D-Suite

Customer Requirements and Core LV Network Functions

Future Networks

SP ENERGY NETWORKS

Issue Record

DATE	ISSUE	STATUS
07/06/2023	1.0	Final Draft

Issue Authority

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Glossary of Terms

TERM	DEFINITION
AC	Alternating Current.
CBA	Cost Benefit Analysis.
DC	Direct Current.
DER	Distributed Energy Resource.
DNOs	Distribution Network Operators.
ENA	Energy Network Association.
GB	Great Britain.
GHG	Greenhouse gas.
HVPD	High Voltage Partial Discharge Ltd.
IGBT	Insulated Gate Bi-Polar Transistor.
kV	Kilo-Volts
kW	kilo-Watts.
LCT	Low Carbon Technology
LV	Low Voltage
LVDC	Low Voltage Direct Current.
MV	Medium Voltage
MVDC	Medium Voltage DC
NC	Normally Closed Circuit
NIA	Network Innovation Allowance
NO	Normally Open Circuit
NPV	Net Present Value
OHL	Overhead Line
R&D	Research and Development
RIIO-ED1	Electricity Distribution 1 Regulatory Period
STATCOM	Static Synchronous Compensator
TRL	Technology Readiness Level
UK	United Kingdom
VSC	Voltage Source Convertor
WP	Work Package

1. Project Background

The record numbers of electric vehicles, renewable energy sources and heat pumps being introduced to our energy system has created an opportunity for innovative technologies that have not been conventionally considered.

Following an assessment of the energy innovation landscape, it has become clear that there has been limited research on the LV focused power electronic technologies. This might be due to the perception of the cost and size of power electronic devices. Medium Voltage (33kV or 11kV) has been the typical limit where the business case can be easily found.

Over the past decade, several innovation projects have trialled technologies such as smart transformers (LV-Engine), soft open points (FUN-LV) and active harmonic filters (LV Voltage Solutions). These project raised the Technology Readiness Levels (TRLs) significantly, yet have not been largely adopted under Business as Usual (BaU), across the UK. Barriers remain, which are leading network operators to choose other solutions. The D-Suite project aims to remove these barriers by:

1. Providing optimised design of several D-Suite Power Electronic Devices suitable for LV deployment that are capable of operating in a coordinated control regime or a stand-alone control solution.
2. Addressing the detailed operational and public safety requirements, protection considerations and overall network interface requirement in the hardware designs.
3. Providing a coordinated control algorithm to maximise the existing network utilisation.
4. Providing a holistic and systematic approach to identify the niche scenarios for a practical guidance for the future network planning and investment; and
5. Trialling the 1st GB demonstration of a resilient D-Suite enabled LV network (SIF-Beta).

Compared with conventional solutions, D-Suite technologies can better address both thermal and voltage issues that are increasingly experienced in LV networks. The starting TRL of this project is approximately 4-5, and will benefit from dedicated innovation support to uplift the readiness of the following technologies:

- LV Distributed STATCOM (D-STATCOM). This technology has never been deployed in UK network.
- Distributed Soft Open Point (D-SOP) – D-Suite aims to build up on the technology developed by UKPN to trial a more flexible and controllable solution.
- Distributed Smart Transformer (D-ST) -- D-Suite will build up on learning from LV Engine project to fit a partially rated power electronics within slim design distribution transformer; and
- Distributed Harmonic Filter (D-HF) -- There are number of solutions in the market that need further development for LV applications.

In addition to those well-established ENA and IEC standards for network interfaces, insulation requirements etc. the D-Suite project will ensure the compliance with safety requirements in power electronics specified in IEC 62477 and for monitoring equipment in BS EN 61010. IT and OT cyber security of the control system shall be implemented based on those specified in IEC 62433, recommendations by ENA OT/IT taskforce and SP Energy Networks' cybersecurity requirements.

2. D-Suite Technologies and Their Use Cases

Voltage Rise (VR) is a concern on LV feeders with high penetration of Photovoltaics (PV). High penetration of PV also causes protection issues, increased feeder losses, transformer and cable rating issues, sudden voltage rise and reverse power flow. These problems can be exacerbated if high PV penetration is unbalanced between the three LV phases.

Voltage Imbalance (VI) is a major power quality problem in low voltage residential feeders, due to the random location and capacity of single-phase rooftop photovoltaics (PV), Plug in Electric Vehicles (PEV) and Heat Pumps (HP). National standards specify that the nominal voltage at the source should be in a narrow tolerance range of 230 V with a tolerance between+10% and -6%. According to IEC 61000 and EN 50160 standards, the allowable limit for VI is limited to 2% in LV networks for 95% of the data measured over a 7-day period in 10-minute RMS values. Additionally, Engineering Recommendation P29 also limits the VI to 1.3% at the load point. [1]. The two issues of VR and VI can be address in different ways by the D-Suite Technologies, such as the D-STATCOM.

2.1 D-STATCOM

A D-STATCOM is a Power Electronic Device (PED) consisting of a DC voltage source, inverter circuit, coupling transformer and a PED switching control module [2]. The DC-voltage source is usually a capacitor though D-STATCOMs can use a DC battery. A D-STATCOM is a form of Voltage Source Converter (VSC), which is connected to LV feeders in a shunt configuration and can generate or absorb reactive power on each of the 3 LV phases to the required level.

The reactive power level required can change quickly, due to network changes, Like all PEDs, D-STATCOMS provide rapid changes to the reactive power level , leading to a fast dynamic response to stabilise voltage amplitude, provide harmonic control, power factor correction, voltage flicker suppression, and sustain reactive current on the LV distribution network [3].

D-STATCOM configurations, topologies and control strategies vary, depending on their application and the LV network problem they are trying to mitigate. In general, limited D-STATCOMS are cheaper, due to a lower number of Power Electronic switches and passive components but solve a reduced number of LV network problems. For example, a single DC capacitor with a three phase, 3 leg converter (Figure 1a) may not be able to provide full compensation for reactive power level requirements in an LV network with high LCT penetration. A Three phase, four leg converter (Figure 1b) has higher compensation capability but requires more complex control due to the higher number of switches and passive components, which drives up cost.

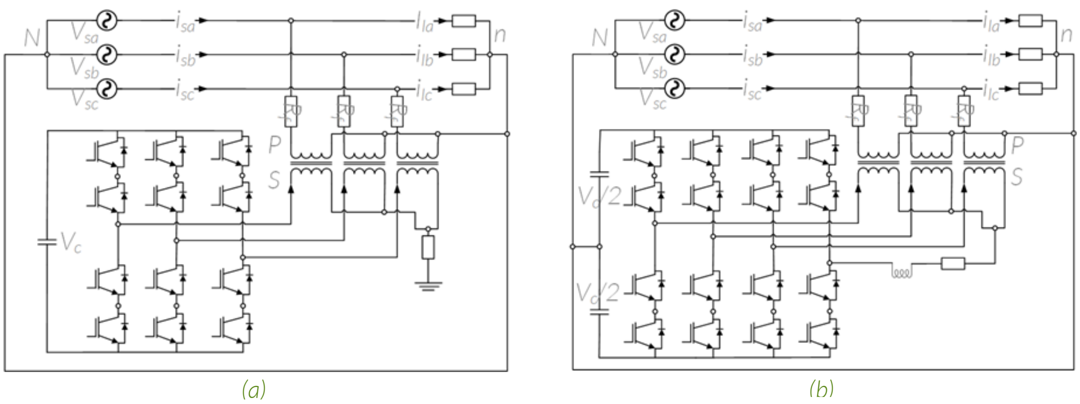

Figure 1. D-STATCO0.M examples with coupling transformer connecting onto an LV 3-phase network. (a) A 3-phase, 3-legged converter with a single DC capacitor. A three-phase, four-legged converter with split capacitor.

To select the most cost-effective solution, D-Suite will focus predominantly on two of the main the LV network problems, D-STATCOMs can be used to solve; voltage rise and phase imbalance due to high LCT penetrations. D-STATCOMs have been shown to reduce voltage rise on LV feeder, by employing Pulse Width Modulation Control carrier-based scheme. A voltage reduction of 6.3% was achieved with a 60% penetration of EVs, bringing the network back to within statutory limits over the entire feeder. If voltage rise issues are not mitigated, it can make voltage imbalance problems more severe.

LCT VI is more likely to occur at the end of LV feeders, since the largest voltage deviations occur at these locations, which make percentage changes larger. Monte Carlo PV phase distribution studies have shown, a D-STATCOM placed at 2/3 along the feeder length can reduce the VI from 2% to 0.4%, at the Point of Common Coupling (PCC). At the end of the feeder, the VI was reduced from 2.5% to 0.65% as shown in Figure 2.

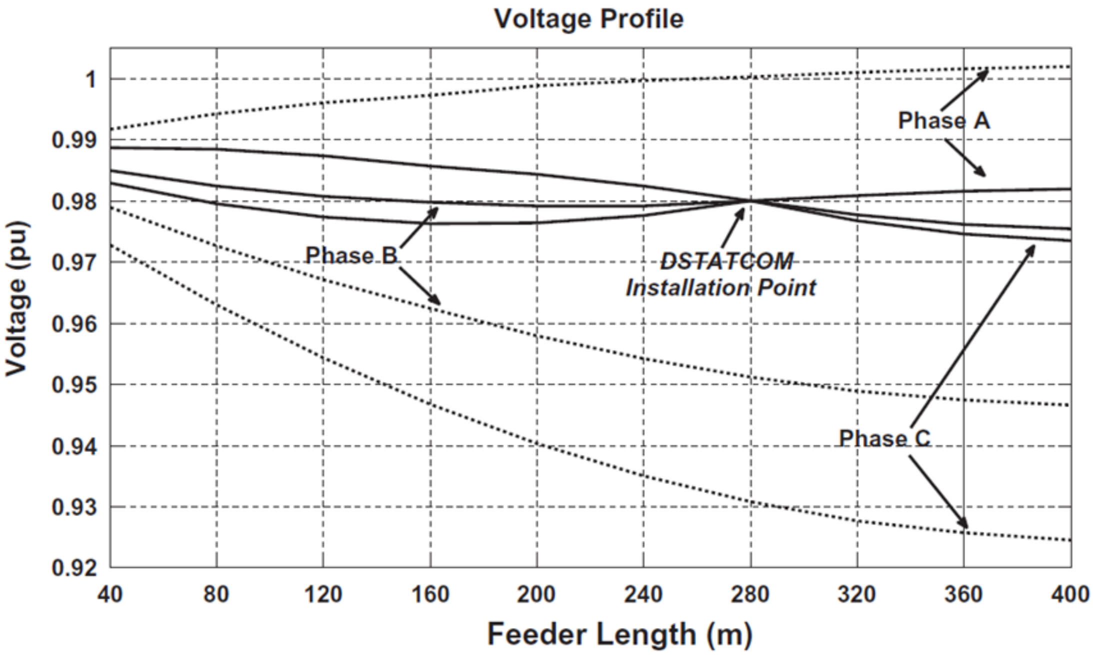

Figure 2. Feeder phase voltages, on each phase, with no D-STATCOM compared against feeder phase voltages with a D-STATCOM installed at three different locations along the LV feeder.

The installation point has a large effect on the effectiveness of the -DSTATCOM voltage imbalance reduction. When the D-STATCOM was installed at the at 1/3 of the feeder length the VI increased from 0.65% to 1.3% when compared with the 2/3 length installation location. Various optimum location methodologies exist, but iterative placement methods have shown optimum placement can be calculated for in a low number of iteration steps, utilising simple algorithms using real world networks. The Project will extent this methodology in the SP Energy Network models developed as part of this Work Package.

2.2 D-SOP

A D-SOP is a PED, comprising of at least one back-to-back AC-DC converter. The D-SOP allows the control of real power through its DC bus and independent reactive power flow control at points of common coupling. D-SOPs can be installed at a normally open points or between separate LV feeders, which can be at different voltage levels. As part of the Flexible Urban Networks – Low Voltage (FUN-LV) project, two-terminal (240 kVA) and three-terminal (400kVA) SOPs were developed.

Previous work has demonstrated D-SOPs can successfully be used to equalise Transformer demand, for transformers connected to the D-SOP terminals, by controlling the power flow through the D-SOP DC-bus. In the FUN-LV Project, the results of field trials show [4] a reduction of maximum Transformer utilisation of between 7% – 27% and a reduction of average transformer utilisation of between 0% -

11%. In this control mode, network designers can use D-SOPs in networks where two adjacent primary or secondary substation which have contrasting utilisations. Part of the D-Suite Alpha stage work will be development of load flow algorithms to detect candidate sites as part of the LV-Design tool development.

