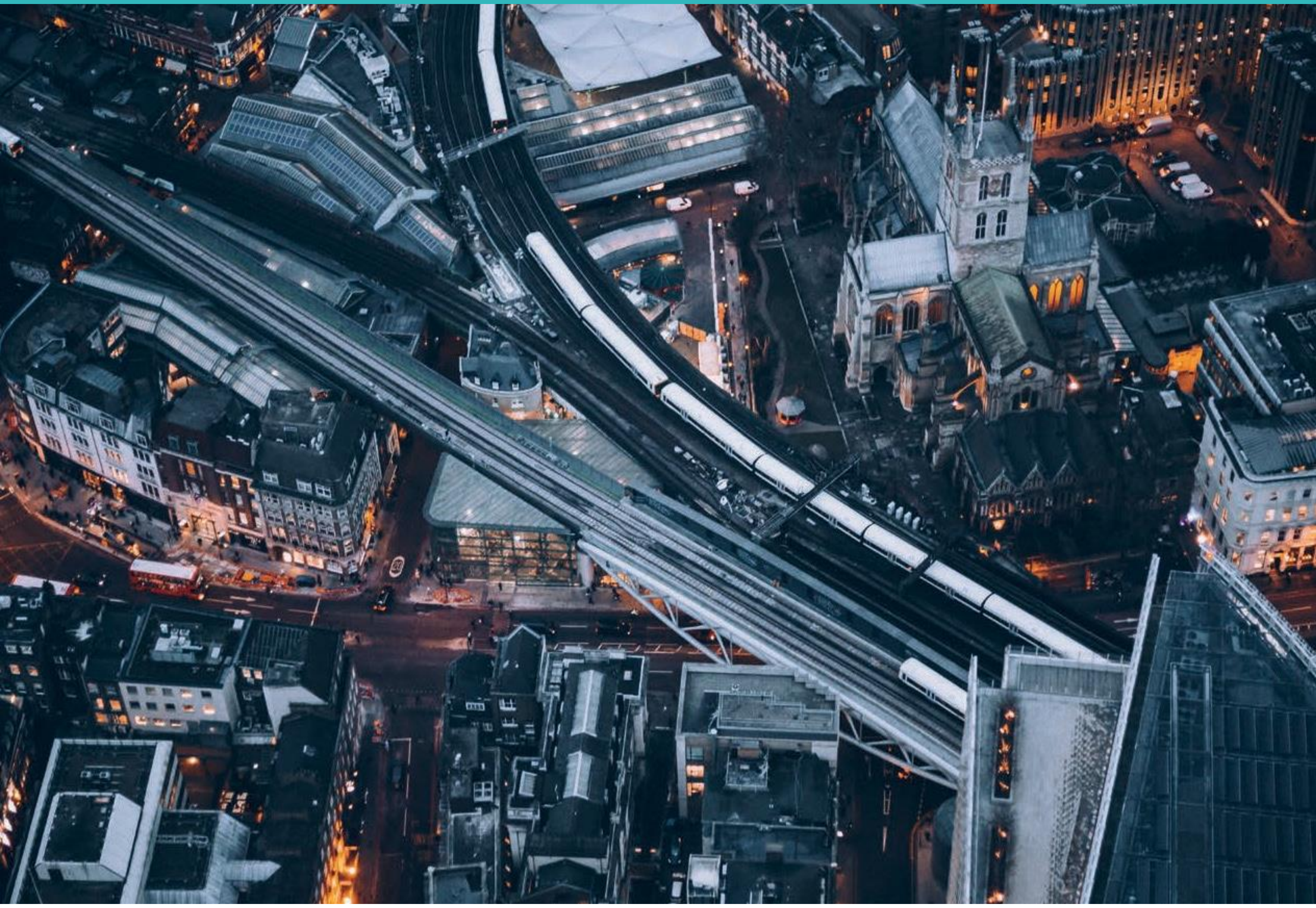

REPORT

SILVERSMITH LV Voltage Control Selection Methodology

Prepared for: National Grid

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Final Approval

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Executive Summary

Background to the Project

Great Britain is undergoing a transition to renewable and distributed energy. Many energy customers are becoming more involved in the energy system, transitioning from simply being electricity consumers to electricity prosumers. This is being led through the electrification of transport (i.e. electric vehicles) and heating (i.e. heat pumps) along with the continued growth in distributed generation, most commonly solar photovoltaics (PV). Low Carbon Technologies (LCTs) such as Electric Vehicles (EVs) and heat pumps are forecast to witness vast uptake rates over the next few decades. The combined effect of these technologies will have a profound effect on the electricity network. Large numbers of these technologies will be deployed on the Low Voltage (LV) networks, which will place significant additional demand on it, in many cases beyond which the network was designed for. National Grid[1] manage the LV network across their licence areas in the East Midlands, West Midlands, South West, and South Wales, and have commissioned this study to help increase their understanding of the challenges and opportunities for new technologies across their LV network.

As National Grid transitions towards management of an active LV network, this must be delivered in a manner which enables customers to install LCTs at the foreseeable uptake rates. This has to be achieved while minimising costs to consumers resulting from network augmentation but continuing to provide a safe and reliable supply of electricity. Additionally, network management should be fair to all electricity consumers, regardless of whether they own LCTs or not. It is therefore important to maximise value extracted from the existing LV network in order to minimise network costs arising from network reinforcement. The aim of the SILVERSMITH project is to identify novel technological solutions that will enable network operators to more effectively manage their LV networks. Previously a Request for Information (RfI) and literature review process has been conducted to identify novel technologies that have potential value to network operators. The findings are covered in the report EA16141–TR2 SILVERSMITH Literature Review. The aim of this section of the SILVERSMITH project is to perform a Cost Benefit Analysis to determine which of these novel technologies offer value to the network operators and on which feeder types.

This project utilises EA Technology's Transform Model, a techno-economic parametric electricity network modelling tool capable of conducting a Cost Benefit Analysis to identify the most cost effective solutions to resolving network forecast constraints. The EA16141-TR1 SILVERSMITH Network Study Results report identified the types of constraints experienced across National Grid's four licence areas, and how this varied across licence area and DFES (Distribution Future Energy Scenarios) scenario at a network level. Analysis was also presented that identified the types of constraints that were forecast on each LV network archetype. The EA16141-TR4 SILVERSMITH Functional Requirements report analysed which BaU solutions were utilised to resolve the constraints across National Grid's four licence area, and compared this to the BaU and novel solutions deployed in a study performed with the novel solutions from the Literature Review in addition to the BaU solutions. This was done at a network level, compared across licence areas and DFES scenarios. Analysis was also presented showing which solutions offered value at an LV network archetypal level.

The aim of this report two fold:

- Firstly, to help network planners identify which novel technologies should be considered when planning network upgrades. To do this, this report links the constraints analysis with the solutions analysis, showing what technologies get deployed to resolve which network constraint(s). It then breaks this down to an archetypal level, recommending technologies that should be considered for each type of constraint forecast to be encountered.

[1] National Grid Electricity Distribution, part of the National Grid group, were previously known as Western Power Distribution and renamed in September 2022.

- Secondly, the report aims to help direct future innovation activity, by identifying areas where gaps exist in available BaU and novel technologies.

It should be noted that this analysis focuses on technical solutions and flexibility was not directly considered as a solution. This was due to significant uncertainty in flexibility service availability and the costs associated with procuring. However, this report has highlighted the opportunity for flexibility services required to postpone network reinforcement across each network archetype. This typically ranges in a net demand change of between 0.7kW and 2.1kW per customer and the potential for this should be considered further as part of cost benefit analysis for deployment of each technical solution.

Conclusions

The following conclusions can be drawn from the detailed analysis carried out in the production of this report and highlighting the learning established in this phase of the SILVERSMITH study.

C1. Similar solutions are selected to be deployed across all four of National Grid's electricity distribution licence areas. The proportion of solution deployment is sensitive to the LCT uptake rates on each licence's area feeder set. The solutions chosen by network planners should be based on the network constraint type and extent of constraint witnessed on the specific feeder.

C2. The number and types of distinct solutions required across National's Grid network is independent of the scenario. Regardless of the actual LCT uptake rate, the distinct solutions will be utilised for particular feeders due to the variability in clustering of LCT deployments. Network planners do not need to be concerned about the uptake rate of LCT across the system, instead they should focus on the constraint type and extent caused by LCTs on each individual feeder.

C3. To defer network reinforcement for a 5-year period from time of first network constraint, between 0.7kW and 2.1kW per customer are required depending upon the network archetype.

C4. Both smart transformers and OLTCs offer a potential option to improve voltage management and increase headroom for PV export with the preferred option being dependant on the granularity of control. Statcoms offer some potential, particularly to individual voltage constrained feeders with some spare thermal capacity, with greatest benefit being realised when they can be located at remote end of feeders.

