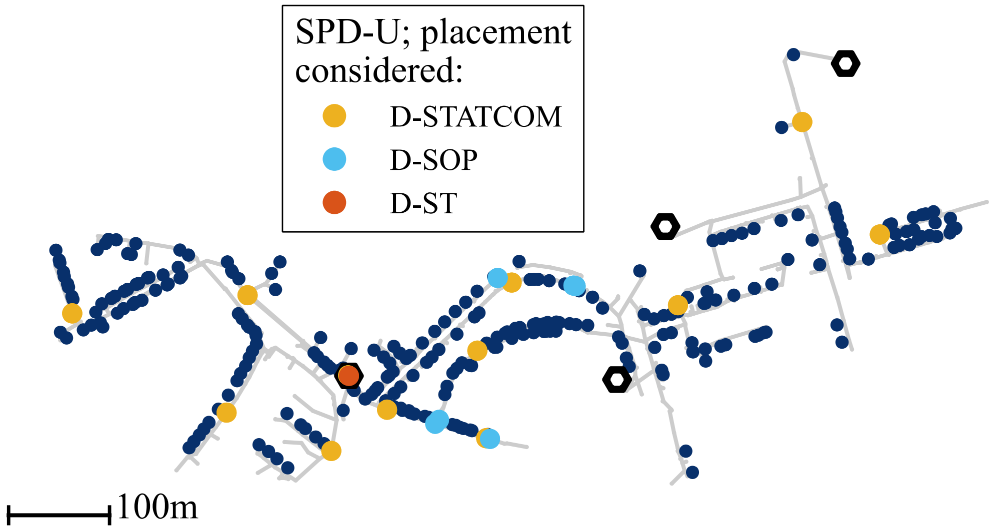
5. Appendices

5.1. Appendix A: Candidate Siting of D-Suite Devices

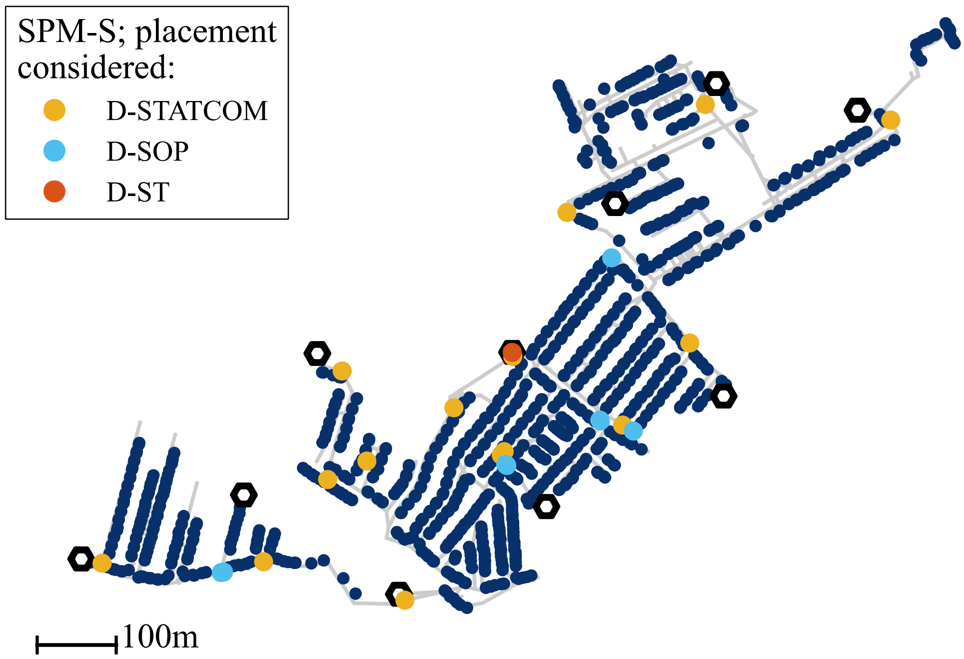
In this Alpha phase of the D-Suite project, a range of D-Suite devices were placed across a range of candidate locations for each of the six networks via a manual approach. Candidate D-STs were placed at secondary substations and D-SOPs at normally open link boxes. All candidate locations of each network considered in network analysis are plotted in Figure 13 (A)-(F).