Other D-SOP functionalities includes optimisation of the feeder voltage profiles, feeder load balancing either side of the D-SOP and losses minimisation in connected LV feeders and transformers. Studies have shown DER penetration levels of 90% [5] can be accommodated, when using the voltage profile improvement optimisation objective. This can be at the cost of network losses, which can be minimised by implementing the losses optimisation objective, with the trade-off that a lower amount of DER (~60%) can be connected. The network level control algorithms similar, but tailored for the network topology, loading and DER distribution on each LV feeder. In the Alpha stage, these network level control algorithms will be developed for DNO LV design engineers.

2.3 D-HF

Devices connecting to the UK distribution network, at LV, must meet the planning limits for harmonic voltages, which can cause increase losses in circuits and equipment, and to cause overheating of rotating plant and capacitors. Network Operators must ensure harmonic voltages are less than compatibility limits, so new equipment has some harmonic voltage headroom under which to connect. For LV networks, the Total Harmonic Distortion (THD) at the Point of Common Coupling (PCC) shall be below 4% of the nominal voltage [6].

In addition to the THD, planning levels exist for all harmonic voltages at shown in Table 1. The Network operator is responsible for taking measurements of the background harmonic voltages, using IEC 61000-4-30 compliant Power Quality monitors, to assess the available harmonic headroom. For customers connecting equipment to LV networks, if the equipment is compliant with relevant international product standards, they may connect under self-certification or submit equipment information to the Network Operator for connection once an assessment has been completed. If the equipment parameters are greater of those allowable at the point of connection, the background harmonic level need to be measured and the connecting equipment assessed against the background levels. If the combined background and equipment harmonics exceed the planning levels, the Network Operator will either need to reinforce the network to increase the Short Circuit Level at the point of connection or install passive or active harmonic filters to reduce background harmonics.

Table 1. Planning levels for harmonic voltages in 0.4 kV systems and below.

NON-TRIPLEN ODD HARMONINCS		*TRIPLEN HARMONICS*		*EVEN HARMONICS*	
h	*V (%)*	*h*	*V (%)*	*h*	*V (%)*
5	*4.0*	*3*	*4.0*	*2*	*1.6*
7	*4.0*	*9*	*1.2*	*4*	*1.0*
11	*3.0*	*15*	*0.5*	*6*	*0.5*
13	*2.5*	*≥21*	*0.2*	*8*	*0.4*
17	*1.6*	-	-	*10*	*0.4*
19	*1.5*	-	-	*≥12*	*0.2*
23	*1.2*	-	-	-	-
≥25	*25/h*	-	-	-	-

D-harmonic filters (D-HFs) are advanced power-quality devices designed to mitigate the detrimental effects of harmonics in distribution networks. When connected in parallel with feeders, D-HFs can actively detect and counteract harmonic currents generated by non-linear loads, such as electronic equipment and variable speed drives, thereby ensuring a clean and stable power supply to connected loads. The Low Voltage Network Solutions project installed two Active Filters at Dunton Green and Howard Street substations in 2012. The Active filters were able to reduce the harmonic currents between 95 and 90% for harmonic orders up to the 15^{th}. This is an alternative to network traditional reinforcement and passive filters, which need to be tuned as the network changes, in future cases this will be due to rapid LCT rollout.

3. Network Topology Selection Methodology

The purpose of this section is to show different sections of the SP Energy Networks electrical network that are subject to future thermal and voltage issues at both HV and LV. Several different topologies were analysed, to highlight the differences between them and the issues each of them may experience. The circuits have been chosen based on predicted future thermal and voltage issues, simultaneously occurring at HV and LV, based on the network's anticipated future LCT and distributed generation uptake.

NAVI is an SP Energy Networks design platform, which automatically creates a connected network model from GIS data. It creates an "analytics" ready model which can be used as the basis for network analysis. It offers visual representation of networks, displayed on a map, and offers various circuit exports to allow design engineers to use different power analysis software applications. The application used for the load flow analysis was DigSilent PowerFactory. Through the various tools in the Power flow software applications, the Project was able to justify the selection of circuits and demonstrate the future issues that may arise on them. The Project has developed a methodology for extracting present-day demand at LV and HV, and for forecasting future demand by predicting LCT penetration. The circuit analysis began with applying a methodology for calculating network constraints using present-day LCT penetrations.

3.1 PRESENT AND FUTURE DEMAND FORECAST

3.1.1 At Low Voltage: ADMD without Low Carbon Technology

SPEN LV network design policy document ESDD-02-012 outlines the SP Energy Networks methodology for calculating the customer demands with the After Diversity Maximum Demand (ADMD) approach. ADMD is used in electricity distribution networks where demand is aggregated over a large number of customers. It assumes that demand will generally peak at similar times for customers; however, the more customers that are aggregated together, the less likely all customer peak demand will occur coincidently. The ADMD figures for each house will vary, depending on the size of the house, the type of heating system installed, and the presence of LCTs. A baseline ADMD is firstly identified based on the house size. Subsequently, additional modifications are made for electrically heated homes and domestic EV charge point equipment. Furthermore, adjustments are made to the values based on the number of customers being aggregated on LV circuit to find the present ADMD value for all customers.

Present ADMD values, assume 2021 as the base year, which was chosen because 2021 is the year the SP Energy Networks Distribution Future Energy Scenarios (DFES) start from. DFES are forecasts that help network operators understand how consumption may evolve over the next 30 years. These scenarios are informed by engagement with industry, government, and key stakeholders. Combined with SP Energy Networks data and regional information, a model of future underlying domestic demand on our network was developed. However, this model focuses solely on future domestic ADMD without the added demand from LCTs. Separate methodologies used to forecast future low carbon heating and electric vehicle demand will be outlined. The Project used NAVI to forecast future baseline ADMD with additional demand from LCT penetration. NAVI produces a model of the network that highlights the utilisation of the cables, which describes what percent of the cable's rating the current running through it is, with Figure 3 showing a high-level example. Additionally, this ADMD approach focuses on low voltage networks; a different approach, outlined next, produces estimates for high voltage networks.

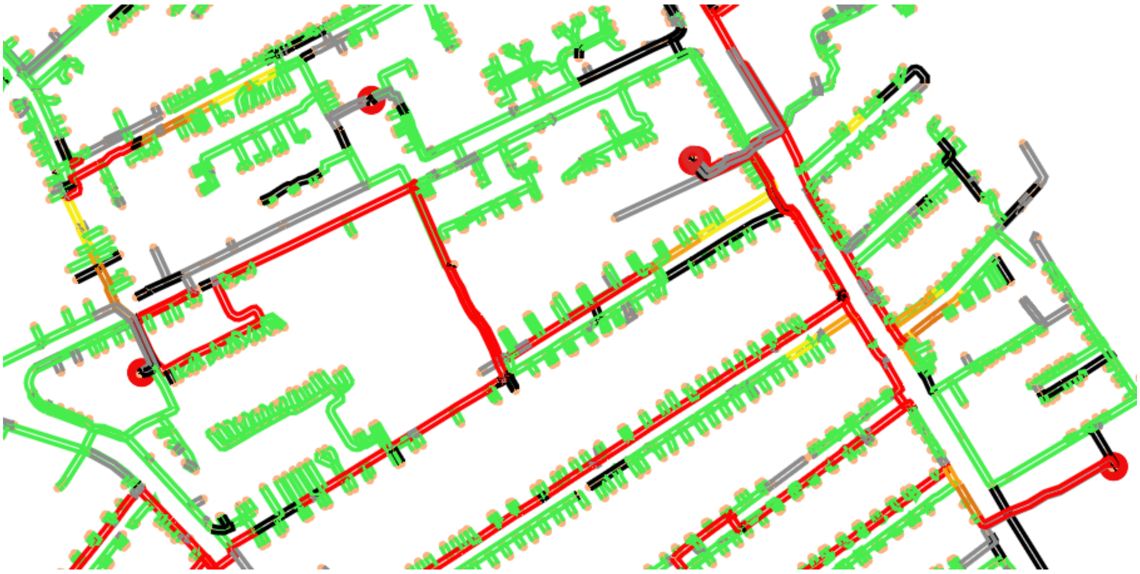

Figure 3. High-level overview of NAVI-based forecast LV demand with LCT penetration showing colour banding representing thermal constraints on an LV network.

3.1.2 At High Voltage: Normalised Maximum Demand without Low Carbon Technology

Preparation of the HV system load data uses historical performance to provide a baseline for the assessment, then superimposes variables which will provide an estimate of future demand. Firstly, the fundamental differences in the basic network design and topology for SP Distribution (SPD) and SP Manweb (SPM) need to be identified, as they affect how demand is aggregated, and subsequently forecast. SPD operates grid supply points which are radial, enabling load to be assessed based on site demand. SPM, on the other hand, operates an interconnected network, which requires assessment to be based on group demand. The high-level approach for load estimation and future demand, however, is broadly the same for both network arrangements.

The baseline data requires a Normalised Maximum Demand (NMD) to be established for each substation in SPD, and each substation group for SPM, to forecast future demand. Firstly, the measured demand from the previous 12 months must be identified through historian data systems. Secondly, normalised or corrected maximum demand must be established, as opposed to the most recent measured maximum demand, which requires correcting for the presence of generation and abnormal running, and comparing with NMD of recent years to identify anomalies and trends. Finally, future demand requirements can be forecast, and they include the following drivers:

- Background or generic load growth, which provides an assessment of the changes arising from lifestyle factors such as changing consumer goods and energy efficient equipment.
- Impact of LCT uptake. Its profile will be determined by factors such as government incentives or increasing gas prices.
- More local factors based on local trends, scheduled interventions, market or stakeholder intelligence.

To highlight the issues that will arise from future LCT uptake the Project will use NAVI, which considers the issues at HV as an aggregate of the issues predicted at LV. Figure 4 shows a high-level example of how NAVI will be used to visualise the anticipated HV issues due to future LCT uptake. With the methodology for baseline demand outlined, we will outline how The Project forecast future LCT uptake and its associated demand requirements.

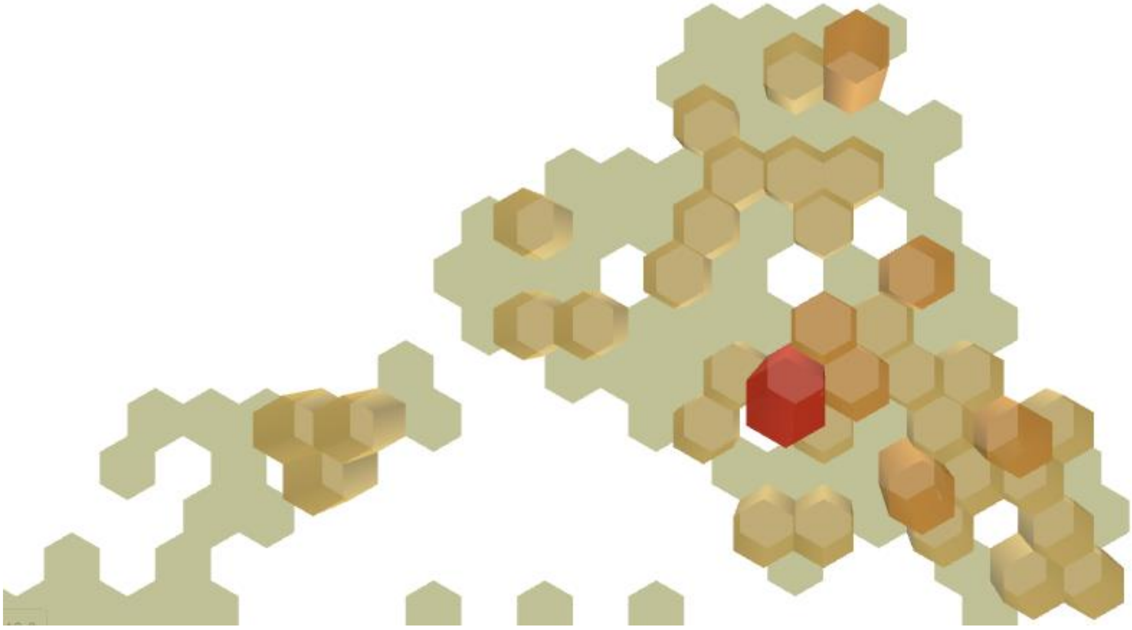

Figure 4. High-level overview of NAVI-based forecast HV demand with LCT penetration. Each Hexagon represents a geographic area containing up to 500 customers fed through the primary substation.

3.2 FORECASTING FUTURE LCT UPTAKE

So far, the methodology for estimating demand at LV focused on establishing a baseline ADMD. The baseline ADMD includes traditional household demand but does not consider future LCT penetration. Due to government incentives, such as the planned rollout of 600,000 heat pumps a year from 2028, the ban on new ICE vehicles by 2030 and, ultimately, the net zero target for 2050, the network is expecting a large uptake of heat pumps, EV chargers and distributed generation. Therefore, a methodology for forecasting the demand from each of the three LCTs has been developed. The first methodology is on estimating the future uptake and subsequent demand of low carbon heating in the form of heat pumps.