C5. Network meshing is an effective solution to increase thermal capacity but consideration around fault levels and protection systems is required on a case-by-case basis. Difficulties associated with retrofitting network meshing to existing networks mean this solution is unlikely to be suitable for wide scale roll out, however it could be valuable for specific cases.

C6. Novel solutions offer savings over BaU costs through deferral of investment. Sensitivity studies show that these savings are robust against variations in network topology and LCT uptake rates.

Next Steps

The final stage of this project is the production of a Technology Witnessing Report (EA16141 – TR7 Technology Witnessing and Final Recommendations). This report will summarise the technologies studied over the course of the SILVERSMITH project, categorising them as either technologies that meet or exceed the functional requirements and that offer the network operator value today or as technologies currently unable to provide the specification required to be of value to the network operator. The report includes recommendations to the network operator focusing on areas for future innovation. It will recommend novel technologies that offer value to the network operator in managing their LV network, but also recommend innovation activity in areas where currently technologies do not knowingly exist but could, if developed, offer value to the network operator. Additionally, the requirements of any gaps where technologies currently do not exist but would offer value to the network operator in controlling the LV network. Finally the report will consider where changes to either regulatory or commercial models may be required to enable the use of innovative technologies, including mentioning the role flexibility (not considered throughout this project) could have in controlling the LV network.

Recommendations

R1. Review data from flexible interventions as flexibility markets develop, to consider how cost effective flexible solutions could be for resolving network constraints.

R2. Development of innovative technologies that could offer between 20% and 80% thermal transformer capacity at less than £16,000 per feeder (for underground feeders supplied by GMTs) or £7,500 per feeder (for overhead feeders supplied by PMTs) would offer significant value to the network operator and reduce unnecessary capacity overprocurement.

R3. To effectively manage LV customer voltages using novel solutions, some form of monitoring of feeder voltages through smart meters or network monitoring and feedback loop to establish target set-points will be needed.

R4. Innovative technology offering significant thermal cable capacity release suitable for retrofit across all feeders, would offer significant value to the network operator.

Contents

Appendices

1. Definitions

BaU	Business as Usual
BESS	Battery Energy Storage System
BV	Best View
CBD	Central Business District
DFES	Distribution Future Energy Scenarios
DSR	Demand Side Response
EV	Electric Vehicle
GB	Great Britain
GMT	Ground Mounted Transformer
HV	High Voltage
LCT	Low Carbon Technology
LtW	Leading the Way
LV	Low Voltage
OLTC	On-load Tap Changer
PMT	Pole Mounted Transformer
PV	Photovoltaics
RfI	Request for Information
RIIO-ED2	Revenue = Incentives + Innovation + Outputs – Electricity Distribution 2
RTTR	Real Time Thermal Rating
SP	Steady Progress
Tx	Transformer
V2G	Vehicle to Grid

2. Background and Introduction

Great Britain is undergoing a transition to renewable and distributed energy. Many energy customers are becoming more involved in the energy system, transitioning from simply being electricity consumers to electricity prosumers. This is being led through the electrification of transport (i.e. electric vehicles) and heating (i.e. heat pumps) along with the continued growth in distributed generation, most commonly solar photovoltaics (PV). Low Carbon Technologies (LCTs) such as Electric Vehicles (EVs) and heat pumps are forecast to witness vast uptake rates over the next few decades. The combined effect of these technologies will have a profound effect on the electricity network. Large numbers of these technologies will be deployed on the Low Voltage (LV) networks, which will place significant additional demand on it, in many cases beyond which the network was designed for. National Grid[2] manage the LV network across their licence areas in the East Midlands, West Midlands, South West, and South Wales, and have commissioned this study to help increase their understanding of the challenges and opportunities for new technologies across their LV network.

As National Grid transitions towards management of an active LV network, this must be achieved in a manner which enables customers to install LCTs at the foreseeable uptake rates. This has to be achieved while minimising costs to consumers resulting from network augmentation but continuing to provide a safe and reliable supply of electricity. Additionally, network management should be fair to all electricity consumers, regardless of whether they own LCTs or not. It is therefore important to maximise value extracted from the existing LV network in order to minimise network costs arising from network reinforcement.

2.1 Literature Review

The Literature Review [1] conducted earlier in this project identified novel technologies that could offer potential for increasing headroom on the LV network. A Request for Information (RfI) was conducted as part of this process, where providers were asked to give details about how their technologies could potentially help to increase headroom on the LV network.

2.2 Network Study Results Report

The Network Study Results report [2] presented analysis that identified the types of network constraint forecast to be encountered across National Grid's licence areas. This was delivered through use of the EA Technology Transform Model® which enables a parametric based analysis for different LCT uptake scenarios and how they will impact the network. National Grid's existing Transform models were updated based on the latest scenarios in DFES 2021 [3]. Details of how DFES 2021 data was used to populate the Transform model for National Grid's four licence areas are provided in the report and these models provided the basis for the Functional Requirements studies presented in this report.

The Network Study Results report identified the type of network constraints encountered both at the network level, and on a feeder archetype basis. It highlighted the durations, scenarios and timescales under which network constraints are met, and how this differs across network archetypes.

2.3 Functional Requirements Report

The Functional Requirements report [4] presented analysis that identified what solutions are deployed in two instances; the counterfactual instance where only Business as Usual (BaU) solutions were available to the model to solve network constraints, and the novel instance where both BaU and novel technologies were available to solve network constraints. This was also delivered through use of the EA Technology Transform

[2] National Grid Electricity Distribution, part of the National Grid group, were previously known as Western Power Distribution and renamed in September 2022.

Model® which enables a parametric based analysis for different LCT uptake scenarios and how they will impact the network.

The Transform Functional Requirements report identified the solutions deployed both at the network level, and on a feeder archetype basis. It showed the variation in technology deployment between the counterfactual and novel studies, and also showed how the solution deployed varied by network archetype.

The PowerFactory Functional Requirements report [5] analysed the effect of novel technologies identified in the literature review on the three case study networks. This report discussed the effect of these technologies on the network, assessing their impact on the voltage and thermal capacity of the network. Implications on fault level and harmonics were also discussed qualitatively for those technologies where parameters would be impacted.

2.4 This Report

The purpose of this report is to identify which network constraints are solved by which technologies. In addition, this report aims to give network planners a methodology for identifying which novel technologies should be considered when upgrading the network. This is done on an archetypal basis and a flowchart is provided to help network planners identify which feeder archetype they are working on. This report will present case studies that show how particular technologies are helpful for resolving particular network constraint type on particular LV feeder archetypes.

2.5 Flexibility First

National Grid's RIIO-ED2 business plan, in common with other GB network operators, identifies flexibility services as a key method for managing their networks in the most cost effective manner for consumers. Flexibility can be provided by a wide range of technologies such as:

- Managed EV Charging
- Battery Energy Storage Systems (BESS)
- Commercial and domestic Demand Side Response (DSR)
- Vehicle to Grid (V2G)

Flexible solutions were excluded from analysis for this project. This project focuses on understanding the counterfactual to flexibility, namely network operators reinforcing the network to resolve constraints as they occur. Therefore, this project focuses on technological solutions that comprise of assets that the network operator owns and operates.

Flexibility remains an important option for manging the LV network. Flexibility solutions are expected to offer an alternative method of managing the LV network at a lower cost than the technological solutions, flexibility should be strongly considered in the first instance. As the flexibility markets develop, a clearer picture will emerge of capacity available from flexibility, the willingness of consumers to engage, and the cost of procuring services. This report, particularly section 4.2, explores the alternative technological solutions against which flexibility solutions are expected to compete with. By understanding the best placed alternative technological solution, the network operator can ensure that the price of flexibility is set appropriately to ensure value to customers.

R1. Review data from flexible interventions as flexibility markets develop, to consider how cost effective flexible solutions could be for resolving network constraints.

3. Mapping Constraints to Solution

The analysis conducted for EA16141-TR1 Network Study Results report [2] analysed the constraints facing National Grid's LV electricity distribution networks based on the DFES scenarios Steady Progress and Leading the Way based on National Grid's Future Energy Scenarios. These are the DFES scenarios with the lowest and highest forecast uptake of LCTs respectively. Additionally, the modelling has considered National Grid's Best View, formed from the scenarios considered most likely after significant, detailed stakeholder engagement to determine the most likely growth projection for LCTs. :

Each of the three scenarios represent possible future pathways of LCT deployments across National Grid's four licence areas.[3] BV is considered the most likely scenario, and can be considered therefore as the central scenario. SP reflects a scenario with slower progress towards Net Zero and thus has slower uptake rates of LCTs. LtW reflects a scenario with faster progress towards Net Zero and has higher uptake rates of LCTs.

Through detailed analysis of the Transform Model constraint identification and output, the constraints can be categorised into six common but distinct types.