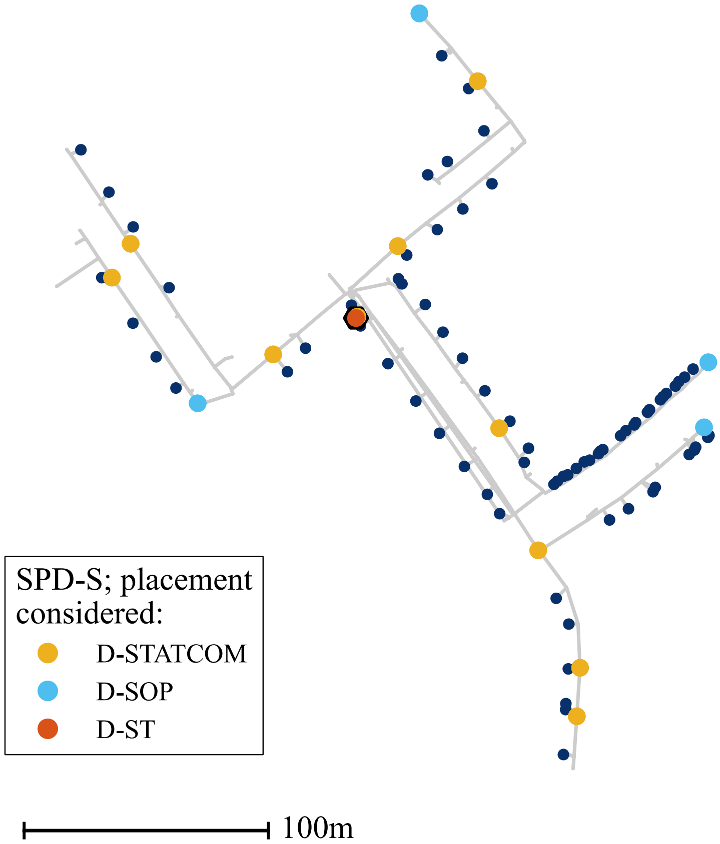
(A): SPM-U


SPD-U; placement considered:
D-STATCOM
D-SOP
D-ST
100m

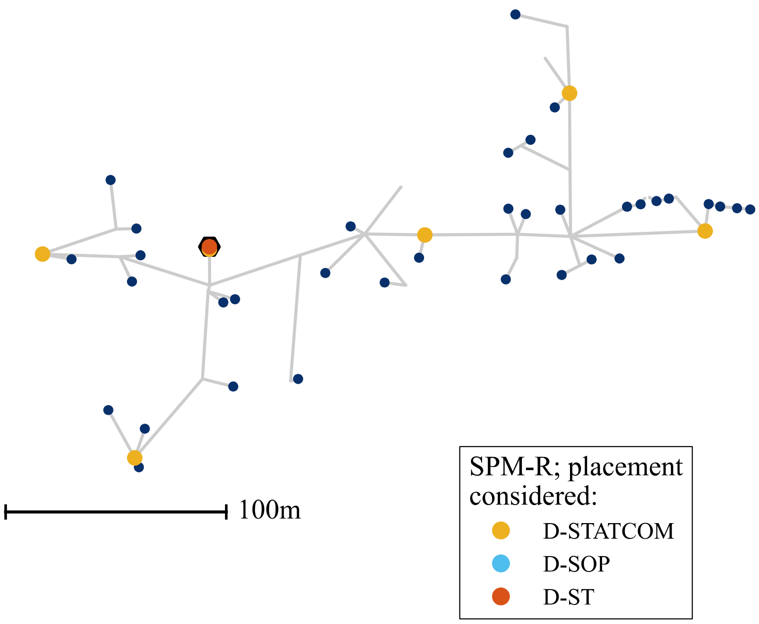
(B): SPD-U


SPM-S; placement considered:
D-STATCOM
D-SOP
D-ST
100m

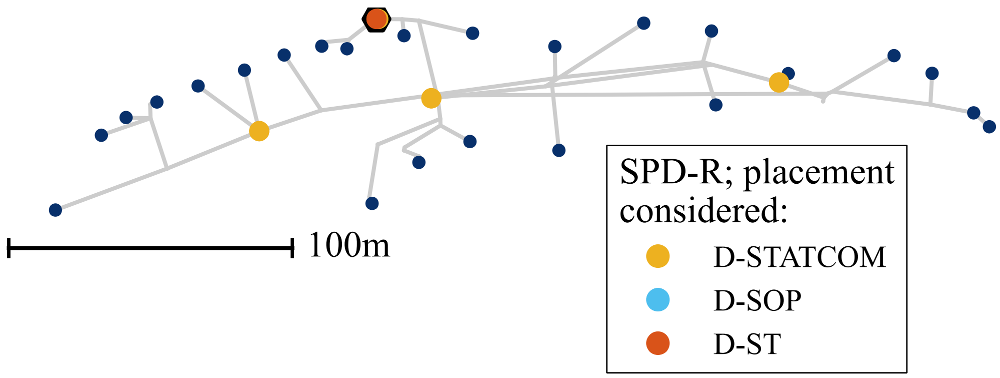
(C): SPM-S


SPD-S; placement considered:
D-STATCOM
D-SOP
D-ST
100m

(D): SPD-S


100m
SPM-R; placement considered:
D-STATCOM
D-SOP
D-ST

(E): SPM-R



(F): SPD-R

Figure 13: Topology of each of the six networks considered for, and potential D-Suite placement options considered in analysis.