3.2.1 Low Carbon Heating

With current low carbon heating reflected in present-day ADMD values, this section will focus on the methodology for forecasting future growth. The Heat-Up project undertaken by SPEN developed a property fabric assessment methodology to deliver data on expected peak heat and sizing of heat pumps across the network. After properties are sized and categorised, they are assigned to adoption groups based on gas supply, whether they are social housing, and whether they are owned or rented.

With this data, a model for forecasting future demand of low carbon heating was developed. While recognising the property parameters that impact calculations, such as size, insulation, and ambient temperature, property specific calculations can be made. A feature of the Heat-Up model is an allowance for different types of heating, as the model assigns percentage split of three low carbon heating types: heat pumps, electric radiators, and district heating. The model then calculates each heating type's annual electrical consumption, then finally uses historical data to assign the seasonal split in the license area as consumptions increases in the colder days. Furthermore, heating demand is assumed to be entirely inflexible in the model. Finally, the forecast demand from low carbon heating can be superimposed on the future base ADMD demand from the previous section. In addition to future demand from heat pumps, a methodology for forecasting demand from electric vehicles was developed.

3.2.2 Electric Vehicles

Like Heat-Up, SP Energy Networks undertook a study (NIA Project EV-Up) to model Electric Vehicle Uptake, with the aim to develop an evidence base for estimating the future EV uptake and their effects on the LV network. The methodology combines the physical ability of consumers to park off-street with key demographic information to obtain a probability to own an EV. Furthermore, data was derived using UK mileage statistics, EV efficiency, and average underlying domestic demand. A portion of the charging demand is assumed to be "flexible" due to the development and anticipated uptake of smart chargers. The results the model produce can ultimately be added to forecast underlying demand and low carbon heating demand to ensure a high level of accuracy in demand forecasts being developed by SP Energy Networks. The next variable that needs to be considered for future household demand is distributed generation.

3.2.3 Distributed Generation

Future Distributed Energy Resource (DER) uptake has not been included in this analysis, though it is very important to model due to its high impact on network voltages. Future work, in the Alpha phase, will model PV uptake on each LV phase, and analyse the issues caused, combined with high LCT uptake, when spread unevenly across the LV phase conductors. The analysis will use derived network models, for Urban, Suburban and Rural LV networks, which have been derived and studied as part of this work package.

4. Networks with Issues at HV & LV Due to Forecast Low Carbon Technology Rollout

To explore the potential use of these power electronic technologies on the LV network, this report will first explore different sets of LV circuits, with three in SPD and three in SPM. Each of the three sets will be of a different type of network as to explore different issues that can arise from the future LCT uptake. Furthermore, the different network topologies will offer different use cases for each of the new technologies being explored.

Networks with present day thermal and voltage issues were chosen, to take a holistic approach. Worst case scenarios in terms of the need for network reinforcement were looked at for circuits with issues at both HV and LV due to high LCT penetration at LV and high customer demands. As described in Section 3, NAVI maps the current demand based on a modelled present-day scenario of its circuits, along with future scenarios. The future scenarios include demand from the expected LCT rollout that matches government policies, such as the target of installing 600,000 heat pumps a year by 2028 and the ban on all new ICE vehicles by 2030, and the SP Energy Networks DFES. Due to ambitious LCT rollout targets, networks were modelled in the present day, 2028, 2036 and 2040. The first network topology selected was an SPM interconnected urban network, as urban networks expect to see the largest future LCT penetration.

4.1 URBAN NETWORKS

Due to time constraints, analysis of urban networks will be completed in the Alpha stage of the project. Therefore, suburban and rural networks were analysed, starting with suburban networks.

4.2 SUBURBAN NETWORKS

Suburban LV networks consist of predominantly residential customers, typically in low density housing rather than high density accommodation found in urban areas, and lower numbers of industrial customers. Suburban networks, before LCT penetration, experience a similar baseline ADMD of our customers. However, suburban networks are expected to see an almost random uptake of LCTs in the form of heat pumps, EV chargers, and distributed generation. In turn, this random LCT penetration can cause both thermal and voltage issues, such as voltage imbalance, reverse power flows, and harmonic issues. Therefore, suburban networks, with anticipated future problems at HV and LV, have been studied. In the SPM license area, the suburban network chosen, SPM-SU, is interconnected between three substations, as shown in Figure 5. As can be seen, SPM-SU currently has three registered 3,5 kVA EV chargers, which is reflected in their present-day ADMDs as an additional load to the baseline ADMD. The network currently has no registered PV installations.

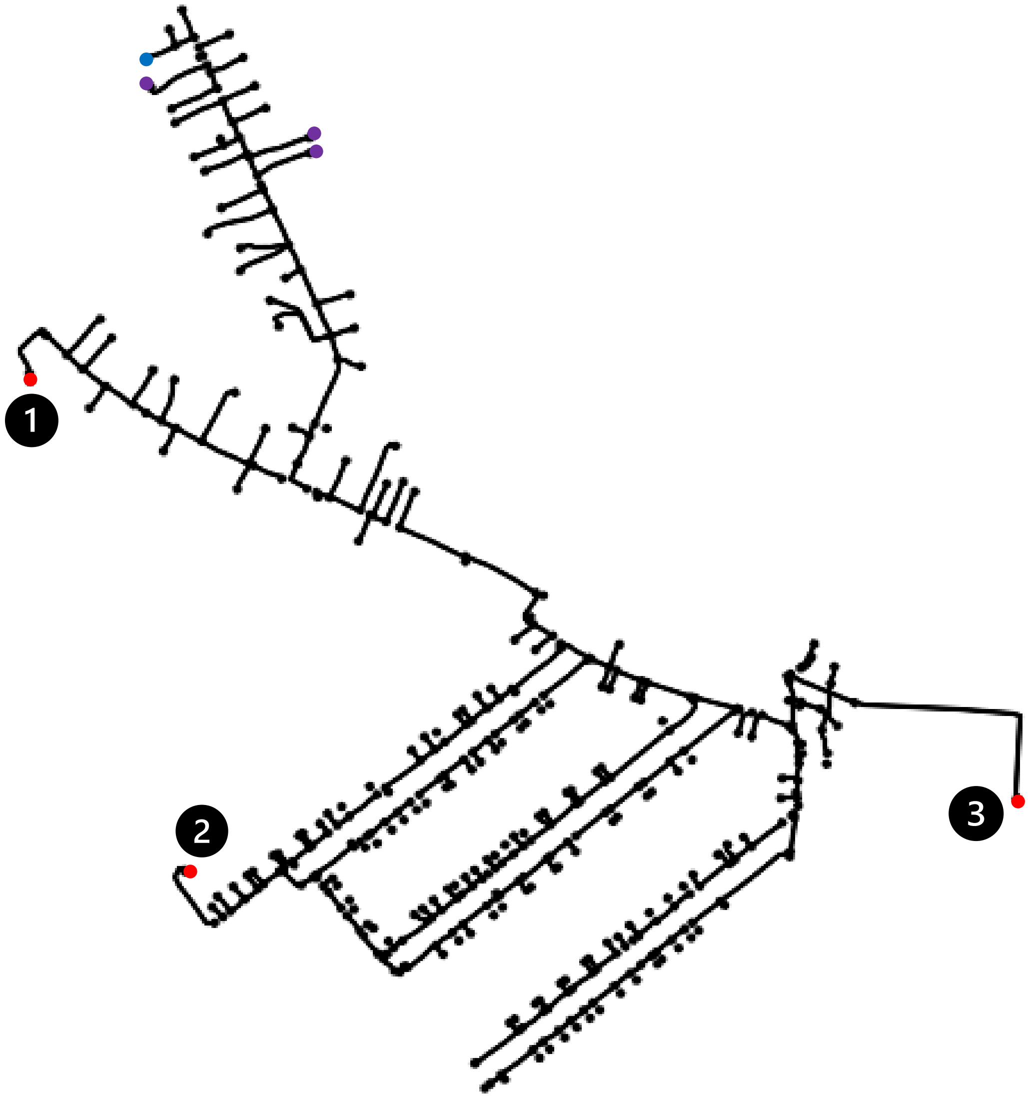

Figure 5. LV interconnected suburban network in Liverpool, with 11 kV – 400 V 500 kVA substations in red (3 in total as numbered), and customer with the highest impedance path in blue (cable length to nearest s/s: 361 meters). Cumulative cable length of mains and services: 4.7 km. Total connected customers: 152. Total circuit calculated ADMD: 619 kW. Number of registered3.5 kVA EV chargers: 3 (in purple). Number of registered PV installations: 0

The load flow analysis was run to obtain thermal and voltage data based on present-day ADMD values. Figure 6 shows the results of the load flow analysis performed on SPM-SU.

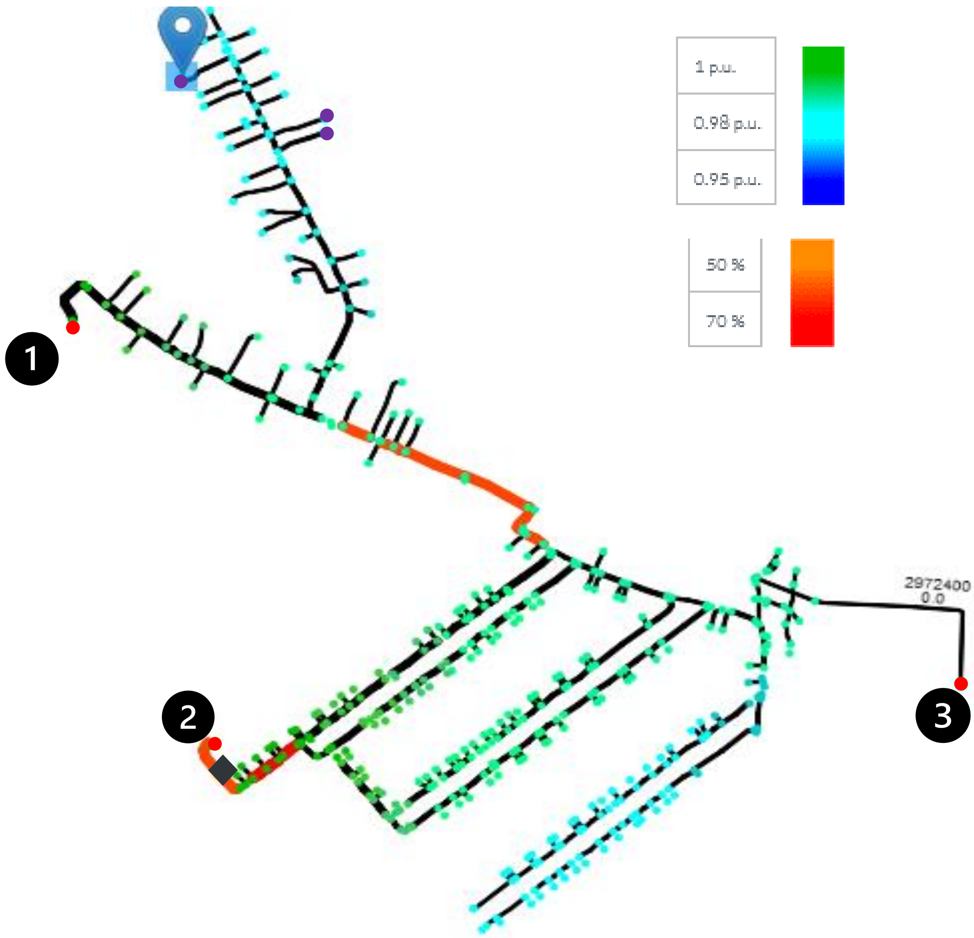

Figure 6. Load flow analysis results of circuit with present day demand and LCTs, with coloured cables representing potential thermal issues, and voltages going from green (highest) to blue (lowest). Point of lowest voltage marked in blue and point of highest voltage marked by grey diamond.

The results were analysed from both a thermal and a voltage perspective. The thermal analysis shows that the first part of network with high thermal utilisation is the outgoing cable from substation 2, where the cables are at around 70% utilisation. Generally, SP Energy Networks' interconnected topologies are not tapered, meaning the cables nearest the substation would have the highest utilisation. This part of the network is vulnerable to thermal issues from higher LCT penetration. The second part of the network with higher thermal loadings is in the middle section, with the cables at around 50% utilisation. The high utilisation is due to the lower cable ratings of the middle section, 310 A, compared to the cables placed before it, 445 A. In terms of voltage, the lowest voltage point has a voltage of 0.98 p.u, at the point furthest away from any substation (361 m). That is because the total impedance of the path from that customer to the substation is the highest on this circuit, 0.16 ohms. As expected, there are no cases of overvoltage, i.e., highest voltage is 0.99 p.u., since there are currently no PV installations registered to the SPM-SU network, and the load profiles of the customers are at the base ADMD.