1. Voltage drop constraints occur when the voltage drop along a feeder exceeds the maximum voltage drop defined as allowed for that particular feeder.
2. Similarly, voltage rise constraints occur when the voltage rise along a feeder exceeds the maximum voltage rise defined for that particular feeder.
3. Thermal Transformer (Load) constraints occur when the maximum net import to a feeder exceeds the thermal capacity of the transformer associated with that particular feeder.
4. Thermal Transformer (Generation) constraints occur when the maximum net export from a feeder exceeds the thermal capacity of the transformer associated with that particular feeder.
5. Thermal Cable (Load) constraints occur when the maximum net import to a feeder exceeds the thermal capacity of the cable as defined in Transform for that particular feeder.
6. Thermal Cable (Generation) constraints occur when the maximum net export to a feeder exceeds the thermal capacity of the cable as defined in Transform for that particular feeder.

Each time a network constraint is identified, Transform deploys the most cost effective solution to resolve that constraint over the next 5 year period. In many instances, after that 5 year period, another constraint occurs due to further deployment of LCTs, requiring another intervention. This is counted as an additional constraint for the purposes of this analysis, since an additional solution is required to be deployed. In some cases a single feeder can be subject to three of four constraints over the course of the study, requiring multiple interventions.

The analysis conducted for EA16141-TR4 Functional Requirements report [4] analysed the BaU and novel solutions selected by the Transform model deployed for the three different DFES scenarios. It considered a large range of novel solutions identified in the Literature Review [1] and RfI process, together with BaU.

This report focusses on providing recommendations and case studies to network planners to help them identify which novel solutions to deploy on which network archetypes, as well as to direct innovation into the functional requirements with areas that can be improved. It is crucial to understand which technologies are deployed to solve the network constraints. The analysis presented in this section maps the solutions deployed across the network to the constraint type that the solutions were deployed to solve. The Sankey diagrams (Figure 1 to Figure 12) presented below link the network constraint type to the solutions used to resolve those constraints. Note that the analysis is restricted to identification of the constraint type(s) that the solution is deployed to resolve in the year when the constraint is first encountered.

[3] National Grid's four licence areas are East Midlands, West Midlands, South Wales and South West.

The Sankey diagrams show that the dominant constraint types forecast across National Grid's electricity distribution licence are thermal transformer and thermal cable under net import and voltage rise. Thermal issues under net import are forecast in only very small quantities. This is consistent with the findings presented in the Network Study report [2].

The solutions deployed to resolve network constraints can be categorised according to the constraint types that they resolve:

1. Solutions deployed to resolve voltage rise constraints by release of voltage headroom. These include:
    a. Manual Tapping of HV/LV Tx [increasing headroom]
    b. Switched Capacitors
2. Solutions primarily deployed to resolve thermal transformer constraints by release of thermal transformer capacity. These include:
    a. LV Pole Mounted 11/LV Tx
3. Solutions primarily deployed to resolve thermal cable constraints by release of thermal cable capacity. These include:
    a. LV New Split Feeder
4. Solutions deployed to resolve both thermal cable and thermal transformer constraints by release of thermal capacity. These include:
    a. LV Underground network split feeder
    b. Manual Phase Balancing
    c. LV Ground Mounted 11/LV Tx
    d. Active Transformer Cooling
5. Solutions deployed to resolve voltage and thermal constraints. These include:
    a. LV Underground Minor works
    b. LV Overhead network Split Feeder

3.1 Variation Between Licence Areas

Figure 1 to Figure 4 show the variation in solution deployment in the BV scenario. The number of distinct solutions deployed across:

- West Midlands: 13 distinct solutions,
- South Wales: 14 distinct solutions,
- South West: 15 distinct solutions.

The solutions deployed across West Midlands, South Wales and South West are identical, apart from the additional solution for South Wales and South West LV Underground Minor Works and the further additional solution for the South West LV Overhead Network Split Feeder. This shows that most solutions are likely to bring value across all four of National Grid's licence areas.

The East Midlands sees a higher number of distinct solutions deployed (22 distinct solutions). The 15 solutions deployed in the South West are all used in the East Midlands. An additional 7 solutions (LV Underground Major Works, LV New Split Feeder, Smart Tx. LV Overhead Major Works, STATCOMS [GMT], STATCOMs [PMT] and Dynamic Network Configuration) are deployed in small quantities. The additional solution deployed in the East Midlands is a result of the East Midlands having the highest forecast uptake rate of LCTs. This results in differing combinations of solutions occasionally needing to be deployed to most cost effectively resolve the network constraints that emerge. This typically occurs on the small proportion of feeders with the highest levels of LCT deployment, hence the low overall level of deployment of these solutions.

The proportion of each distinct solution deployed varies across the licence areas. This variation is caused by differing forecast uptake rates of LCTs across each licence area, presenting different constraint types and extents of constraint facing network operators. The most cost effective solution set is dependent on the extent of the constraint facing each particular feeder, which is sensitive to the rates of LCT deployment. The variation in extent of solution deployment across licence areas is primarily driven by the differing LCT uptake rates coupled with how the LCTs are allocated across each LV network archetype. When network planners are considering which solution(s) offer most value to an individual feeder, the constraint type and extent of constraint of that particular feeder will determine which solution(s) are most appropriate.

C1. Similar solutions are selected to be deployed across all four of National Grid's electricity distribution licence areas. The proportion of solution deployment is sensitive to the LCT uptake rates on each licence's area feeder set. The solutions chosen by network planners should be based on the network constraint type and extent of constraint witnessed on the specific feeder.

3.2 Variation Between Scenarios

Solutions deployed in the same licence area under different DFES scenarios remain largely similar. Typically there is little variation in the number of distinct solution types deployed in the different DFES scenarios. This indicates that there is similar variety in the extent of constraints witnessed across the scenarios, due to the clustering of LCTs such that there is high density of LCTs deployed on particular feeders and low density of LCTs on other feeders.

In some instances, there is a small increase in the number of distinct solutions deployed in more aggressive uptake scenarios (for example 13 distinct solutions are deployed in South Wales SP, LtW 14 in South Wales), since higher uptake rates of LCTs slightly shift the cost benefit on certain feeders occasionally favouring different solutions. More significant variation is witnessed in the proportions of each solution deployed to resolve the network constraints. Solutions that release higher amounts of headroom are often deployed proportionally more in LtW, whereas solutions that release smaller levels of headroom are often deployed proportionally more in SP. Note that this is proportional, typically most solutions get deployed more in LtW than in SP as higher LCT deployment causes more network constraints.

The number of solutions deployed in each scenario and licence area can be explored further using the interactive html versions of the Sankey diagrams which are uploaded online as detailed in Appendix I. Comparing Figure 2, Figure 6, Figure 10 show a good example of this effect. Solutions such as LV Pole Mounted 11/LV Tx, LV Overhead Minor Works, LV Underground Network Split Feeder and LV Ground Mounted 11/LV Tx that release large amount (of in this case thermal) capacity are deployed proportionally more in the LtW scenario compared to the SP scenario. Solutions such Manual Phase Balancing and Network Data Monitoring that provide smaller amounts of capacity release get deployed proportionally less in the LtW scenario compared to the SP scenario.

The similarity in the solution types deployed across the three DFES scenarios indicates that regardless of the eventual uptake of LCTs, similar solutions will be required. The proportion of each solution deployed and total number of solutions deployed will vary depending on the eventual LCT uptake rate. The similarity in solutions deployed ensures that advice regarding which to consider when planning network upgrades can be given in confidence despite uncertainty in the eventual LCT uptake rates. The clustering of LCTs will result in some feeders witnessing all types and extents of constraints in all three scenarios. For this reason, network planners do not need to concern themselves with the specific scenario trajectory but instead focus on the particular constraint and extent of constraints that is present. The next section of this report focuses on which technologies network planners should consider for each network archetype depending on the constraint type.

C2. The number and types of distinct solutions required across National's Grid network is independent of the scenario. Regardless of the actual LCT uptake rate, the distinct solutions will be utilised for particular feeders due to the variability in clustering of LCT deployments. Network planners do not need to be concerned about the uptake rate of LCT across the system, instead they should focus on the constraint type and extent caused by LCTs on each individual feeder.