5.2. Appendix B: LCT Allocation Software Model

The study in the report requires a model of demand and its growth over an extended period, as the uptake of LCT is dependent on socio-economic factors as it is necessary to model the specific way LCTs will be applied to housing stock. This appendix presents the methodology for sampling the uptake of LCTs on the networks and applying one or more profiles of LCT from the datasets discussed in Table 5. The model structure i.e., how frequently and which LCTs are sampled from are outlined. Finally, some further issues encountered in the modelling process have been outlined that can be addressed in the Beta phase of the project to improve the accuracy further.

The simulation proceeded by loading uptake curves ,Table 20, and choosing a FES scenario. The sampling method is based on sampling, for every customer and for every year, the specified profiles from the LCT profile dataset. A seeded pseudo random number generator (PRNG) is used so that simulations are reproducible.

The model definition permits dynamic assignment, where the type and number of profiles is assigned stochastically at runtime. For example, which uptakes should apply and whether a subset of relevant profiles should be used. The definition of the model can, for example, prevent smart-charging being used in on-street charging networks, but also permit interventions such as resistive heating conversion to heat pump technologies. The other elements of the model were defined through static variables, such as the estimated sizing of any photovoltaic array or property size. The implementation of static and dynamic assignments is an implementation detail of the model which gives ample flexibility the methodology described below.

The LCT's treatment in the software model is as follows.

1. Base loading (Smart Meters)
    a. Weighted sample dependent on property size. Draws one of small, medium or large.
2. Electric Vehicle Charger

a. Weighted sample dependent on property size. Draws one of small, medium or large.

b. Drawn per parking space, with an uptake driven choice between smart-charging profile or regular.

c. If on-street parking, instead draw once with 75% chance without smart-charging.

   i. On-street parking assumed for urban networks with no driveways (SPM-U, SPD-U, SPM-S.)

   ii. SPM-U may have an issue with EVUP parking. See Table 21.

d. EV Uptake and EV smart-charging uptake are used from Table 20.

3. Solar PV

   a. Derive static orientation relative to feeder section tangent.

   b. Sizing was applied by taking the EVUP footprint halved and reducing a further 30% and presenting it at 35° as a rooftop before sizing the array on a PV density of 160 W/M^2.

   c. However, if the building had more than three storeys no PV was applied. If multiple customers occupied the same building, only one can has a PV profile applied.

   d. Profiles were applied by uniformly sampling any valid profile of orientation with respect to the orientation of the customer i.e. An East-West Customer may sample a uniformly east or west facing array.

4. Electric heating

   a. Using static estimate of occupancy from property size.

   b. Uptake governed by curve in Table 20.

   c. For SPM-U alternative resistive to heat pump refit-uptake was used (Figure 14).

The methods used to determine LCT uptake are based on a national uptake, and so interactions at a local level (e.g., community-wide actions) are not modelled. This may, for example, underestimate effects whereby LCT at one property makes neighbours more likely to purchase that same LCT. Additionally, changes in population or sociodemographic distribution for the areas represented by the networks are not modelled. Via inspection from satellite imagery, networks such as SPM-S and SPD-U do not appear to have suitable rooftop buildings for PV.

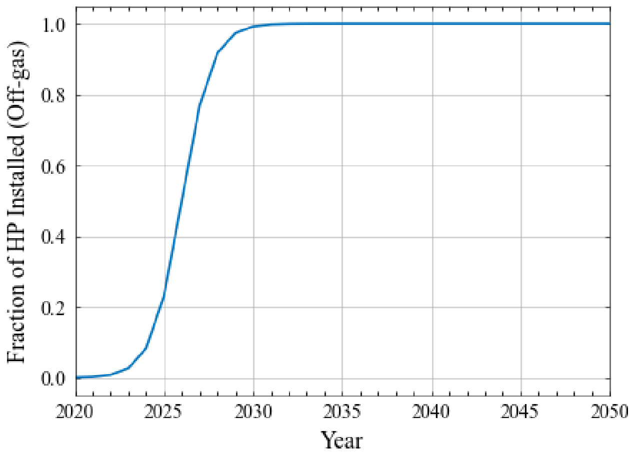


Figure 14: The heat pump uptake, based on a logistic function curve used for SPM-U parameterised as limit of 1, growth 1.2 and a midpoint 2026. This results in a sharp uptake compared to the FES however due to energy costs associated with resistive heating customers are incentivised to do so and may draw on funding to do this.

Table 16: Renewables Ninja Photovoltaic output sizing. These parameters provided to the model produce a system output for the PV array and associated converter. In the absence of tracking, the combination of sizing and orientation are generated for the MERRA-2 weather year of 2010 for the locales of Wrexham and Glasgow.

Variable	Value
Point (lat/lon)	SP Distribution – Glasgow (55.8617 / -4.2583) SP Manweb – Wrexham (53.0430 / -2.9925)
Dataset	Merra-2 (global)
Weather year	2010
Capacity	1kW, 2kW, 4kW
System loss	0.1
Tracking	None
Tilt	35°
Orientation (azimuth)	100° (East), 180° (South), 260° (West)

Table 17: Heating Demand parameters as used in Renewables Ninja. A range of parameters are combined to generate a heating load for a household. A range of weather and building characteristics are used to provide a heating load for the MERRA-2 for the year 2010 at Wrexham and Glasgow. Several temperature thresholds are generated.