Next, a suburban network in SPD, SPD-SU, was analysed. A network in a busy residential suburb of Edinburgh was chosen with similar concerns over future HV and LV issues due to higher LCT penetration. The network currently has two registered 3.5 kVA EV chargers, and no registered PV installations. Compared to SPM-SU, SPD-SU is a radial network, which could experience larger voltage drops due to the furthest customers having a higher total impedance from their nearest substation, and the larger number of customers being supplied by one substation. Figure 7 shows the diagram of the network.

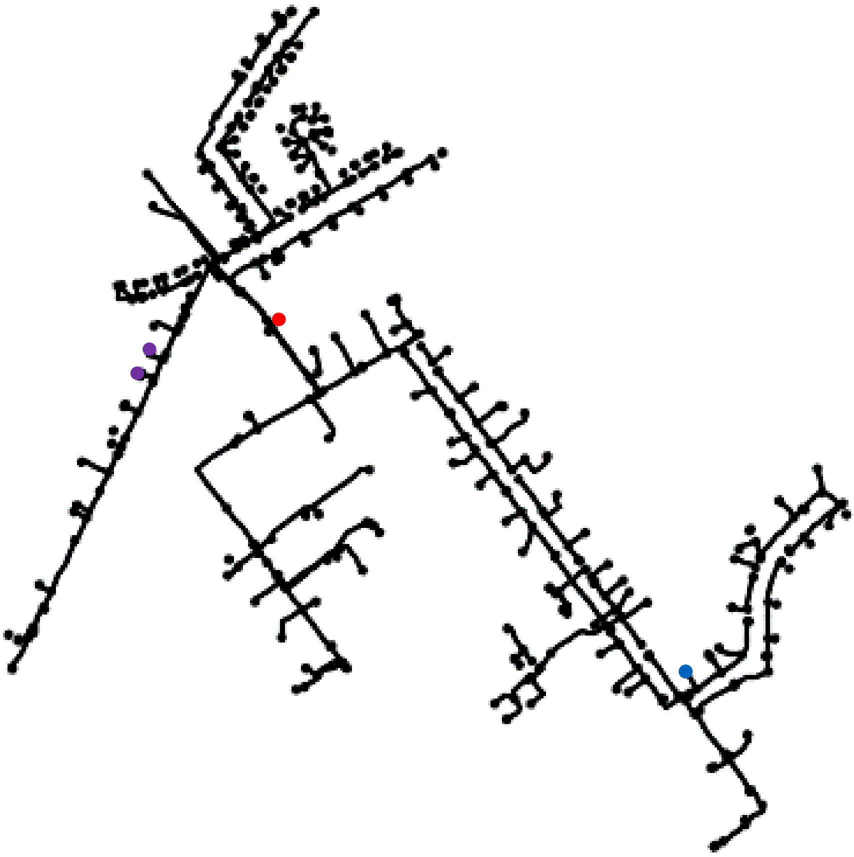

Figure 7. LV radial suburban network in Edinburgh, with the 11 kV – 400 V 1 MVA substation in red, and customer with the highest impedance path in blue (cable length to nearest s/s: 857 meters). Cumulative cable length of mains and services: 5.3 km. Total connected customers: 370. Total circuit calculated ADMD: 609 kW. Number of registered EV chargers: 2 (in purple). Number of registered PVs: 0.

A load flow analysis was then run to justify the selection of this circuit and pinpoint its potential issues, shown in Figure 8. The area has high probability of future EV and heat pump uptake, due to the nature of the houses and the economic capabilities of the customers.

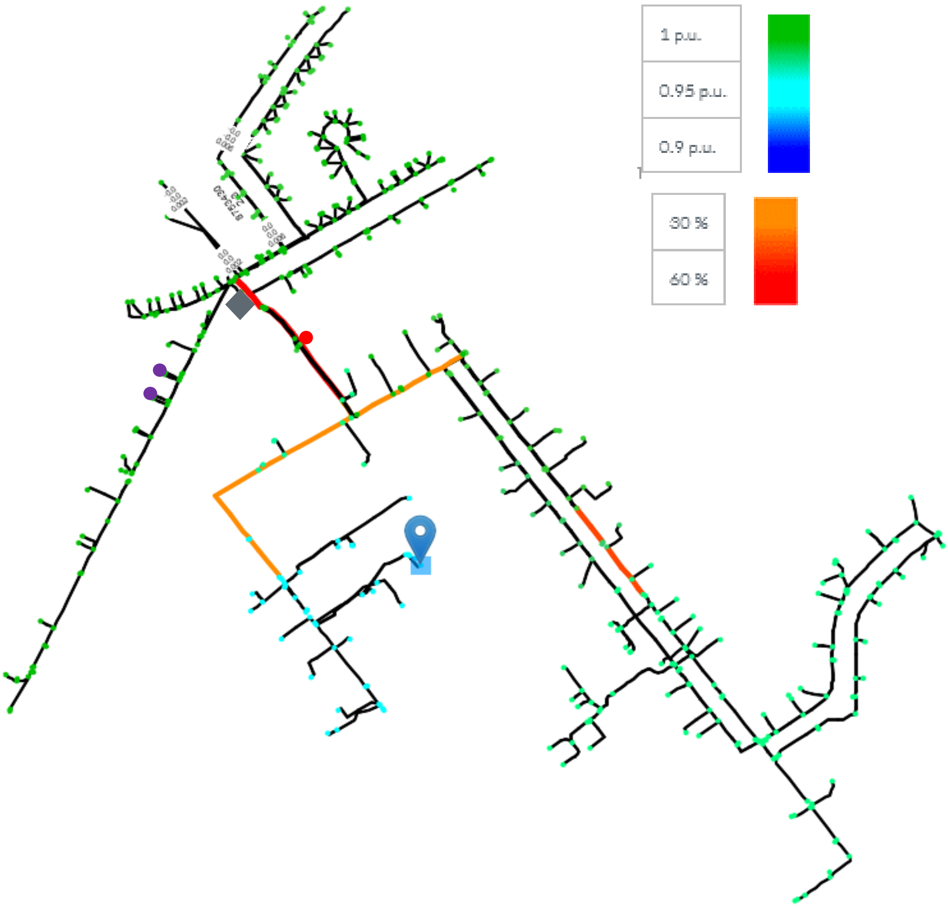

Figure 8. Load flow analysis results of circuit with present day demand and LCTs, with coloured cables representing thermal issues, and the lower voltages shown in blue. Point of lowest voltage marked in blue and point of highest voltage marked by grey diamond.

The thermal results show that the cables nearest the substation are the heaviest loaded at over 60% utilisation. There is a section in the middle of the circuit with 40% utilisation, due to its cable rating of 140 A, as opposed to the 345 A rated cables used ahead of it. In the present-day scenario, the impact of the two EV chargers is not causing overloading of the network; however, a higher uptake in LCTs in the coming years will see the cables approaching their ratings, causing thermal issues. The results show that the voltage is dropping as the customers become further away from the substation, and there are not any voltage issues. The lowest voltage point, as highlighted in Figure 8, has a total impedance to the substation of 0.48 ohms. The lowest voltage is 0.94 p.u., which is lower than the lowest voltage in the corresponding SPM_SU network. That is common for radial networks compared to interconnected ones, as the longest total impedance back to the substation in SPM-SU is 0.16 ohms, compared to 0.48 in SPD-SU. The next network topology that will be explored is rural networks with an example from each of SPM and SPD.

4.3 RURAL NETWORKS

The final network topology explored is rural networks. Rural networks are where substations may be supplying a low number of customers, and do not have the ability to be interconnected with other networks due to the distance between them. Although they feed much less customers than urban and suburban substations do, they tend to be more problematic in terms of customer minutes lost due to their geographical locations, their vulnerability to storms, and the difficulty in restoring them quickly.

Furthermore, the ratings of rural transformers are typically lower than the ones in the other topologies. Therefore, even if they will not expect the same volume of EV charger and heat pump uptake, a low number of new installations can lead to the circuit overloading the transformer. Figure 9 shows a rural network in Anglesey in the SPM license area, SPM-RU. The network consists of overhead line cables and is fed from a single, radial, 25 kVA, pole-mounted substation, and is supplying 11 customers with a total ADMD of 19.5 kW. The distribution lines are all overhead lines on this network. The network has no registered EV chargers but has a registered 3.6 kW PV installation highlighted in Figure 9.

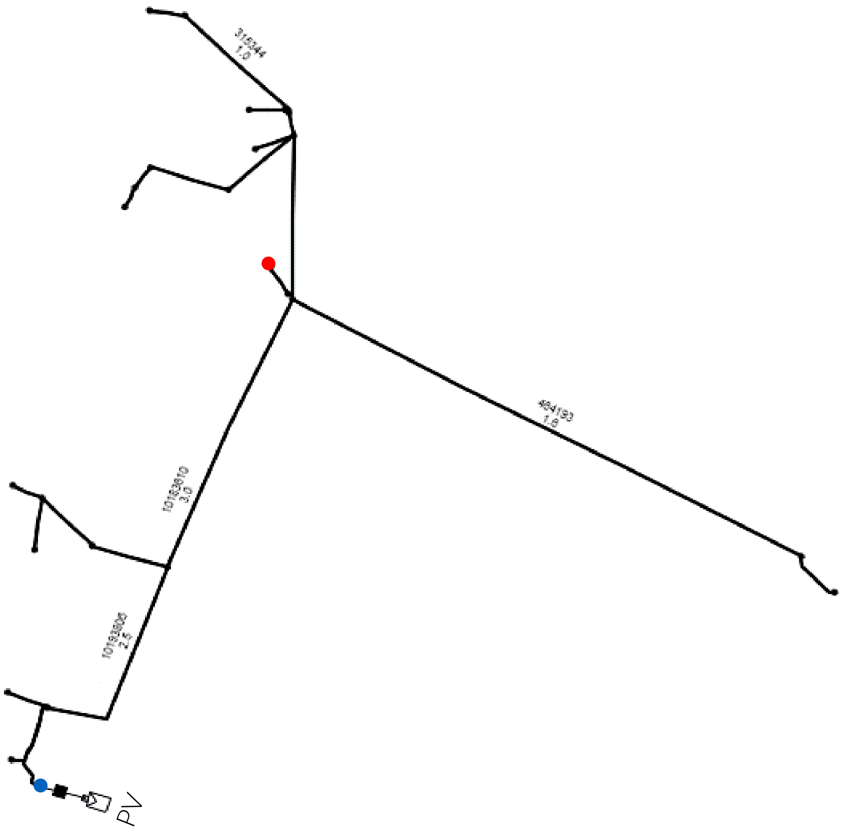

Figure 9. LV radial rural network in Anglesey, with 11 kV – 400 V 25 kVA substation in red, and customer with the highest impedance path in blue (cable length to nearest s/s: 266 meters). Cumulative cable length of mains and services: 0.7 km. Total connected customers: 11. Total circuit calculated ADMD: 19.5 kW. Number of registered 3.5 kVA EV chargers: 0. Number of registered PV installations: 1 (as marked)

The load flow analysis was run to obtain thermal and voltage data based on present-day ADMD values. Figure 10 shows the results of the load flow analysis performed on SPM-UR.