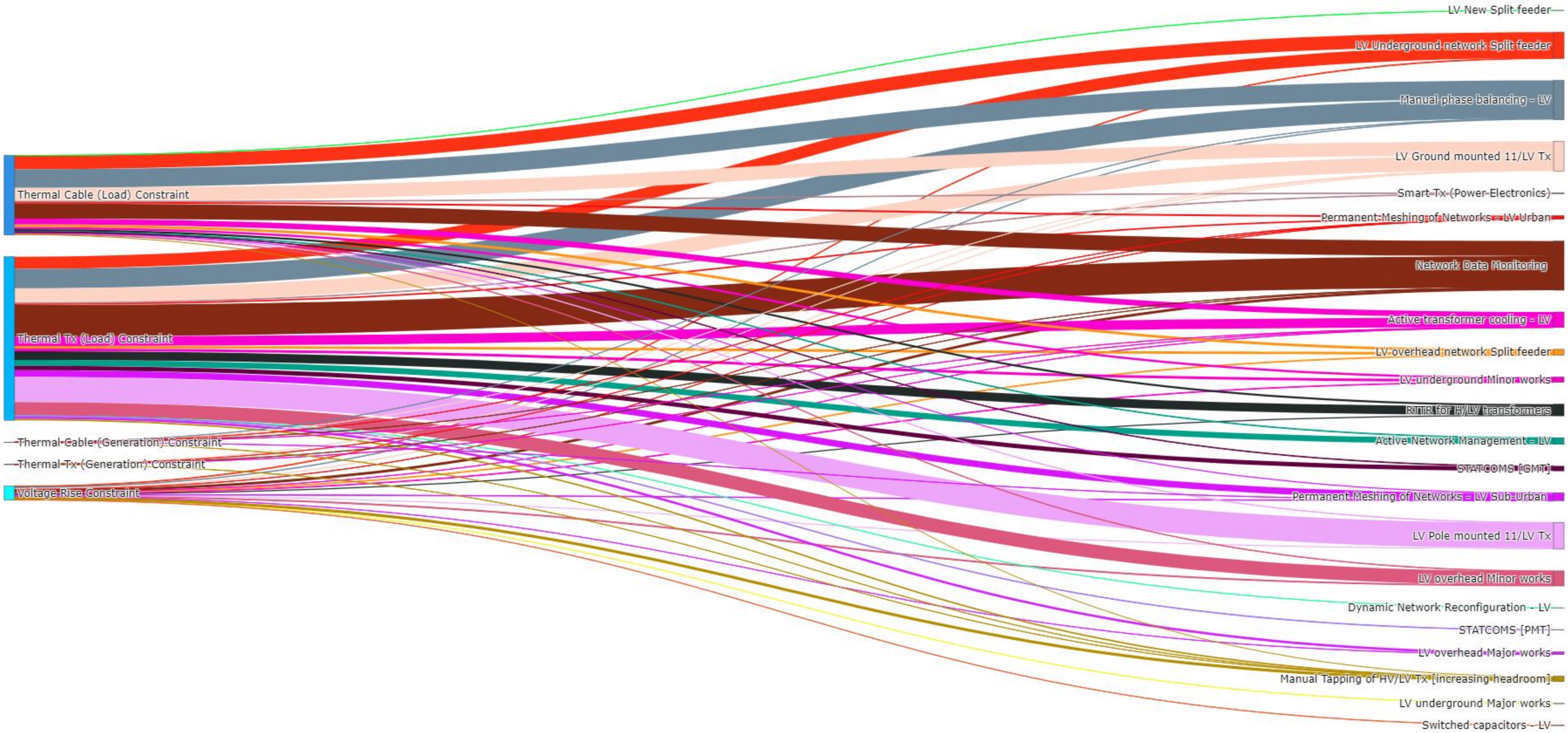


Figure 1: Mapping of Network Constraint types to Solution for East Midlands, BV scenario

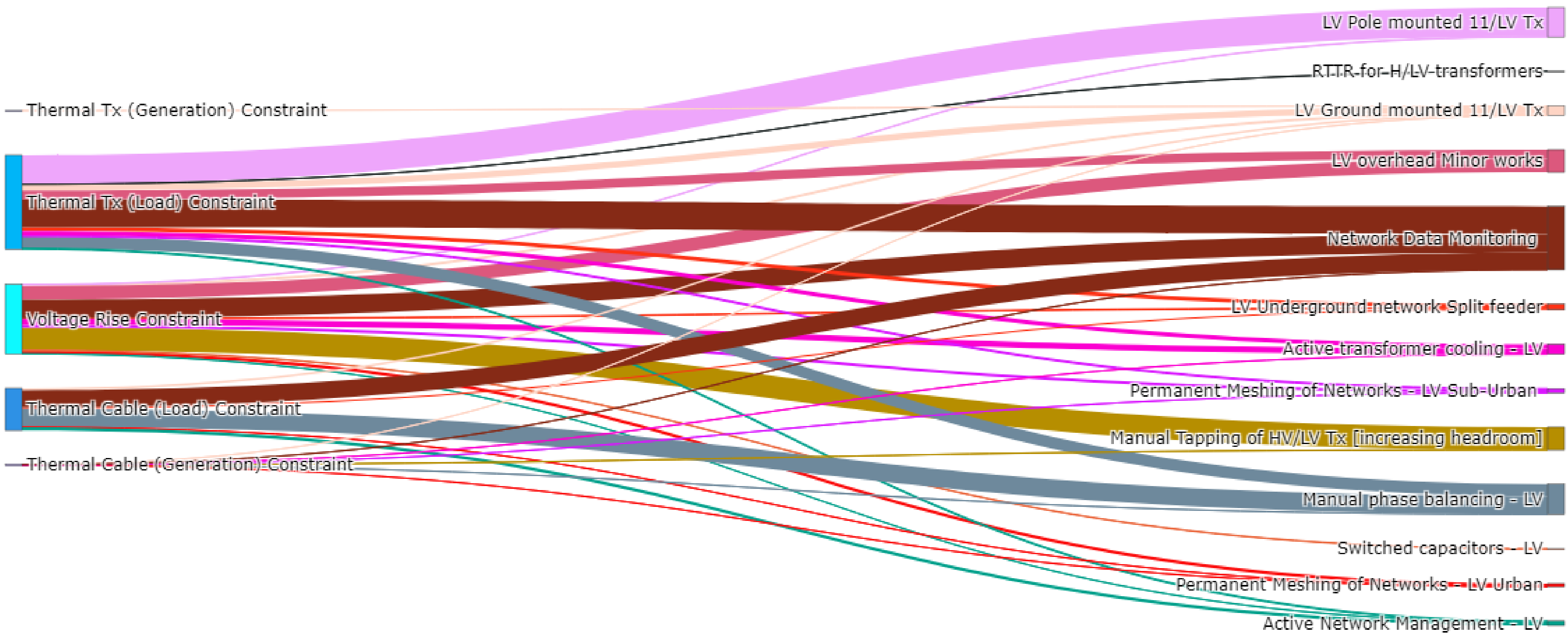


Figure 2: Mapping of Network Constraint types to Solution for West Midlands, BV scenario

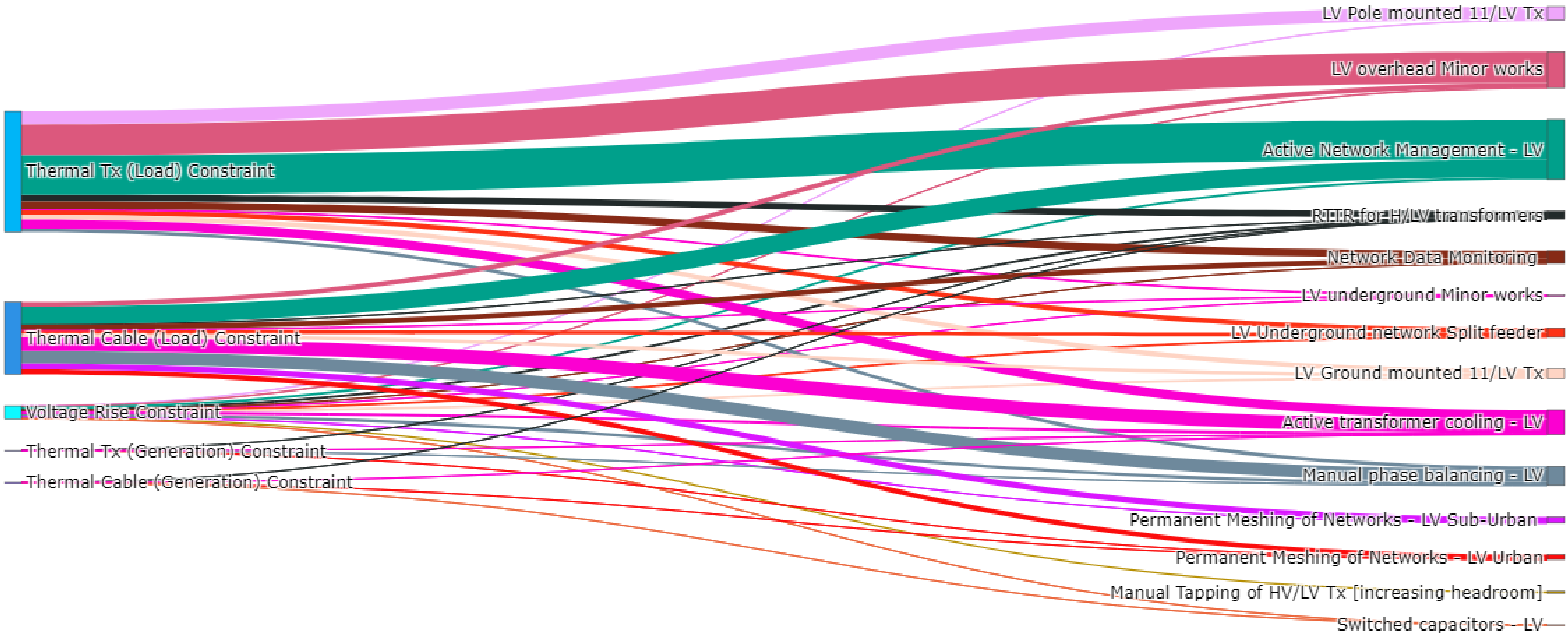


Figure 3: Mapping of Network Constraint types to Solution for South Wales, BV scenario