Variable	Value
Point (lat/lon)	SP Distribution – Glasgow (55.8617 / -4.2583) SP Manweb – Wrexham (53.0430 / -2.9925)

Dataset	Merra-2 (global)
Weather year	2010
Heating/cooling threshold	11-17 °C / 17-23 °C
Base power	0 kW
Heating power	0.025 kW/°C per person for electricity demand 0.100 kW/°C per person for gas demand
Cooling power	0.050 kW/°C per person for electricity demand
Smoothing (days)	0.2 to 0.8
Solar gain	0.004 to 0.020
Wind chill	-0.05 to -0.35
Humidity discomfort	0.00 to .10

Table 18: EV Quantile Weightings, smaller households get a charger from the lower quantiles. This in effect relates size of the property with increased demand resulting from (assumed) increased driving activity. These figures are open to revision but are limited by the metadata available on charging activity and lifestyle.

	Quantile Weight		
Property Size	Lower [0, 0.33)	Middle [0.33, 0.66)	Upper [0.66, 1]
Small	0.5	0.25	0.25
Medium	0.25	0.5	0.25
Large	0.25	0.25	0.5

Table 19: Smart meter quantile weightings, smaller households are assigned lower usage profiles. These assume an overall lower level of demand in smaller and less populated households. Limited data is available to link size of household to its demand in the underlying dataset's profiles, but the Experian classes were used to reweight according to the relative occurrence of a quantile with relative occurrence of the Experian class in the HEATUP data. This permits accounting for relative changes in affluence due co-location on networks that are not present in the CLNR data.

	Quantile Weight		
Property Size	**Lower [0.02, 0.60]**	**Middle [0.20, 0.80]**	**Upper [0.40, 0.98]**
Small	0.38	0.34	0.27
Medium	0.32	0.35	0.33

Large	0.22	0.33	0.45

Table 20: Listing of series used in determining penetration and uptake of LCT. The series number is given from the FES report [5] or the otherwise listed source.

LCT	FES series	Remark
EV	EC.11: Battery electric cars on the road	A 5-year lag was used to represent second hand uptake.
EV Curtailment	EC.12: Reduction in unmanaged peak demand for EV charging due to smart charging	
Heating	EC.08: Annual heat pump installations	NB: a logistic function was applied to refitting from resistive heating in SPM-U (Figure 14).
PV	Northern PowerGrid DFES PV Uptake	See [6]

5.2.1. Peak Load Forecast

The simulation was run across each network for each of the years from 2023-2050, matching the FES. Each year was sampled twenty times to assess the range of values at the peak demand. The Leading the Way (LW) scenario was considered for assessing rates of load growth and congestion. This quickly produces high uptakes of LCTs and therefore an increasing peak demand, as shown in Figure 15. All networks see a doubling in peak demand per customer, largely driven by a peak in EV uptake in the mid-2030s. Heat-pumps also provide increasing baseload in seasonal heating. The larger ranges are reflective of smaller customer sizes in the rural networks. SPM-U's initial decrease in demand is caused by a refit of resistive electric heating to heat-pump based heating, lowering heating demand. The other five networks do not have resistive heating at the outset. The demand peak and slight decline in later year of the model in the 2040s are due to Leading the Way's assumptions around increased use of public transport and a corresponding diminishing EV ownership.