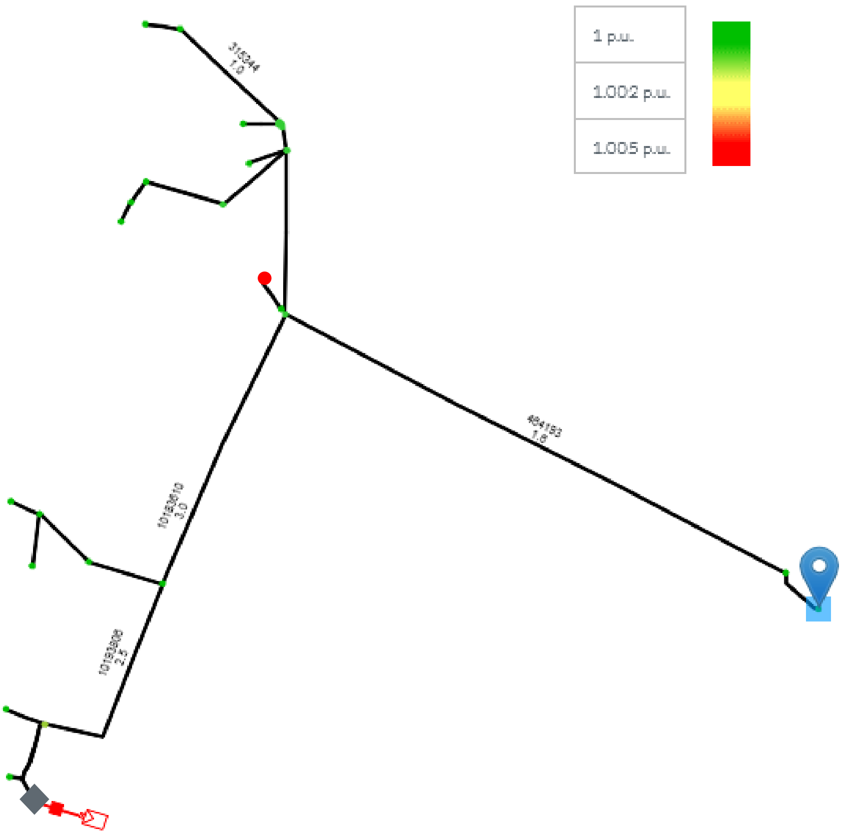

Figure 10. Load flow analysis results of circuit with present day demand and LCTs, with coloured cables representing thermal issues, and the green dots marking the voltage. Point of lowest voltage marked in blue and point of highest voltage marked by grey diamond.

In terms of the thermal results, there are no thermal warnings on any of the cables, as their utilisation is below 5% due to the low number of customers and their low demands. The potential concern, however, comes from potentially overloading the transformer, which is currently operating at 66% of its rating based on present-day ADMD without LCT penetration. The analysis shows that there are instances of overvoltage caused by the presence of the PV on the circuit. At the PV terminal, the voltage is 1.003 p.u., despite having the highest impedance back to the substation, i.e., 3.14 ohms. Thus, the lowest voltage is marked with a value of 0.999 p.u. and a total impedance to the substation of 2.52 ohms. These impedances are higher than the ones in SPM-SU and SPD-SU due to the overhead line cables having higher impedances, the weak circuitry found in rural networks, and the smaller cross-sectional areas of the cables.

Next, a rural network near Dumfries in SPD, SPD-UR, will be analysed. The circuit consists of both underground and overhead lines and is supplied by a radial 50 kVA transformer that feeds 24 customers with a total ADMD of 40 kW. The circuit has no registered LCTs on it. Figure 11 shows SPD-UR.

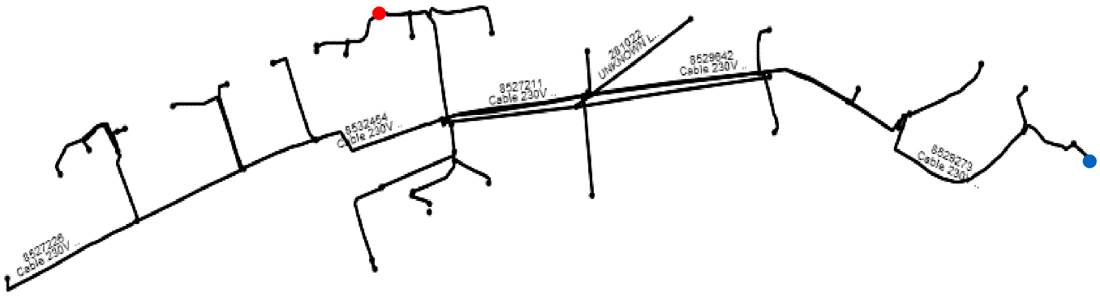

Figure 11. LV radial rural network near Dumfries, with 11 kV – 400 V 50 kVA substation in red, and customer with the highest impedance path in blue (cable length to nearest s/s: 279 meters). Cumulative cable length of mains and services: 1.1 km. Total connected customers: 24. Total circuit calculated ADMD: 39 kW. Number of registered 3.5 kVA EV chargers: 0. Number of registered PV installations: 0

The load flow analysis was run to obtain thermal and voltage data based on present-day ADMD values. Figure 12 shows the results of the load flow analysis performed on SPD-UR.

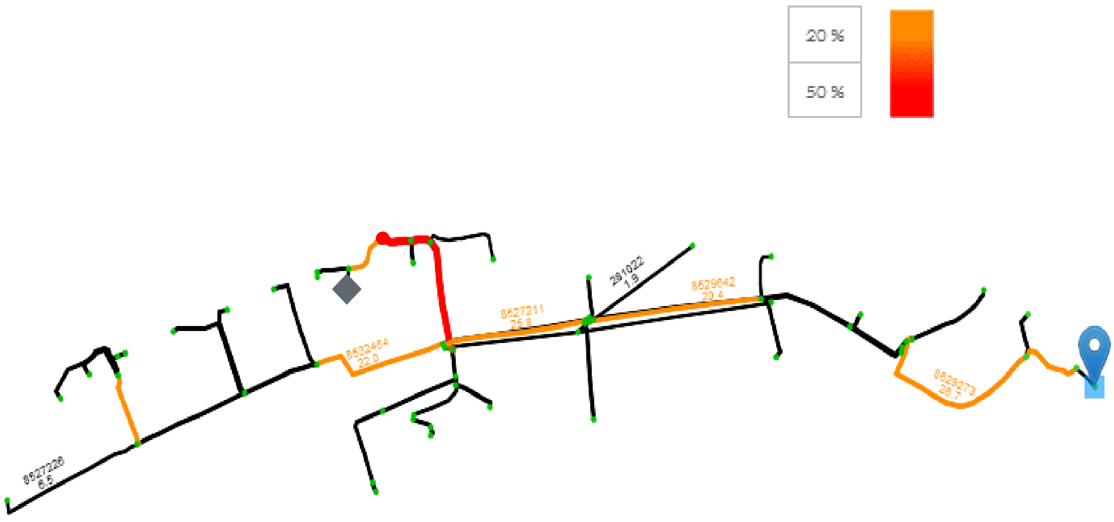

Figure 12. Load flow analysis results of circuit with present day demand and LCTs, with coloured cables representing thermal issues, and the green dots marking the voltage. Point of lowest voltage marked in blue and point of highest voltage marked by grey diamond.

In terms of the thermal results, the cables nearest the substation are the heaviest loaded at over 60% utilisation. The other coloured cables are above 20% utilisation and are spread out on the network due to their relative cable ratings. The rating of the cables nearest the substation is 225 A, while the cables that are orange are 137 A rated. The results show that the voltage is dropping as the customers become further away from the substation, but due to the shorter distances and the smaller number of customers, the lowest voltage is 0.99 p.u. and has an impedance of 5.54 ohms back to the substation.

Again, the impedance is the lack of PV installations registered to the circuit means there are no points of overvoltage. and there are not any voltage issues.

5. Demand & Load Growth Forecast

Having chosen six circuits from different network topologies in both the SPM and SPD license areas in Section 4, The Project used the LCTUp functionality on NAVI. LCTUp gathers data from both EV-Up and Heat-Up to forecast demand and load growth in baseline ADMD and increased LCT penetration. The circuits were analysed over the following years: present network, 2028, 2036, and 2040. From the forecast demand, the issues anticipated at LV can be highlighted, and aggregating those issues at LV then gives us an idea of the HV issues that we anticipate. The limitation of this method is that it only shows anticipated thermal issues on the cables, and not voltage issues. Furthermore, the circuits are analysed in an ideal way, assuming the circuits to be balanced. In the Alpha stage study, the analysis will be extended to include imbalanced networks.

5.1 URBAN NETWORKS

Due to time constraints, analysis of urban networks will be completed in the Alpha stage of the project. Therefore, suburban and rural networks were analysed, starting with suburban networks.

5.2 SUBURBAN NETWORKS

Starting with SPM-SU, The Project used NAVI to visualise the anticipated HV problems of the circuit due to increased LCT penetration. Figure 13 shows a high-level overview of the HV network in the Liverpool region, highlighting the area where SPM-SU is located.

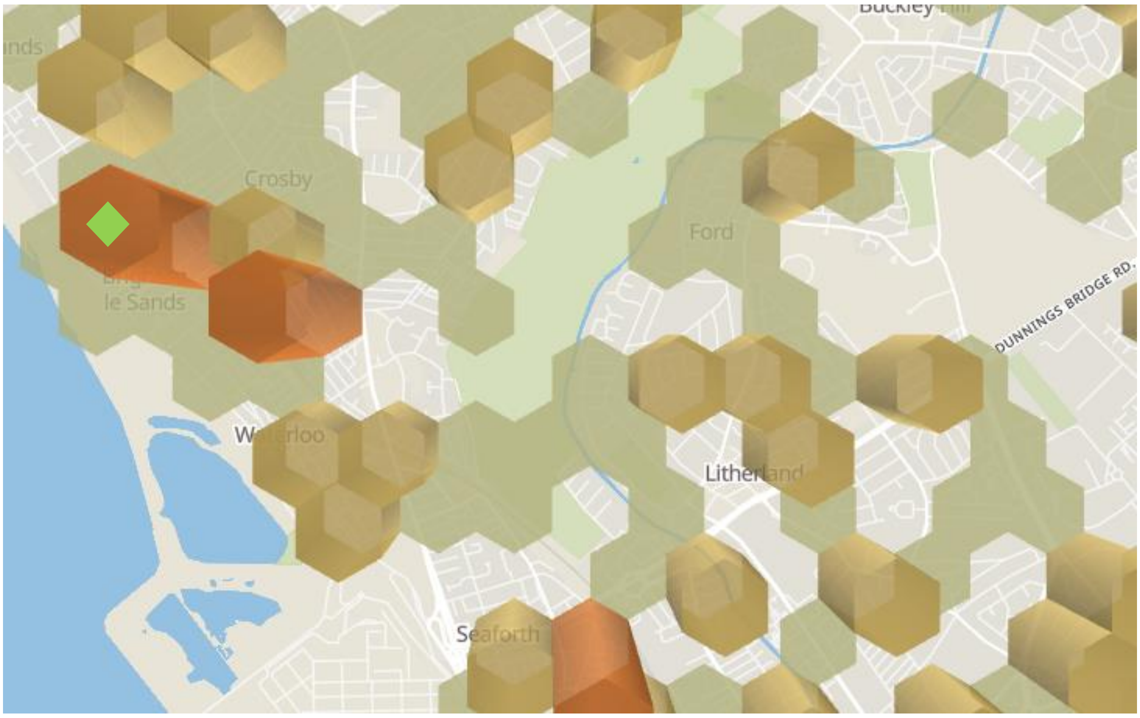

Figure 13. High-level image of HV network in Liverpool, with the higher hexagons highlighting the parts of the network that are expected to have issues due to future LCT penetration. The green diamond marks where SPM-SU is located

Due to the issues at HV, SPM-SU was analysed at LV with its present-day baseline ADMD, along with its forecast baseline ADMD and demand from LCT penetration for 2028, 2036, and 2040. Figure 14 shows the results of the analysis.