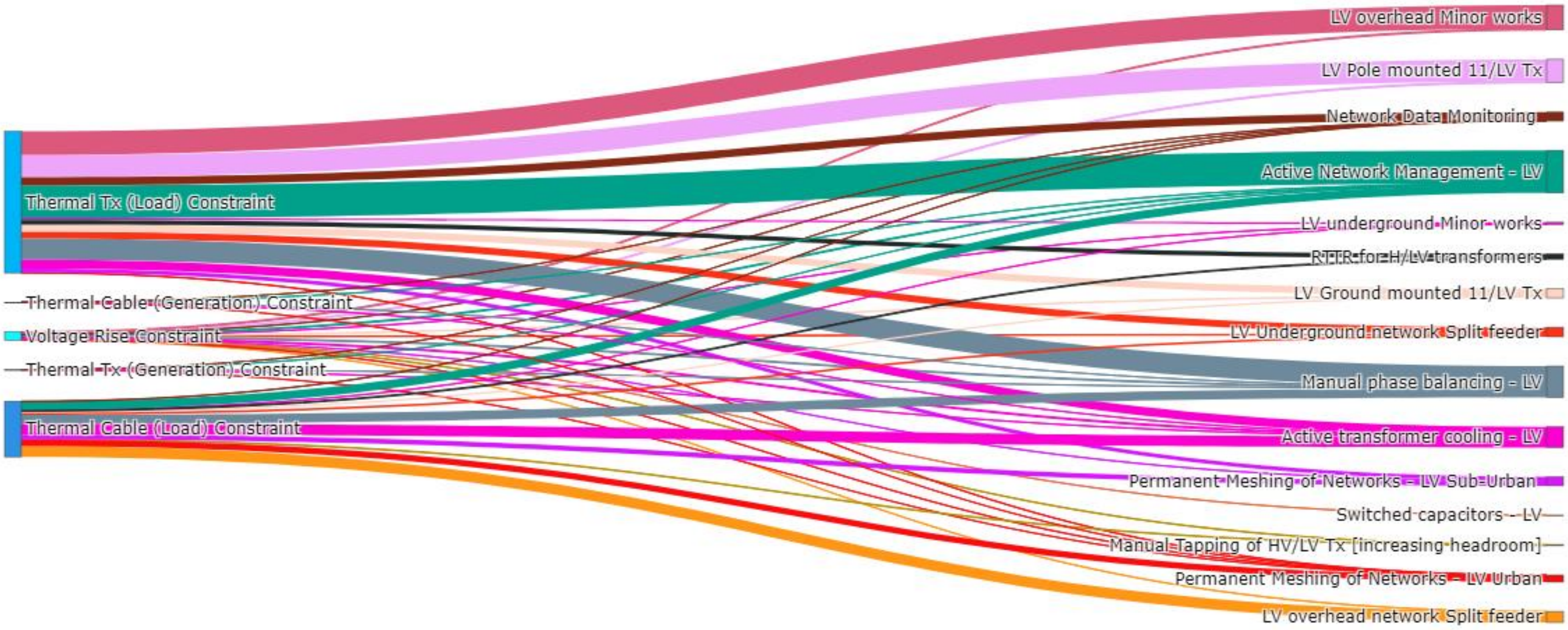


Figure 4: Mapping of Network Constraint types to Solution for South West, BV scenario

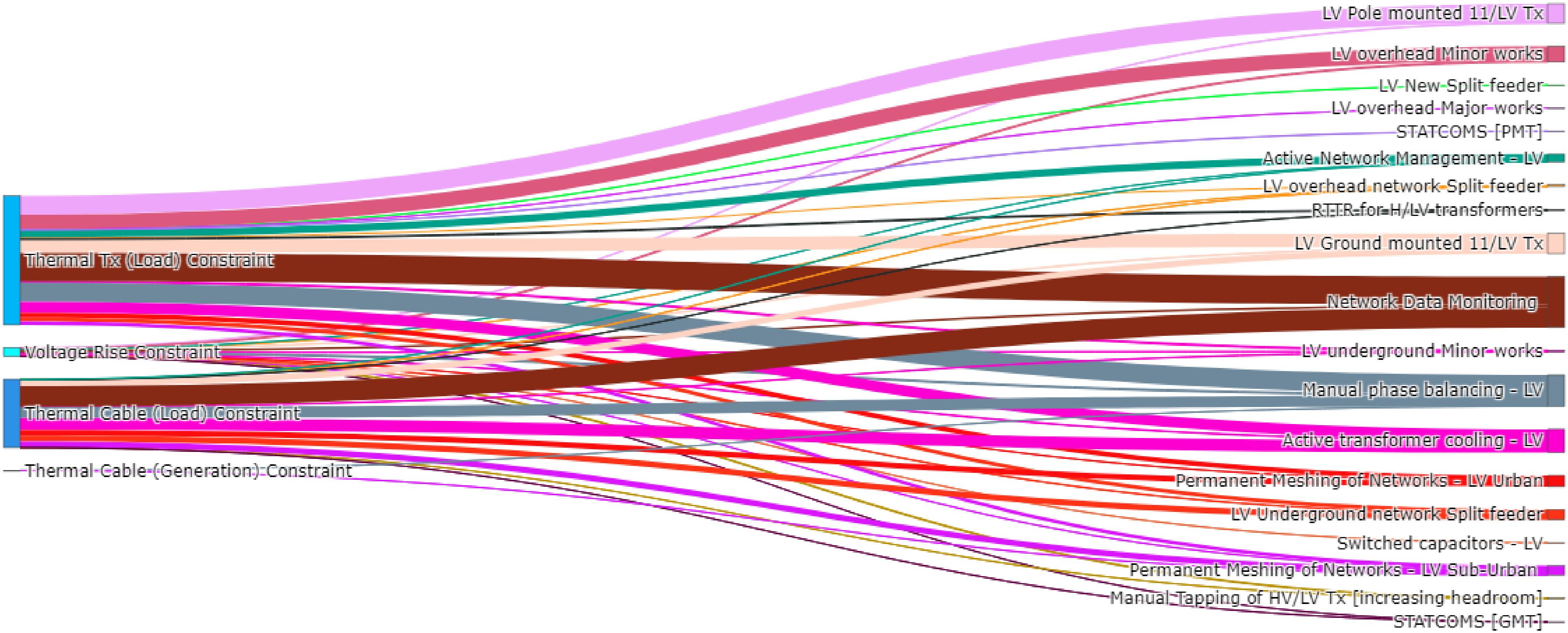


Figure 5: Mapping of Network Constraint types to Solution for East Midlands, SP scenario