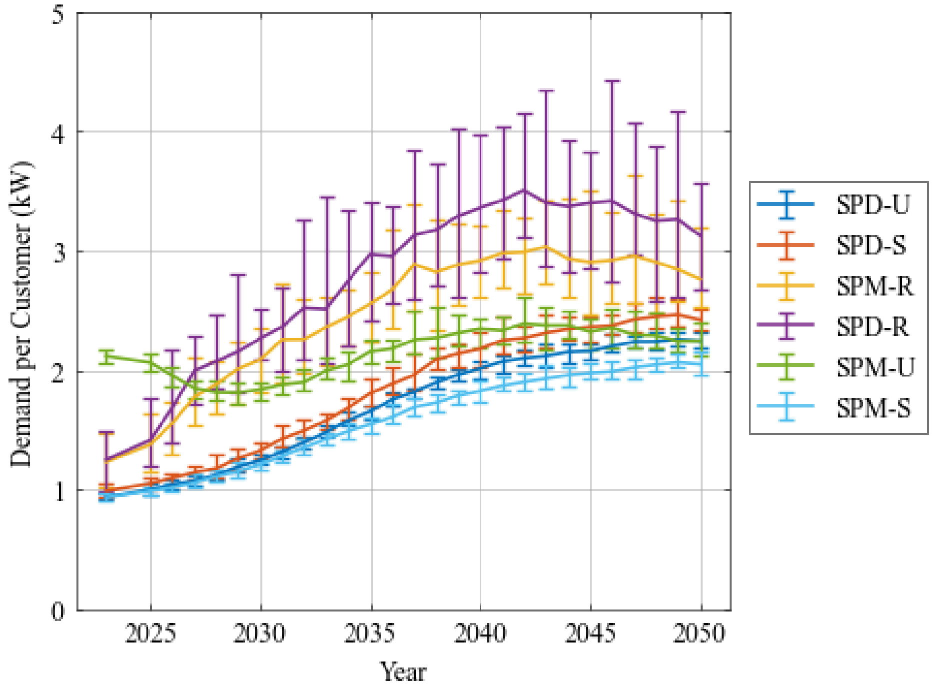


Figure 15: Yearly peak demand per customer under Leading the Way, based on sampling 20 times a year. Error bars indicates the minimum and maximum while the series plots the mean. Rural networks having fewer customers are most uncertain but have ample need and space for EV charging. While those in urban and suburban networks see limited growth due to lack of charging spaces. A slower ramping heat pump demand sustains growth through the latter half of the scenario. PV is largely absent due the peak loading being in the dark winter evenings.

To explore other possible scenarios, and their impact on load growth 5-year rolling percentage change is plotted in Figure 16 for each of the four FES scenarios. LW and Consumer Transformation (CT) result in larger amounts of LCT in LV networks. Whereas there are limited LCTs installations under Falling Short (FS) and System Transformation (ST) scenarios, which instead have slower HP/EV uptake and an increased range of heating types of hydrogen heating. This largely causes these two-scenario pairings to behave in a similar way.

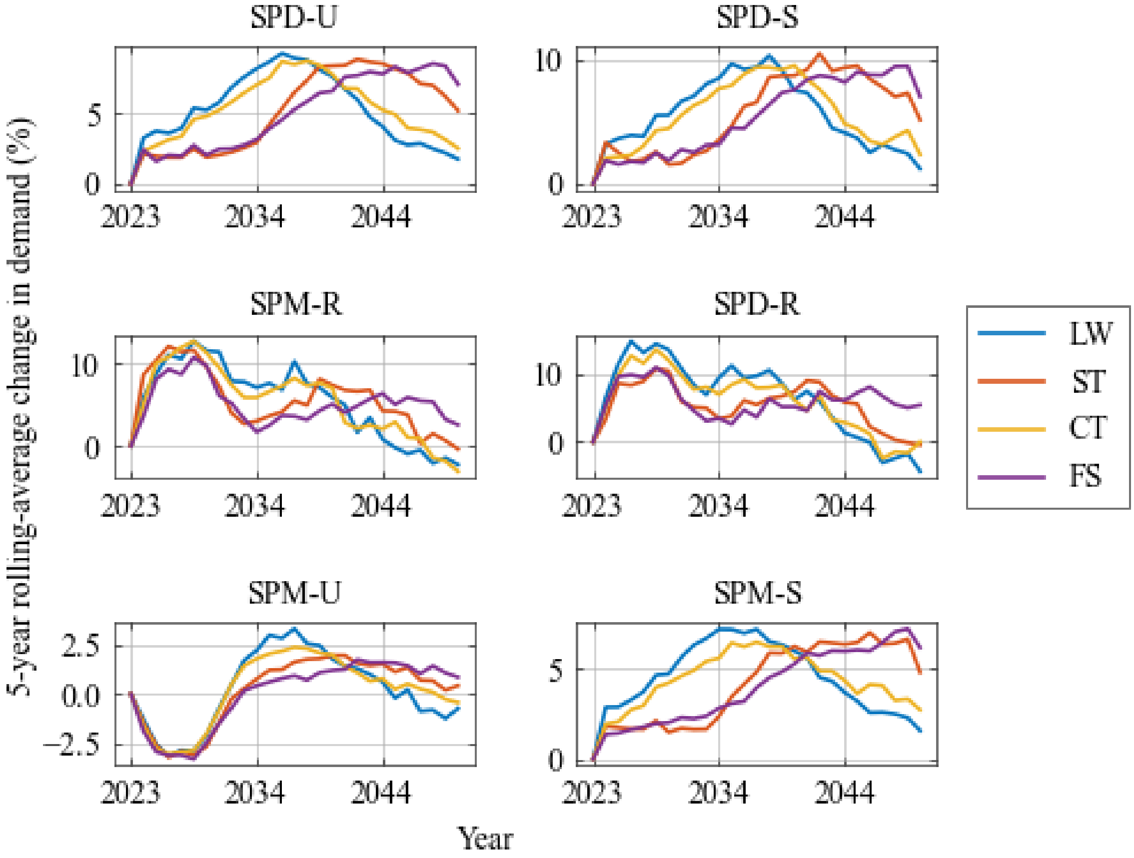


Figure 16: Percentage change in 5-year moving average by scenario for each network. The six networks have each see growth with the largest driven by EV growth in rural and sub-urban. Moderate or tapering growth occurs in the latter half due to the assumptions of changing social norms or delayed HP and EV uptake.