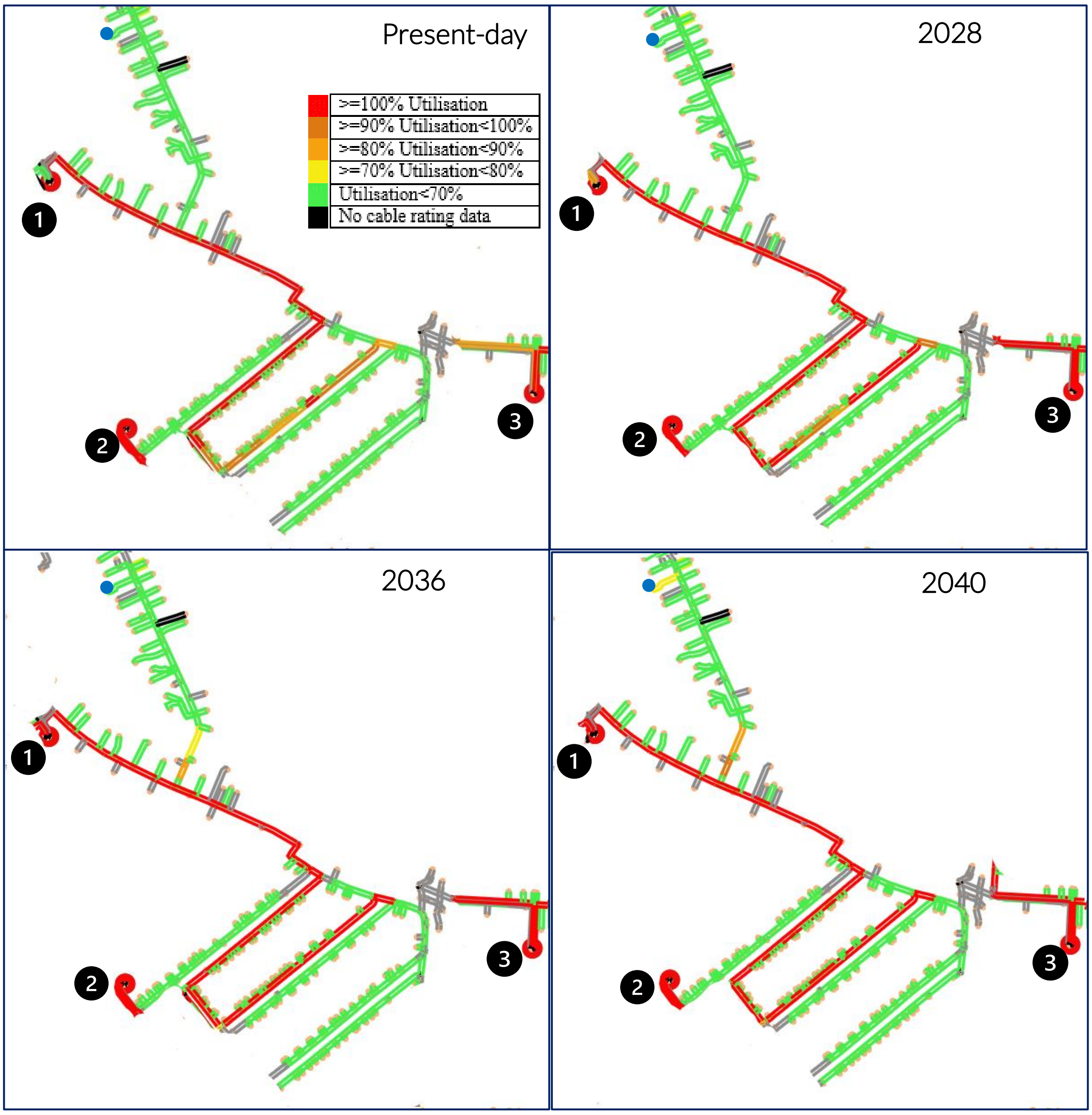

Figure 14. Present-day state of three-way interconnected SPM-SU using NAVI LCTUp functionality with baseline ADMD of 619 kW, alongside forecast demand due to LCT penetration of SPM-SU in future years. Calculated total circuit baseline ADMD + LCT demand value; 2028: 727 kW, 2036: 862 kW, 2040: 951 kW. Customer with lowest voltage marked in blue.

The analysis shows a noticeable increase in the demand of the network from our present-day data to the expected demand in 2040. As can be seen from the time-stamped shots in Figure 14, thermal issues, in the form of increased cable utilisation, are highlighted in their predicted locations on the circuit. The present-day total ADMD is 619 kW, while, when accounting for baseline ADMD and demand from heat pumps and EV charges, the total demand for the three years is 727 kW in 2028, 862 kW in 2036 and 949 kW in 2040. From 2028 onwards, the baseline ADMD of the circuit is 673 kW. Thus, the increase from year to year is coming from greater LCT penetration, so the increase from heat pumps and EV chargers were explored separately. Figure 15 shows the demand from heat pumps, extracted from Heat-Up data as outlined in Section 3.2.1, and the demand from EV chargers, extracted from EV-Up data as outlined in Section 3.2.2.

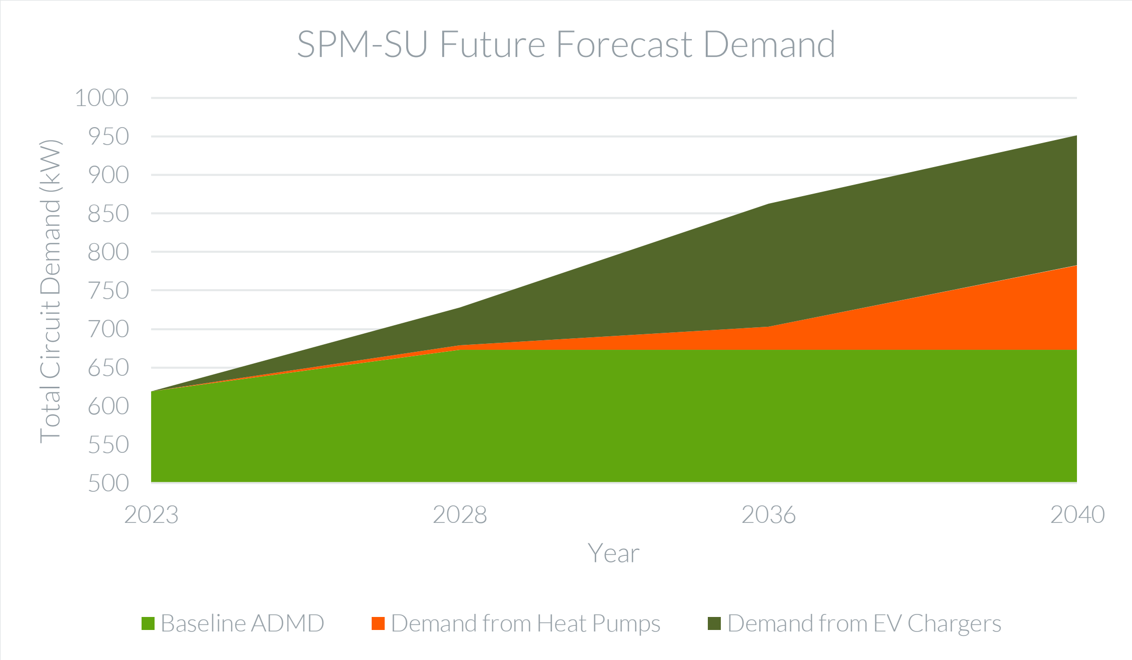

Figure 15. Demand increase on SPM-SU from present-day state to 2040 due to increased heat pump and EV charger penetration separately

The chart in Figure 15 shows that, from the present-day until 2036, the demand from EV uptake makes up most of the increase in demand, accounting for 159.5 kW of the 243 kW extra demand on our present-day demand, i.e., 66% of the total demand increase being due to EV charger uptake. Most of the extra load from EV chargers appears between 2028 and 2036, as that period sees an increase of 110 kW – roughly a rate of 14 kW a year. One of the key factors in that increase is the plan for the U.K. to ban new internal combustion engine vehicles in 2030. Meanwhile, demand from heat pumps accounts for 36 kW of new demand on the circuit between now and 2036. Between 2036 and 2040, however, the increase in demand is predominantly due to heat pumps, as it is estimated to cause an 80 kW demand increase on SPM-SU, during which a 10 kW demand increase from EV chargers is expected. Concerning heat pumps, that increase is due to the drop in heat pump costs, and the need to accelerate heat pump deployment as we approach the U.K.'s net zero target for 2050. Demand side response and flexible charging, alongside more widespread public EV charging stations, are the main drivers behind the smaller increase in demand from EV chargers. The analysis performed was idealised as we assumed balanced networks; the issues that may arise from imbalanced networks can arguably be more severe and will be explored in the Alpha stage of the study.

Next, SPD-SU was analysed, with Figure 16 showing a high-level overview of the HV network in Edinburgh, while highlighting the section of the network where SPD-SU is located.

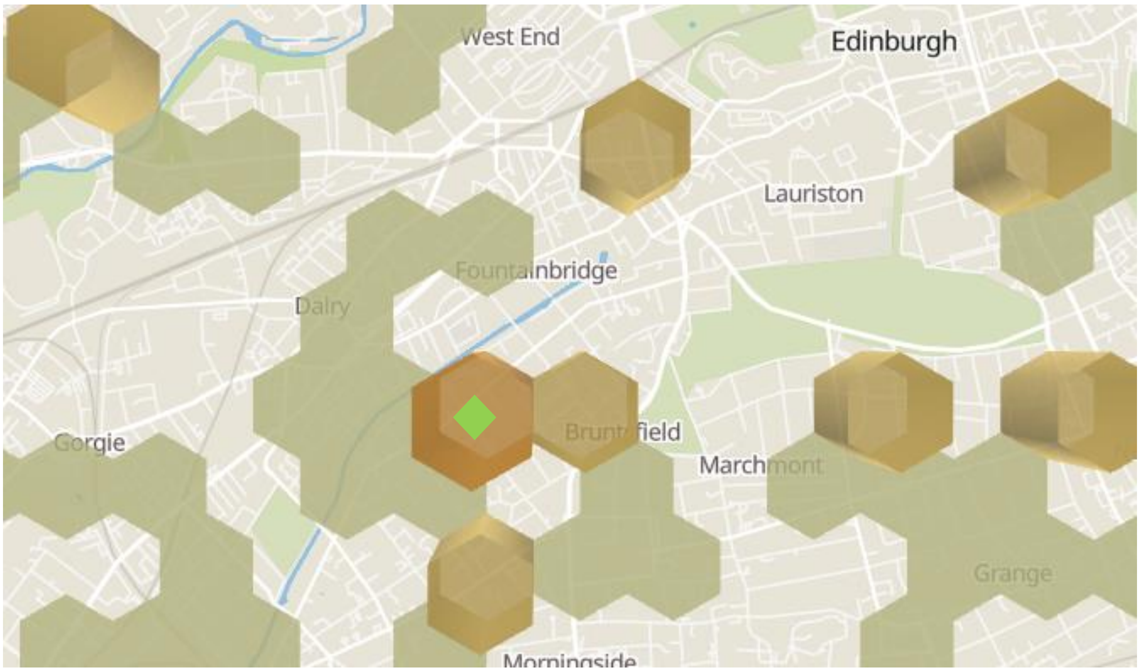

Figure 16. High-level image of HV network in Edinburgh, with the higher hexagons highlighting the parts of the network that are expected to have issues due to future LCT penetration. The green diamond marks where SPD-SU is located.

SPD-SU was then analysed at LV with its present-day baseline ADMD, and with its future forecast ADMD and LCT demand for 2028, 2036, and 2040. Figure 17 shows the results of the analysis.

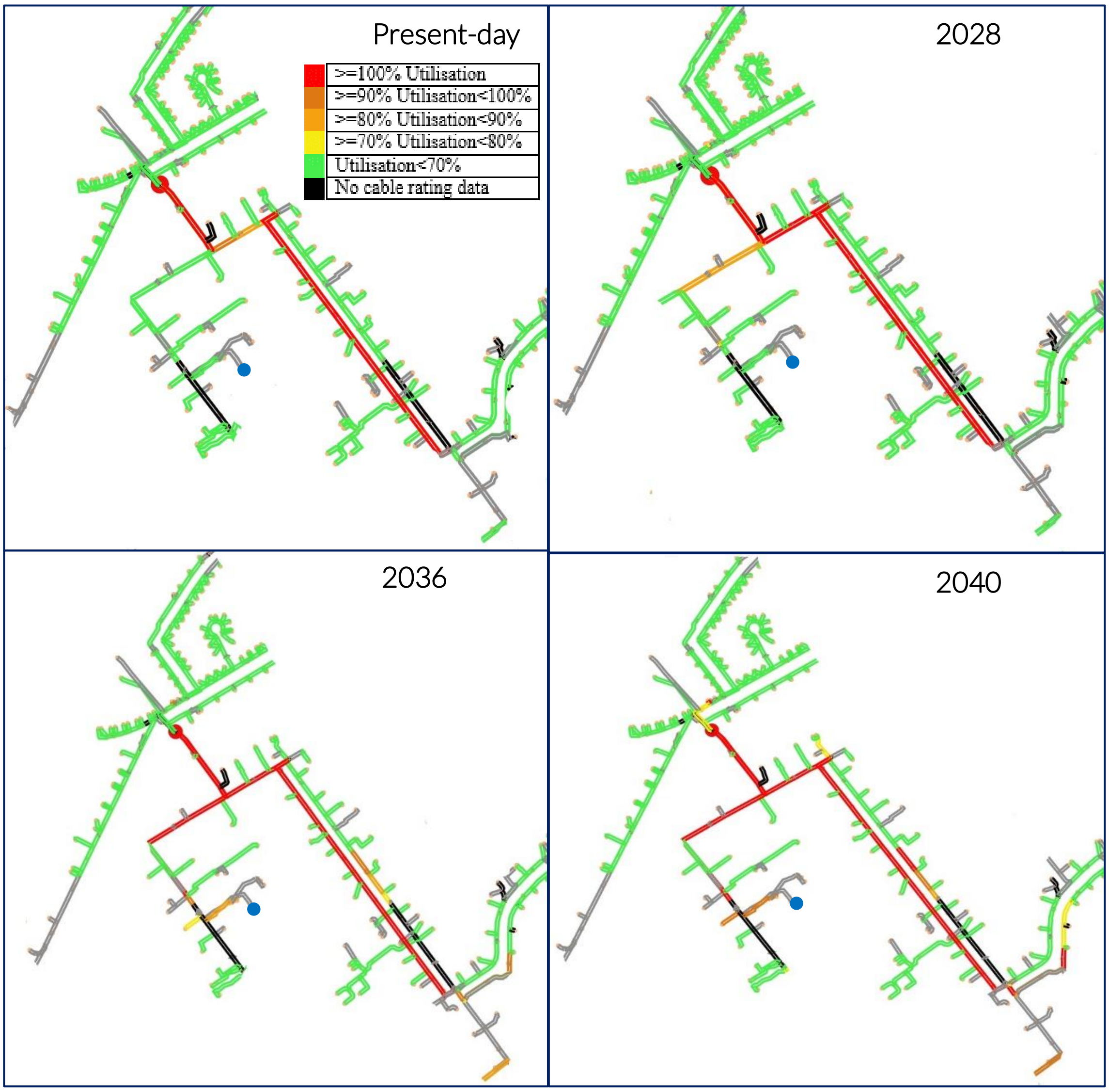

Figure 17. Present-day state of radial SPD-SU using NAVI LCTUp functionality with baseline ADMD of 609 kW, alongside forecast demand due to LCT penetration of SPD-SU in future years. Calculated total circuit baseline ADMD + LCT demand value; 2028: 775 kW, 2036