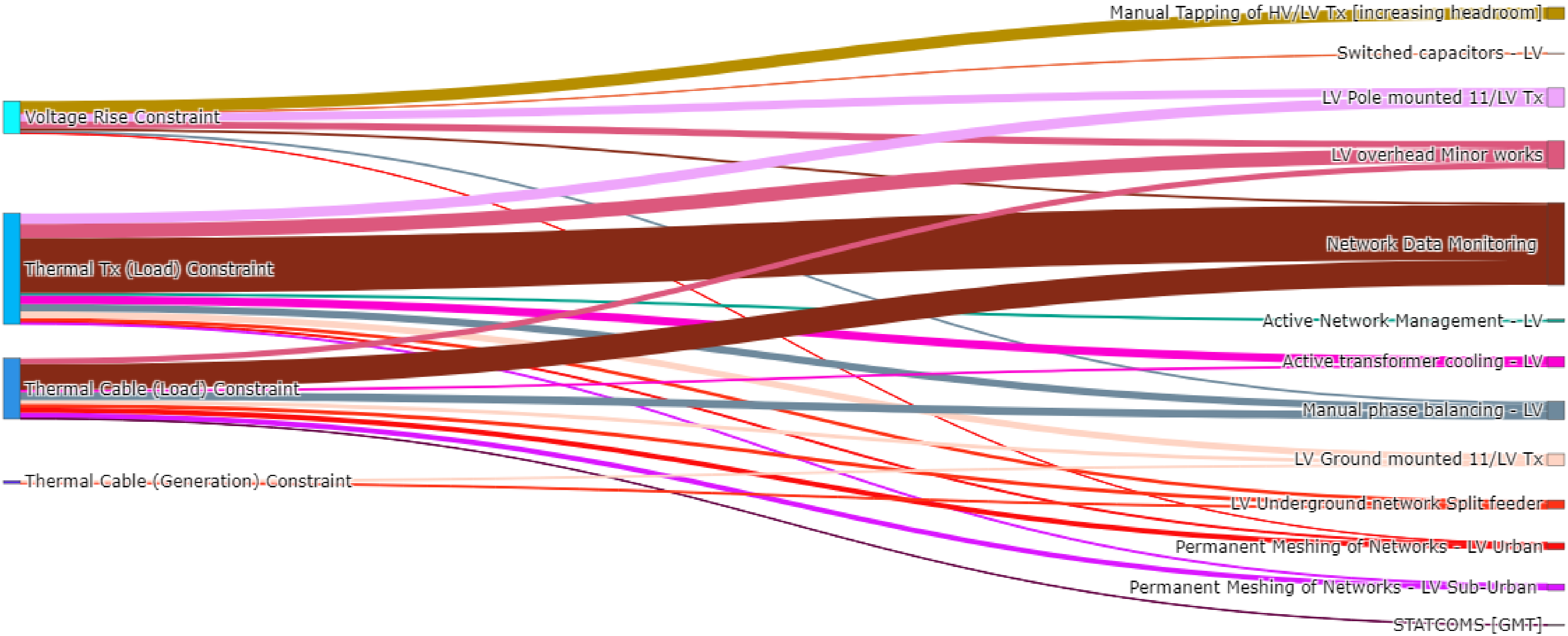


Figure 6: Mapping of Network Constraint types to Solution for West Midlands, SP scenario

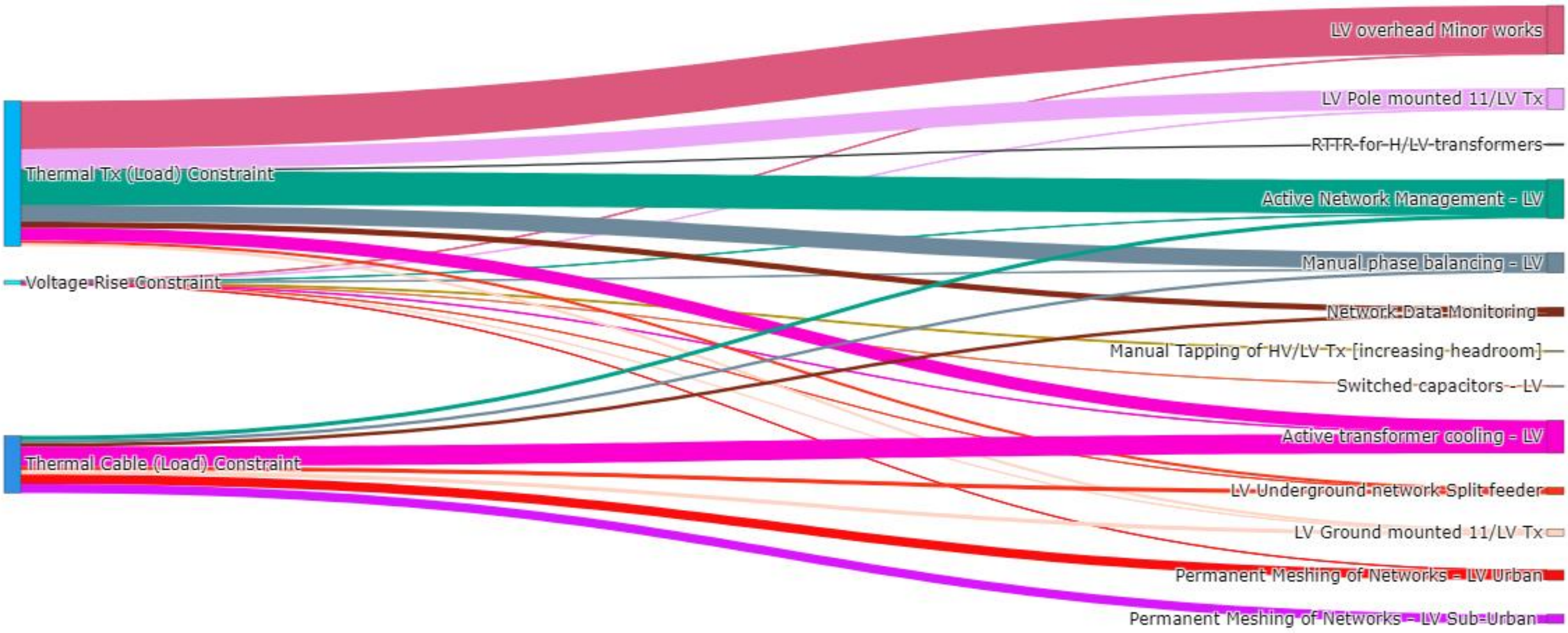


Figure 7: Mapping of Network Constraint types to Solution for South Wales, SP scenario

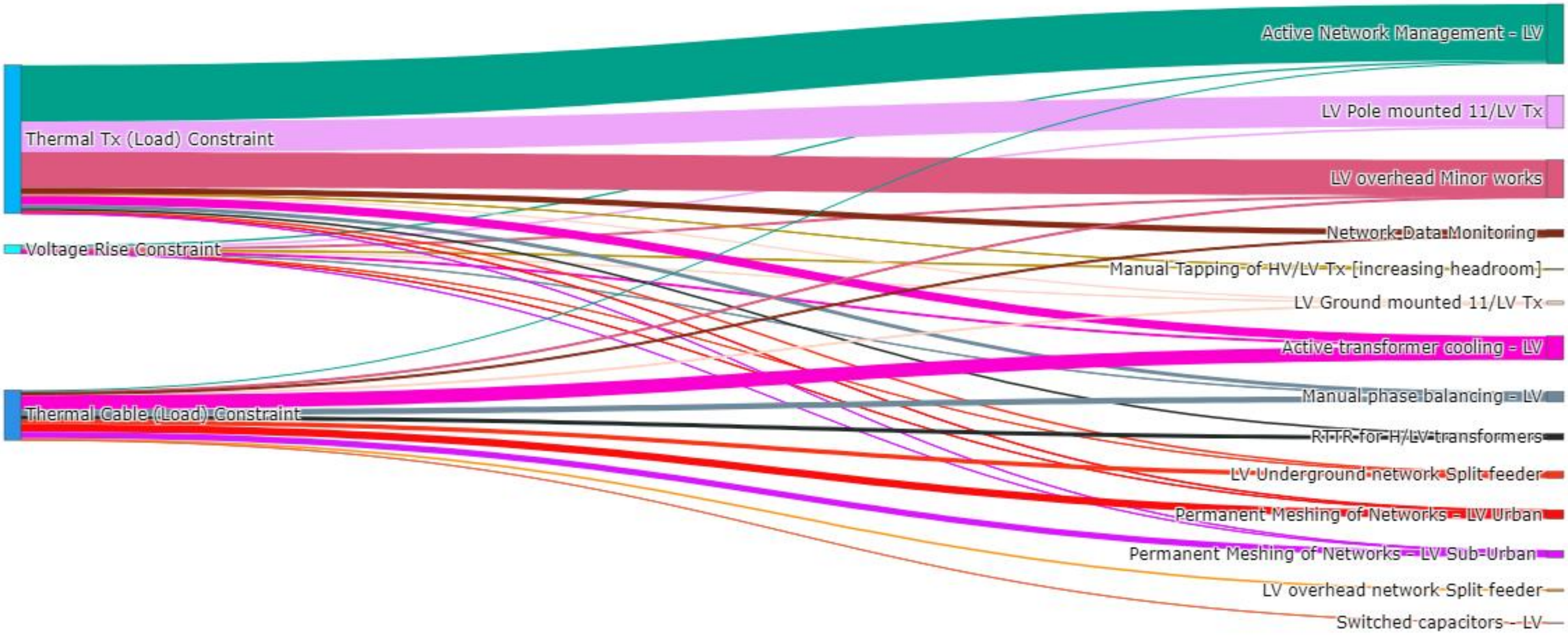


Figure 8: Mapping of Network Constraint types to Solution for South West, SP scenario