The sociodemographic and geography of the networks also affects the rate of growth of LCTs. SPD-U and SPD-S have limited parking available, so have a lower rate of car ownership than the other networks. The terraces of SPM-S can host a substantial amount of EV charging, but the "second-hand car ownership" flag delays this growth. SPM-U is in a neighbourhood which is developing rapidly, and manual inspection through satellite and Streetview services suggests there is a potential underestimate of the amount of EV charging it could host.

The scenarios, generally, have a HP growth in later years. These rates are much lower in ST and FS scenarios. This can be seen in networks which are exceptionally dense (SPD-S and SPD-U), whereas the rural networks and SPM-S is dominated by principally EV uptake only.

Summary of Network Makeup

Several summaries of the underlying datasets are provided in tables to highlight the differences between the networks. Table 21 shows a breakdown of the storeys of the buildings occupied by customers. Note that SPM-R required re-surveying for these datasets. A small degree of industrial and commercial customers is found in the cities but these are a minority due to density of customers on the networks, see Table 26.

Several other tables are included to give a sense of the underlying housing stock. These include: Table 21, a breakdown of property storeys; charging spaces per property in Table 22; PV sizing in Table 23, and PV orientation

Table 24. Table 25 and Table 26 present respectively the heating usage allocations we converged to and the customer numbers as well as amount of industrial and commercial customers.

Table 21: EVUP Building storeys breakdown by network (NB: SPM-U appears have a 2-3 storey new build estate; hence is not surveyed meaning storeys are given as unknown).

EVUP Building Storeys	SPM-U	SPD-U	SPM-S	SPD-S	SPM-R	SPD-R
1	7%	4%	6%		71%	88%
2	11%	4%	85%		14%	12%
3	1%	3%	8%		14%	
4	1%	15%	0%			
5		37%		13%		
6		22%		30%		
7		12%		55%		
8		1%		2%		
9		1%				
Unknown	80%					

Table 22: Breakdown of EVUP charging spaces.

EVUP Parking Spaces	SPM-U	SPD-U	SPM-S	SPD-S	SPM-R	SPD-R
0	41%	97%	42%	100%	11%	4%
1	14%	2%	38%		11%	
2	44%	1%	20%		77%	96%

Table 23: PV Orientations breakdown, the orientations which a roof slope may face for purposes of mounting solar panels.

Orient Code	SPM-U	SPD-U	SPM-S	SPD-S	SPM-R	SPD-R
East or West	23%	22%	29%	29%	54%	29%
South	21%	47%	22%	15%	31%	46%
South-East	30%	14%	37%	31%	3%	12%

South-West	25%	18%	12%	25%	11%	12%

Table 24: PV Installation sizing (W) estimated from HEATUP sizing data.

PV Size (kW)	SPM-U	SPD-U	SPM-S	SPD-S	SPM-R	SPD-R
0	40%	97%	36%	100%	57%	71%
1.0	21%	0%	5%		3%	
2.0	31%	2%	56%		23%	25%
4.0	7%	1%	3%		17%	4%

Table 25: HEATUP adoption group, the types of properties as defined by the HEATUP project [3].

HEATUP Adoption Group	SPM-U	SPD-U	SPM-S	SPD-S	SPM-R	SPD-R
Large Owned or Rented	7%	55%	41%	95%		
Medium And Large Social	6%	10%	13%	5%		
Medium Owned or Rented	5%	29%	33%			
Off Gas	79%	2%	3%		100%	100%
Small Owned	1%	1%	3%			
Small Rented		3%	3%			
Small Social	2%	0%	4%			

Table 26: Network Industrial and Commercial Summary

Network	No. I&C/Residential	% I&C	Notes
SPM-U	4/299	1.3%	Church, small indoor market
SPD-S	24/487	4.9%	Small units, Nursery, several restaurants
SPD-U	38/1353	1.7%	Assorted small units and medium
SPM-S	8/1102	0.7%	1 Medium and otherwise small units
SPD-R	0/24	0%	
SPM-R	0/35	0%	

5.3. Appendix C: Capacity Headroom from D-Suite Devices

For some applications of D-Suite, the congestion mitigation potential is straightforward to calculate. For example, for a D-ST, the voltage control that can be achieved even using a relatively small amount of power electronics results in a large voltage drop mitigation potential. Similarly, a D-SOP mitigating thermal congestion in a network with unity power factor loads is the same as the capacity that it can inject into a transformer or feeder.

In this section we explore the capacity that can be released due to mitigation of current unbalance, based on measured data (Section 5.3.1) , then the additional capacity that can be released due to voltage control from a D-STATCOM (Section 5.3.2).