The analysis shows a noticeable increase in the demand of the network from our present-day data to the expected demand in 2040. The time-stamped shots in Figure 17 show where the anticipated thermal issues, due to increased LCT penetration, will likely occur on the circuit. The present-day total ADMD is 609 kW, while, when accounting for baseline ADMD and demand from heat pumps and EV charges, the total demand for the three years is 775 kW in 2028, 1159 kW in 2036 and 1270 kW in 2040. That is particularly problematic as the transformer rating is 1000 kVA, causing the transformer to overload along with the cables highlighted. The baseline ADMD is predicted to remain the same from now until 2040, meaning we do not predict any new developments or drastic changes to the houses on the circuit. Thus, the increase is caused by heat pumps and EV charger uptake, so the demand from each were explored separately, as shown in Figure 18.

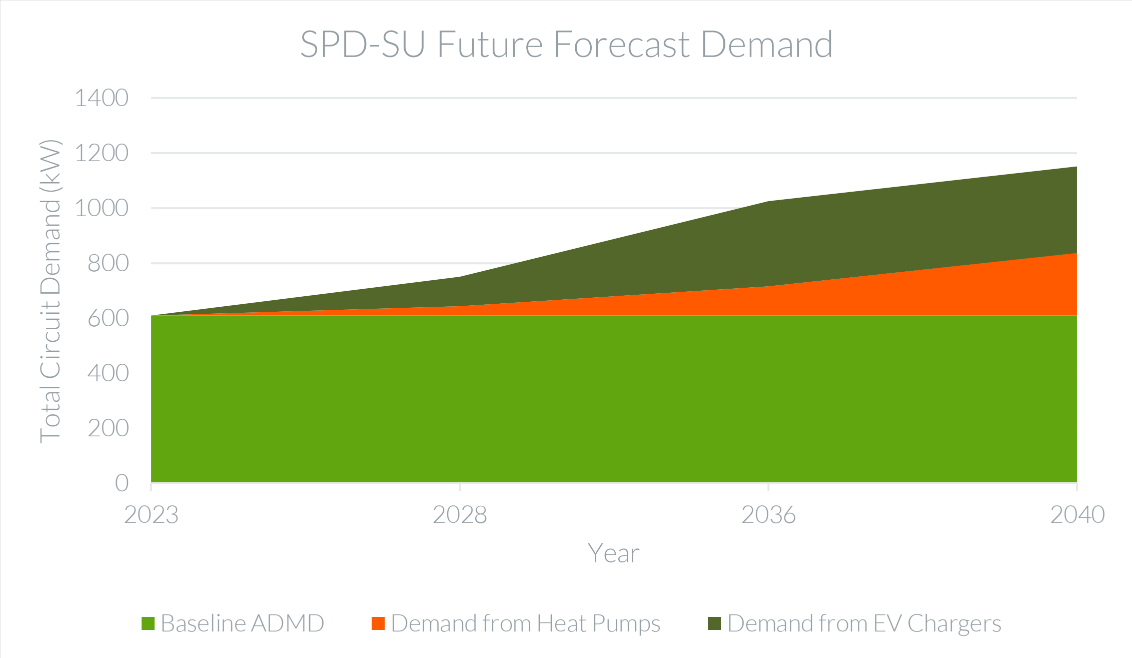

Figure 18. Demand increase on SPD-SU from present-day state to 2040 due to increased heat pump and EV charger penetration separately

The results in Figure 18 show that the rate of demand increase from EV chargers is roughly 20 kW a year from the present-day until 2028, and around 25 kW a year from 2028 to 2036. By comparison, the rate of demand increase from heat pumps is at around 7 kW a year until 2028, and 9 kW a year from 2028 to 2036. That shows that the EV uptake is expected to be higher during that period, as the analysis from SPM-SU also showed a greater increase of EV charger penetration up until 2036. On the other hand, 2036 to 2040 sees a much larger uptake in heat pumps, which accounts for 174 kW extra load in total during that period; meanwhile, EV charger demand is only expected to see an increase of 3 kW between 2036 and 2040. This is, again, similar to the trends concluded from the SPM-SU analysis. The next network topology that was analysed in terms of demand and load growth is rural networks.

5.3 RURAL NETWORKS

Starting with SPM-RU, Figure 19 shows the anticipated HV problems arising from LCT uptake in the area, with the location of SPM-RU highlighted.

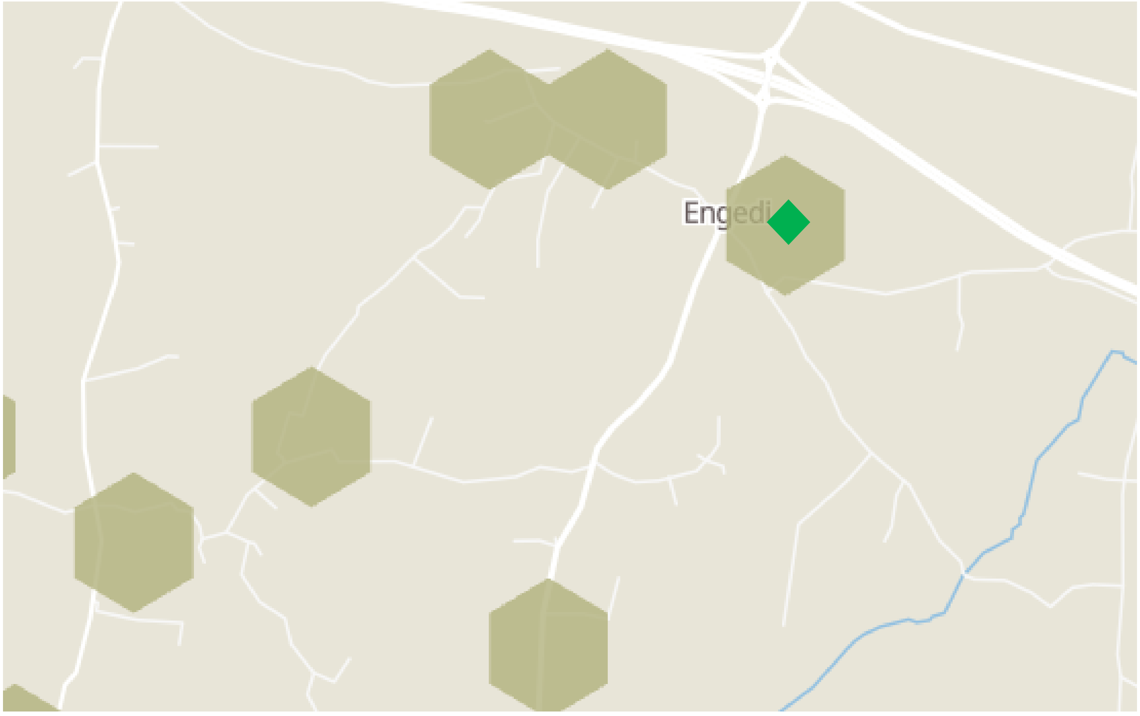

Figure 19. High-level image of HV network in Anglesey, with the higher hexagons highlighting the parts of the network that are expected to have issues due to future LCT penetration. The green diamond marks where SPM-RU is located

Compared to the suburban HV networks in SPM and SPD seen in Figure 13 and Figure 16, the HV issues in Figure 19 are less severe. That is because NAVI identifies HV issues as a build-up of LV issues, and, in rural networks, the total load remains considerably lower than that of urban and suburban networks. Therefore, the total number issues in rural networks, specifically overloaded cables due to future LCT penetration, will not have as significant of an HV impact as urban and suburban networks. SPM-RU was analysed at LV with its present-day baseline ADMD, along with its forecast baseline ADMD and demand from LCT penetration for 2028, 2036, and 2040, as shown in Figure 20.

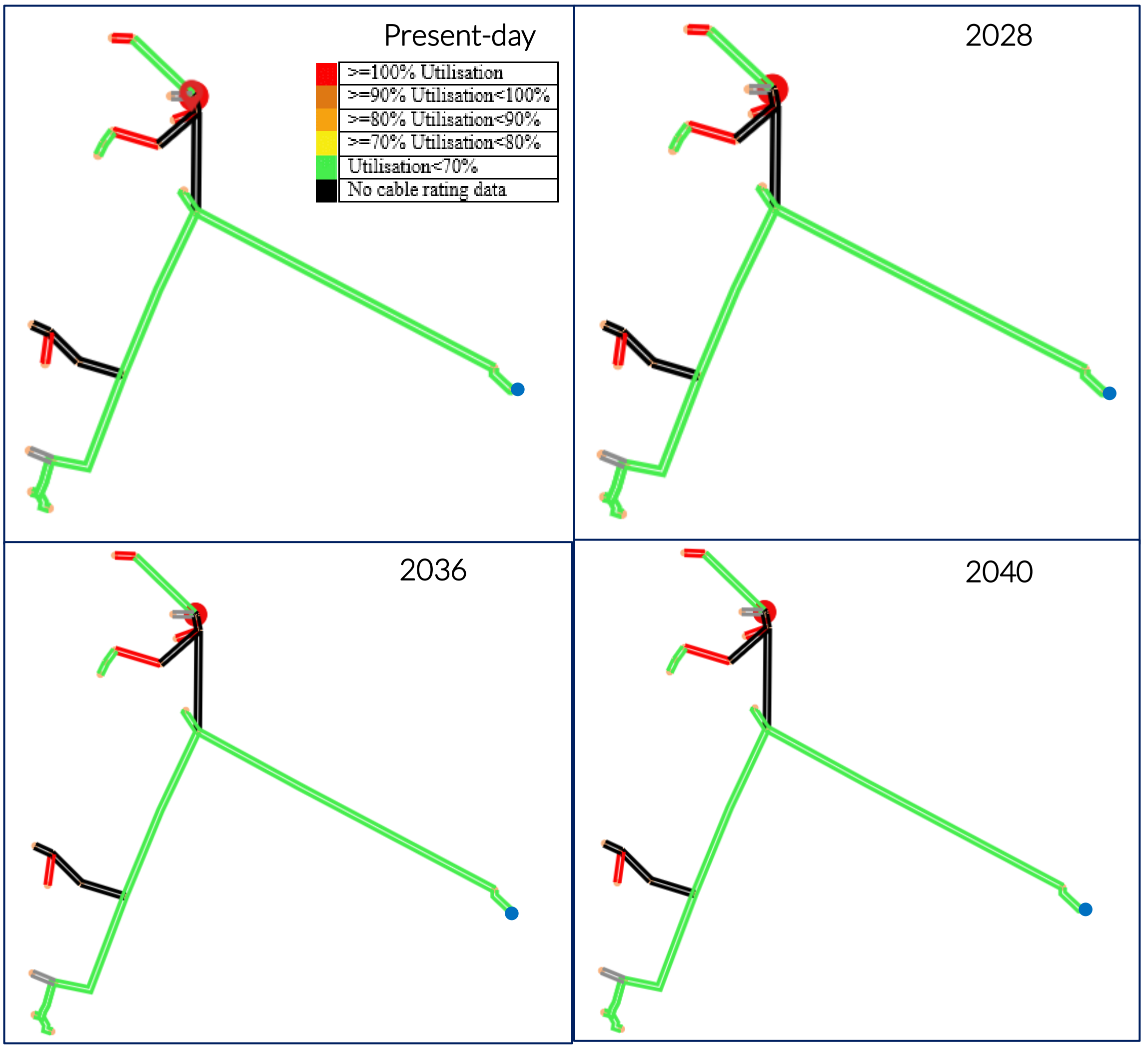

Figure 20. Present-day state of radial SPM-RU using NAVI LCTUp functionality with baseline ADMD of 19.5 kW, alongside forecast demand due to LCT penetration of SPM-RU in future years. Calculated total circuit baseline ADMD + LCT demand value; 2028: 40 kW, 2036: 65 kW, 2040: 65 kW. Customer with lowest voltage marked in blue.