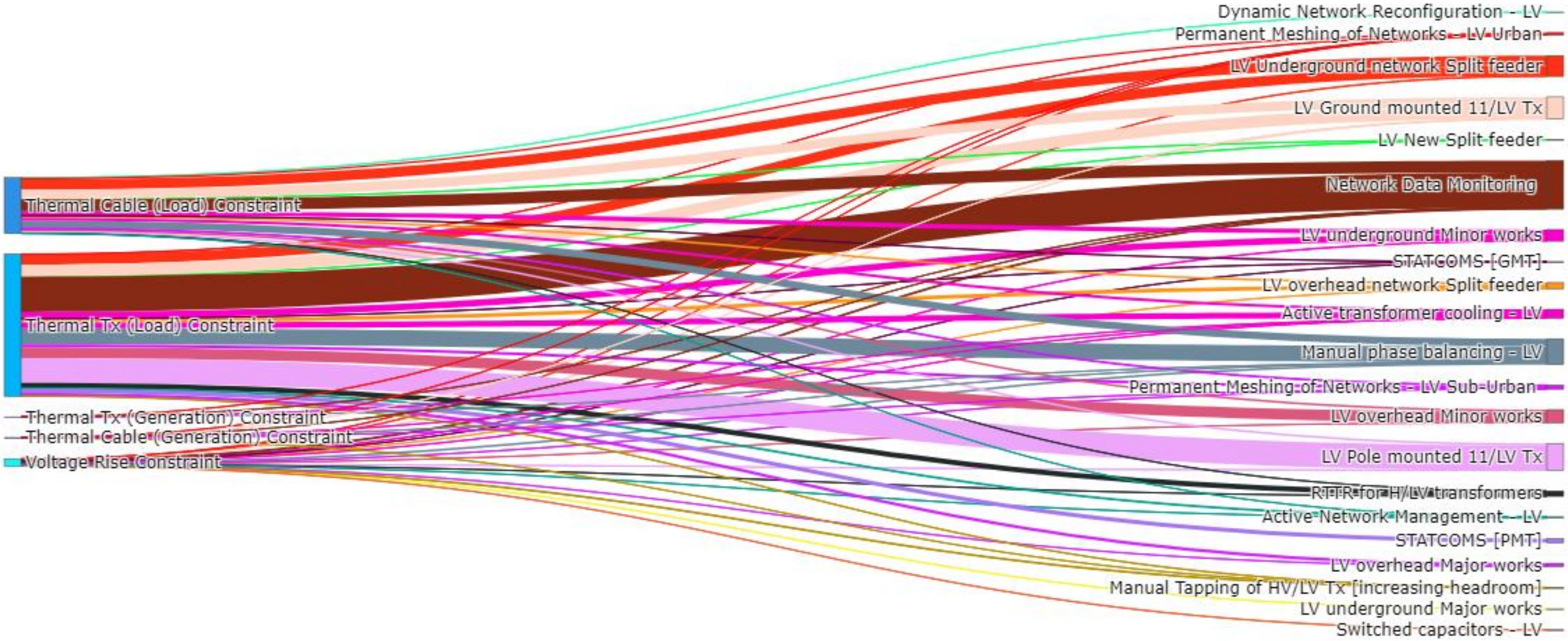


Figure 9: Mapping of Network Constraint types to Solution for East Midlands, LtW scenario

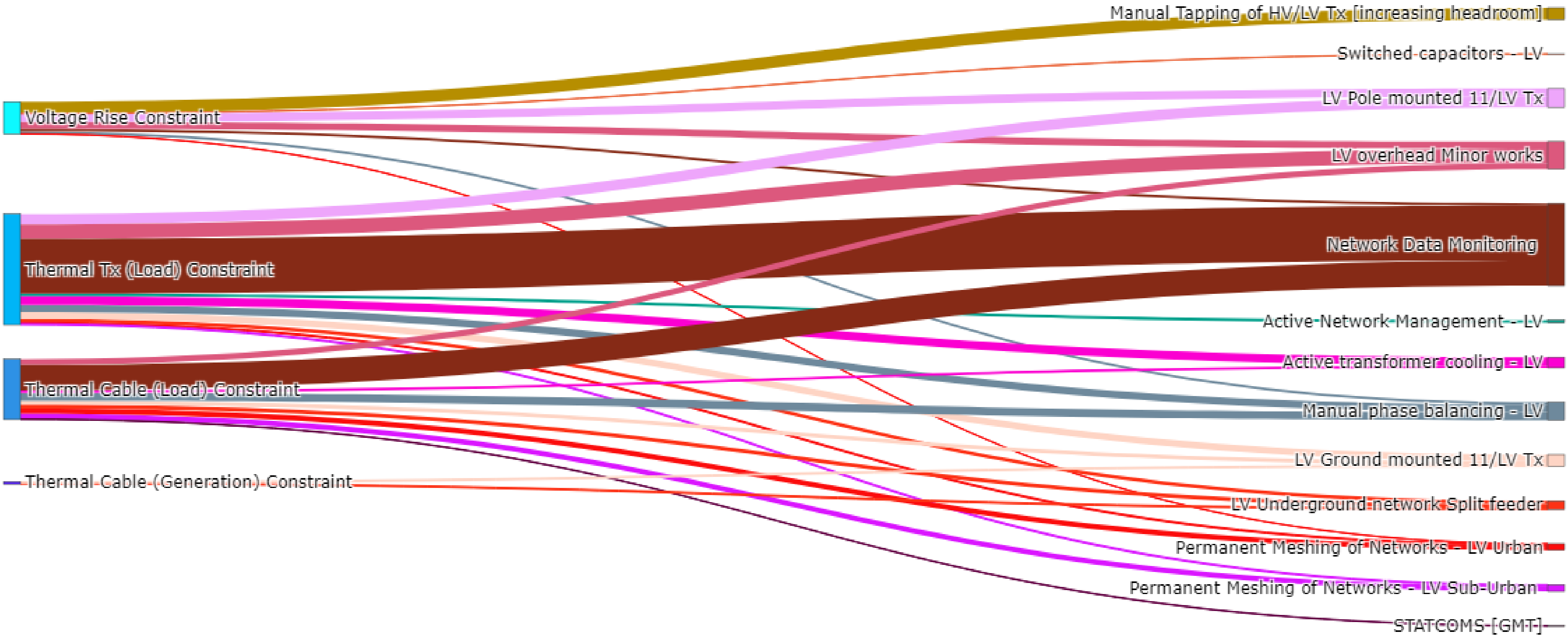


Figure 10: Mapping of Network Constraint types to Solution for West Midlands, LtW scenario

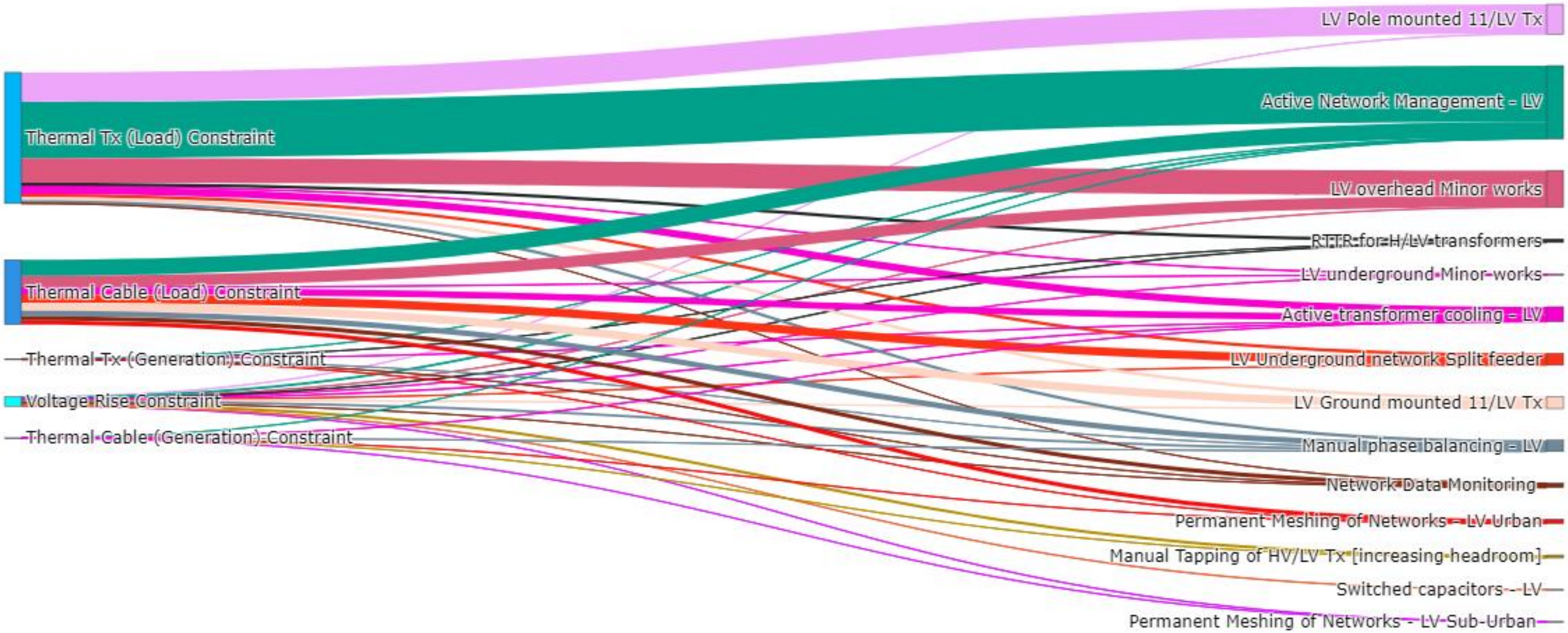


Figure 11: Mapping of Network Constraint types to Solution for South Wales, LtW scenario