5.3.1.Phase Current Balance Factor

The Phase Current Balance Factor (PCBF) is used to indicate the potential benefits of D-Suite devices on the mitigation of phase unbalance. (This factor is introduced as there is no industry-standard approach for communication of impacts of phase current unbalance on network capacity.) The PCBF is a factor defined by the mean over the maximum of the phase currents (or powers), as

$$\mathrm{PCBF} = \frac{P_{\mathrm{Ave}}}{\max(\{P_A,\ P_B,\ P_C\})},$$

where P_A, P_B, P_C are the active powers (or currents) injected into phase A, B, C respectively, and P_{Ave} is the average of those three powers (or currents).

This PCBF definition is given to be directly analogous to power factor, in terms of capacity uplift that can be achieved. For example, for a power factor of 0.9, the loading of a transformer or cable could be increased ~10% by using power factor correction. Similarly, a transformer or cable with a PCBF of 0.9 could release 10% capacity headroom via balancing of the currents in its phases. A balanced feeder will have a PCBF of 100%, as all currents (and powers) are equal. However, for a cable with active powers of 80kW, 100kW and 120kW in phases A, B and C will have a PCBF equal to 83%.

The PCBF, as defined above, is given as a ratio for a given measurement. From a capacity perspective, the most critical point of view for capacity is in terms of the additional headroom that can be achieved. To evaluate this, a load duration curve (LDC)-based approach can be taken. The LDC assuming balanced powers can be determined, then the LDC for the unbalanced system also created (by considering only the maximum power throughout the year). The PCBF at the system peak can then be found as the ratio of the LDCs during that peak period.

These peak PCBF figures have been estimated using 20 VISNET LV monitoring systems, with a total of 85 value streams. The analysis of this data is reported in Section 5.3. The assumed PCBF values for low powers (less than 100 A) and for higher power ratings (more than 100 A) is given in Table 27.

Table 27: PCBF values for low power and high-power ratings based on analysis of LV monitoring at 20 sites (84 values streams) over one winter period.

Mean power rating	Median PCBF
<69 kW (ca. <100 A per phase)	74.2%
≥69 kW (ca. ≥100 A per phase)	85.4%

The assets, a combination of feeders and transformers, were provided with a half-hourly resolution over the loaded period Nov-March over the years 2022-2023. Per asset, the top 360 heavily loaded periods were selected and the PCBFs were plotted against the loading in Figure 17. 360 periods the equivalent of twelve weeks of six evening half-hour periods on five weeknights. For both axes, the top 360 values averaged.

The resulting 84 series are plotted from seven substations included transformers and their feeders, with all 84 times series having less than 5% missing values. (The remainder, of the 120-time series were excluded due as they had a large number of missing data during the winter period.)

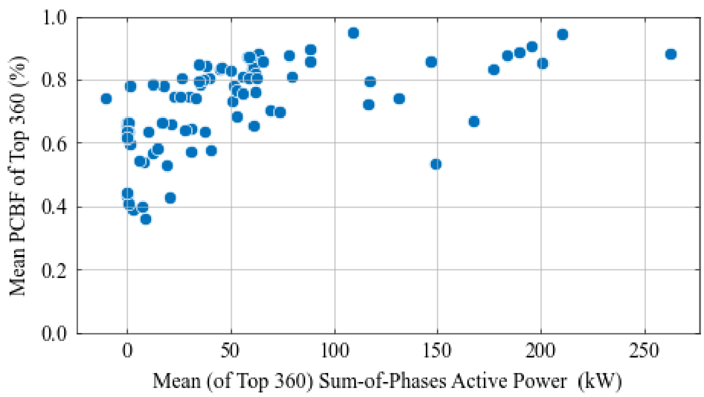


Figure 17: Scatter plot of PCBF against peak loading, demonstrating the PCBF from 85 time series from the 22/23 winter. Note that the PCBF during the system peak is regularly far below 85% both for low and higher powers, indicating potential for active phase balancing via a D-STATCOM or D-SOP.

5.3.2. Deferral Potential from a D-STATCOM for Voltage Control Applications

D-STATCOMs can support voltage control by injecting reactive power. In per-unit, voltage drop ΔV across a network impedance $Z = R + jX$ is given by.

$$\Delta V \approx PR + QX\,,$$

where P and Q are the real and reactive power flowing through the line. A given capacity of reactive power from a D-STATCOM $Q_{\text{D-STATCOM}}$ can therefore enable increased active power load P_{+} (i.e., release network capacity) by injecting enough reactive power to negate the voltage drop caused by the additional load (e.g., by setting $\Delta V = 0$). This gives.

$$P_{+} = -\frac{Q_{\text{D-STATCOM}}}{R/X}\,.$$

A D-STATCOM in a network with a lower R/X ratio can therefore increase network capacity by a greater amount than a network with higher R/X. However, LV networks with long feeders tend to have a higher R/X, as LV cables typically are more resistive than inductive (where HV/LV transformers and the HV network typically have low R/X). From a CBA perspective, networks with longer feeders will also result in a larger potential deferral benefit, since the cost to upgrade the circuits is proportional to their length. As a result, it is likely that the utilization of the D-STATCOM will be lower at LV than higher voltage applications (as the applications will have lower R/X). This point can be seen by considering the R/X ratio across each of the points in the network that have been considered for D-STATCOM placement, as shown in Figure 18.