The time-stamped shots show there are no anticipated thermal issues due to future LCT penetration that will likely occur on the circuit. As can be seen, the cable utilisation does not change reach a utilisation of greater than 70% on most of the network, despite the increased load from LCTs, due to the high cable ratings. The present-day total ADMD is 19.5 kW, while, when accounting for baseline ADMD and demand from heat pumps and EV charges, the total demand for the three years is 40 kW in 2028, 65 kW in 2036 and 65 kW in 2040, which is more than three times the current ADMD. Despite the lack of predicted cable issues, the transformer is expected to be overloaded in the coming years due to its 25 kVA rating. The baseline ADMD is predicted to remain the same from now until 2040, meaning we do not predict any new developments or drastic changes to the houses on the circuit. Thus, the increase is caused by heat pumps and EV charger uptake, so the demand from each were explored separately, as shown in Figure 21.

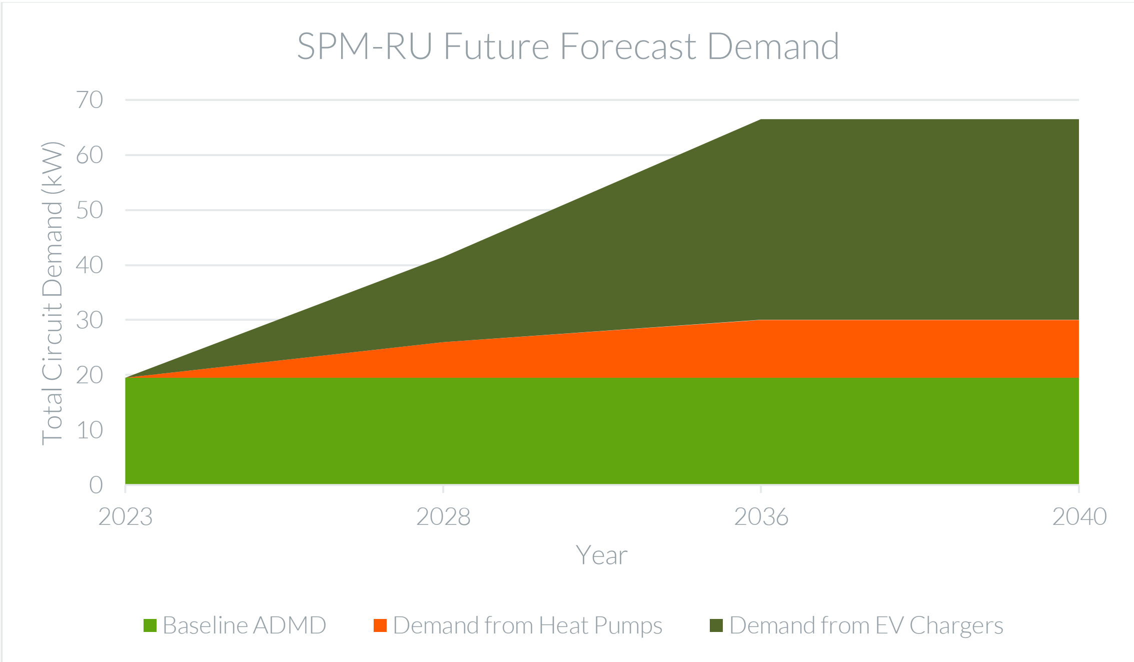

Figure 21. Demand increase on SPM-RU from present-day state to 2040 due to increased heat pump and EV charger penetration separately

The graph shows that the demand from EV chargers is considerably greater than that from heat pumps. That can be explained by the location of the customers; being in a rural area typically means less access to charging stations. Furthermore, rural customers typically have private driveways to accommodate personal EV chargers. For these reasons, EV charging demand is significant, as it is predicted to make up more than 50% of the total demand from the circuit by 2036, or 35 kW of 65 kW. By comparison, demand from heat pumps makes up 10.5 kW of the total circuit demand in 2036, which is just under 20%. Demand from both heat pumps and EV chargers does not increase past 2036, indicating early LCT uptake from customers on the circuit.

Next, SPD-RU was analysed, with Figure 22 showing a high-level overview of the HV network near Dumfries, while highlighting the section of the network where SPD-SU is located.

Figure 22. High-level image of HV network in Dumfries, with the higher hexagons highlighting the parts of the network that are expected to have issues due to future LCT penetration. The green diamond marks where SPD-RU is located.

Like SPM-RU, the future HV issues are less severe and more spread out than the urban and suburban networks. Figure 23 shows the results of the analysis of SPD-SU at LV with its present-day ADMD, and the predicted demand from future LCT uptake.

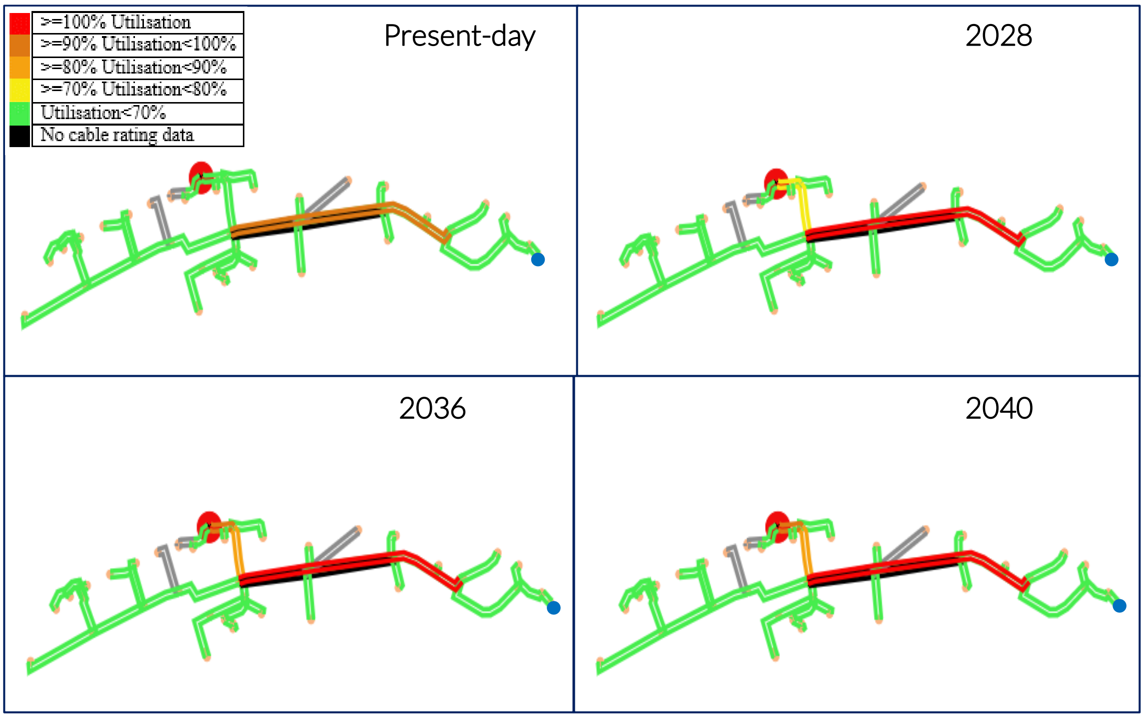

Figure 23. Present-day state of radial SPD-RU using NAVI LCTUp functionality with baseline ADMD of 39 kW, alongside forecast demand due to LCT penetration of SPD-RU in future years. Calculated total circuit baseline ADMD + LCT demand value; 2028: 95 kW, 2036: 125 kW, 2040: 125 kW. Customer with lowest voltage marked in blue.

The analysis shows where the thermal issues are likely to occur on SPD-RU. As can be seen, the set of cables coming out of the substation are the most suspect to future thermal issues, due to the high current passing through them. With the added demand from LCT penetration, that current will only increase, ultimately leading to some cables being overloaded on SPD-RU. The present-day ADMD on SPD-RU is 39 kW; that value, when accounting for demand from EV chargers and heat pumps, is expected to reach 95 kW by 2028, and 125 kW by 2036, which is more that three times the current circuit demand. That suggests the transformer may be overloaded in the near future, as its rating is 50 kVA. The demand from EV chargers and heat pumps will be analysed separately, with Figure 24 showing a breakdown of the demand of SPD-RU up until 2040.

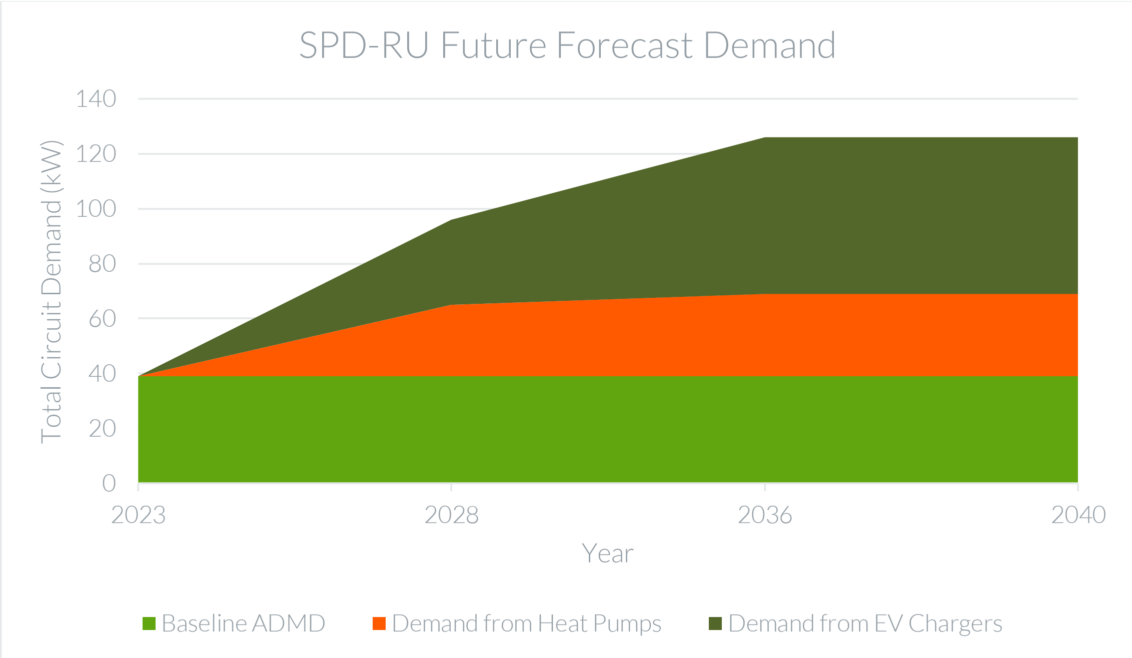

Figure 24. Demand increase on SPD-RU from present-day state to 2040 due to increased heat pump and EV charger penetration separately

The breakdown shows that the demand from EV chargers and heat pumps is similar between now and 2028, with 26 kW coming from heat pumps by 2028 and 30 kW coming from EV chargers. Those high values of demand from a low customer count, as SPD-RU has 24 customers connected to it, suggests early LCT uptake, which can be explained by the lack of barriers that urban and suburban customers face, such as limited space and not having a private driveway for the car. From 2028 to 2036, however, the demand from EV chargers becomes much greater, as that period sees an increase of 26 kW, compared to the 4-kW increase from heat pumps during that period. Due to the remote locations of customers in rural networks, there will be a lack of EV charging infrastructure nearby, creating extra demand for residential EV charger installations. The load is not expected to increase between 2036 and 2040, meaning that demand from LCTs alone is expected to account for over two thirds of the total demand on the circuit by 2036.

6. Discussion and Conclusions

SP Energy networks has described the D-Suite technology use cases and shown LV and HV networks, in the SP Manweb and SP Distribution license areas will encounter thermal and voltage constraints, due to the LCT rollout, which can be mitigated using D-Suite technologies. Even with the idealised case of only modelling balanced networks, numerous networks will require the implementation of solutions to manage violation of voltage thresholds and over utilised circuits and substations, across urban, suburban, and rural networks between the present day and 2040.

Future work will model six selected networks, across SPD and SPM, in greater detail using unbalanced networks, LCT demand profiles across the complete year and the upstream MV network to better understand and quantify the scale of the LV network challenges and how each D-Suite technology will address them.

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