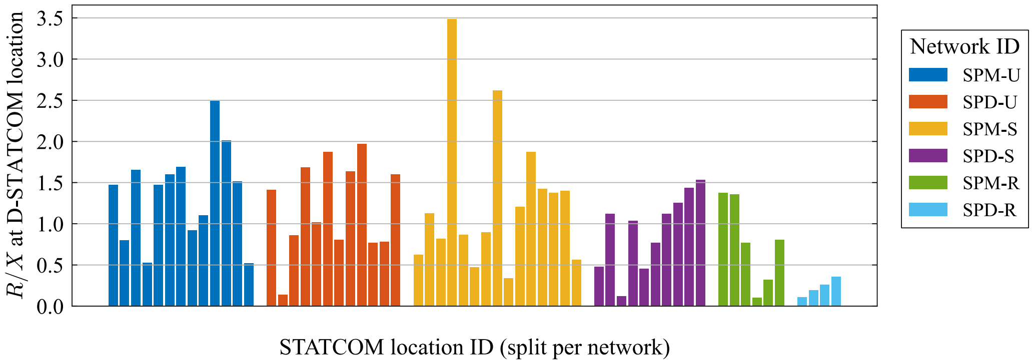


Figure 18: The R/X ratio for all D-STATCOM locations considered across the six networks, highlighting how the utilization of a D-STATCOM for increasing network capacity varies both within and between networks depending on placement.

To consider the network capacity which can be released by the using the D-STATCOM for voltage control, we need to split the voltage into a nominal voltage, V_0, a voltage drop due to load ΔV_{Load}, and a voltage increase due to the D-STATCOM $\Delta V_{\text{D-STATCOM}}$, giving

$$V = V_0 - \Delta V_{\text{Load}} + \Delta V_{\text{D-STATCOM}}\,,$$

or, in the decomposed form in terms of power flows,

$$V = V_0 - (P_{\text{Load}}R + Q_{\text{Load}}X) + Q_{\text{D-STATCOM}}X$$

where P_{Load} and Q_{Load} are the real and reactive power of the load, respectively, and $Q_{\text{D-STATCOM}}$ is the reactive power injected by the D-STATCOM. If the voltage V has reached its lower limit (e.g., V takes the value of the nominal lower voltage of 0.94 pu), the value of the voltage drops due to the load ΔV_{Load} can be increased by a factor due the voltage injection from the D-STATCOM.

Assuming the power factor of the load does not change, the potential load increase can be found by taking the ratio of the voltage drop ΔV_{Load} that can be realised (as the load voltage drop is proportional to the load). The additional capacity enabled due to the D-STATCOM is therefore given by.

$$\text{Load growth (capacity) enabled (\%)} = \frac{(V_0 - V) + \Delta V_{\text{D-STATCOM}}}{(V_0 - V)} - 100\%\,.$$

For example, if the nominal source voltage V_0 is 1.0475 per unit (considering a HV voltage of 1.01 pu and +3.75% secondary transformer voltage boost), and the D-STATCOM enabling a 3% voltage boost at peak load, the additional capacity growth that can be enabled is.

$$\frac{10.475\% + 3\%}{10.475\%} - 100\% = \ 28.6\%\,.$$

Finally, as a D-STATCOM will change reactive power flows on a line, its rating should be limited so that it will not cause thermal issues in network assets. For a given current ampacity of I_{Line} and phase voltage V_{Phase} that is loaded with a unity power factor load I_{Load}, the maximum reactive power that can be injected before causing thermal congestion can be determined as

$$Q_{\text{Max}} = 3V_{\text{Phase}}I_{\text{Line}}\sqrt{1-\left(\frac{I_{\text{Load}}}{I_{\text{Line}}}\right)^2}\,.$$

For example, a 100 A feeder at a voltage of 230 V and loaded to 95 A at unity power factor can inject 21.5 kVAr (31.2 A reactive current) without causing thermal congestion. If the power factor of the load at peak is 0.95 inductive, then the STATCOM can be double this value (43.0 kVAr) without increasing the peak load (as the D-STATCOM will first compensate the load reactive power before increasing the loading).

6. References

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6.1. Acknowledgment

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- Northern PowerGrid for their DFES [6].
- National Grid Energy Distribution (Formerly Western Power Distribution) [7].

7. Contact Details

EMAIL

a.moon@spenergynetworks.co.uk

matthew.deakin@newcastle.ac.uk

POSTAL ADDRESS

Andrew Moon,
Future Networks,
SP Energy Networks,
3 Prenton Way,
Prenton,
Wirral
CH43 3ET

Matthew Deakin,
School of Engineering,
Merz Court,
Newcastle University,
Newcastle upon Tyne,
NE1 7RU