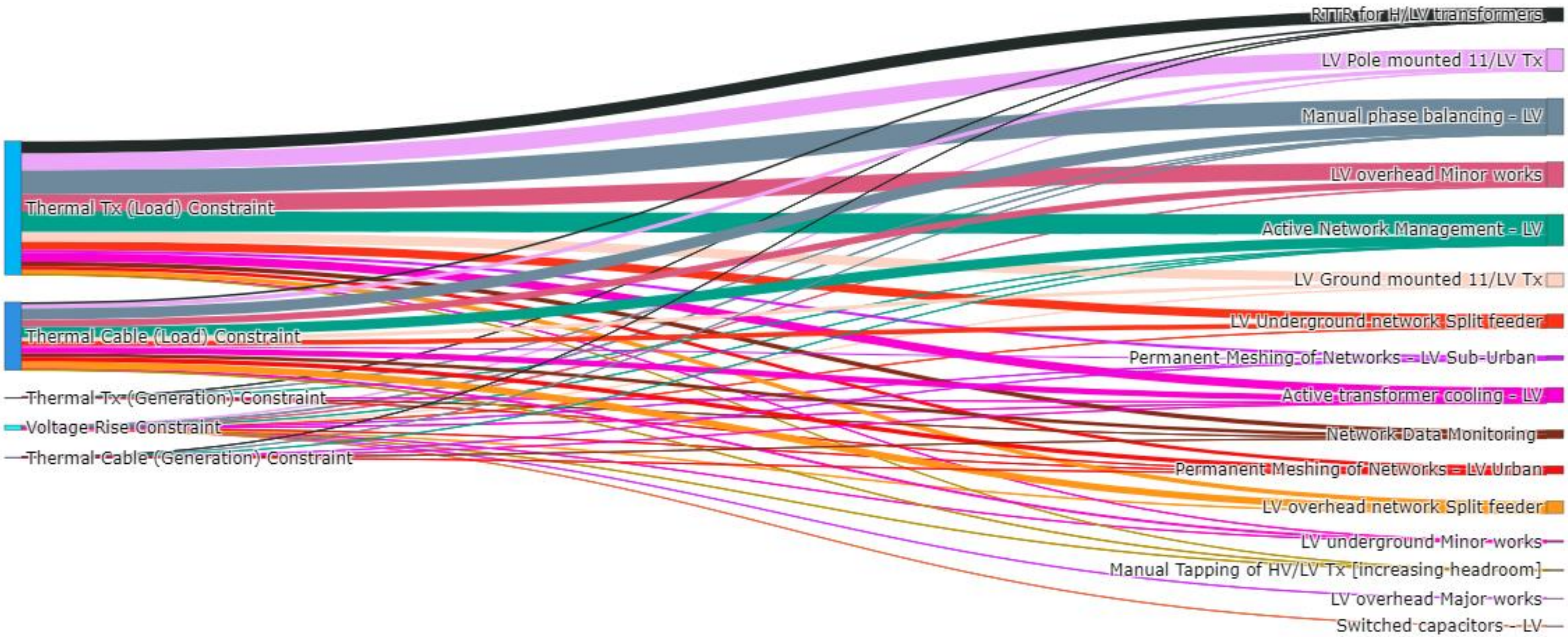


Figure 12: Mapping of Network Constraint types to Solution for South West, LtW scenario

4. Case Studies

The challenges and constraints facing different LV feeders vary widely depending on the feeder properties, the existing and forecast load and generation connected to the feeder, and the solutions available for deployment on each particular feeder. The Network Study report [2] showed that certain LV archetypes could be grouped by similar constraints, which the Functional Requirement report [4] showed were typically solved by similar solutions (both BaU and novel). This section of the report presents case studies that show which technologies should be considered by network planners for each grouping of LV network archetypes.

The doughnut plots in this section of the report show;

- in the inner ring the type of network constraint encountered,
- in the outer ring the proportion of solutions deployed to resolve the constraint type in the inner ring.

The charts show only the subset of feeders for each archetype which encounter network constraints. The Network Study report [2] showed the proportion of feeders of each archetype that experienced each constraint type (and by extension, the proportion on feeders that did not experience any constraints). The doughnut plots are supplemented by charts repeated from the Network Study report [2] that show the proportion of feeders for each network archetype that encountered each constraint type. The solutions selected are taken from the Transform analysis, performed with a set of BaU and novel solutions as presented in the Functional Requirements report [4]. Details of the BaU and novel solutions available to the Transform model can be found in Appendix III and Appendix IV respectively. It is recognised that there may be new technologies which have not been captured or those which appear unlikely but to ensure consistency and transparency data was obtained from previous model development, literature review and RfI process with adjustments to parameters only made where there was a solid justification.

The charts show the solution selected by the Transform model, which selects solutions purely based on the lowest cost option to resolve constraint type considered (thermal and voltage). Although some cost around design and disruption considerations is included, in some cases more detailed investigation on a case by case basis into physical constraints, protection and safety implications is necessary as part of wide scale deployment or policy change.

Solutions are often repeated for solutions that were selected to resolve more than one type of network constraint. It is possible in some cases that both a voltage and thermal constraint occur at the same time and two distinct solutions are required to resolve those constraints one of which may release voltage headroom and the other thermal headroom. Some solutions such as Active Network Management[4] have the capability of simultaneously resolving thermal and voltage constraints. In this instance both solutions would be considered to resolve both issues.

Each time a constraint is encountered, the Transform model solves for the network constraint encountered that year, and for any other network constraint(s) that occur in the immediate 5-years following. In this analysis, each solution is categorised as solving for the constraint type or types encountered when a constraint is first encountered. However, in some cases it is possible that the primary constraint type being solved for is different to the constraint type initially encountered. The Network Study report [2] gives greater details into the types and timing of constraints encountered for all LV network archetypes.

It was shown in section 3 of this report that the solutions deployed are largely independent of the scenario. For this reason, the plots in this section of the report are based on the BV scenario. The Network Study report

[4] Active network management in this context considers dynamic management of the LV network by controlling, for example, normally open points. This allows the network operators to temporarily reconfigure the network to share load and increase available capacity.

showed that the solutions types deployed for the same archetype across different licence areas are broadly similar; the plots shown below are taken from a range of licence areas.

4.1 Case Studies from Transform Analysis

This section analyses the Transform outputs to identify which solution types are used to resolve which types of network constraints on particular LV archetypes.

4.1.1 LV1 (Central Business Districts), LV3 (Town Centres), LV4 (Business Parks) and LV5 (Retail Parks)

LV network archetypes LV1, LV3, LV4 and LV5 are dominated by commercial customers. The Network Study report [2] showed that the dominant constraint types witnessed on these archetypes were voltage rise constraints, which the Functional Requirements report [4] showed were solved by similar technologies. Some thermal constraints under net export conditions (due to embedded generation, primarily PV) are also witnessed on these archetypes. Similar solutions are utilised to resolve those constraints, due to the similar types and extents of constraint witnessed on these LV network archetypes.

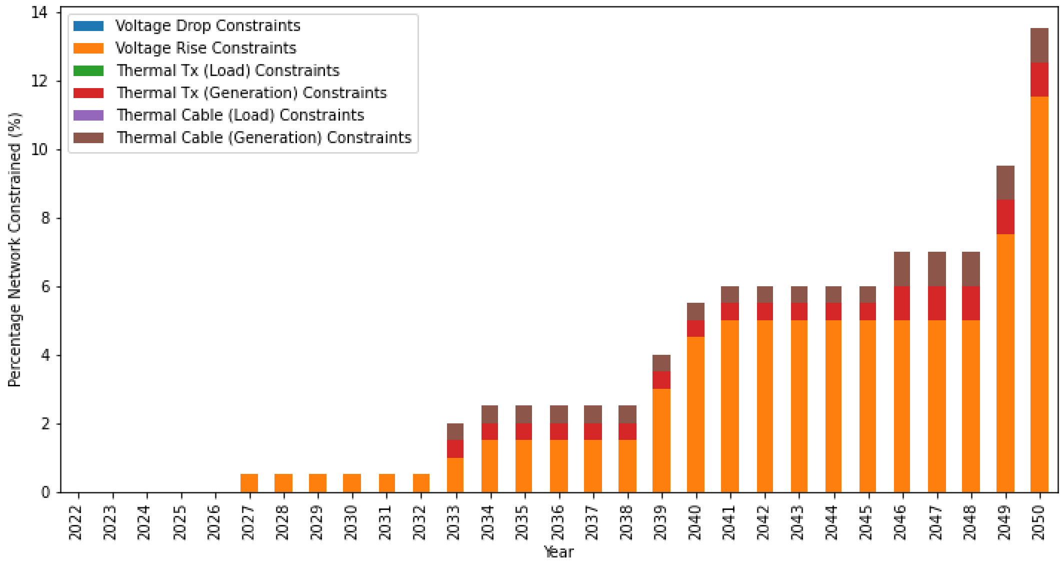


Figure 13 to

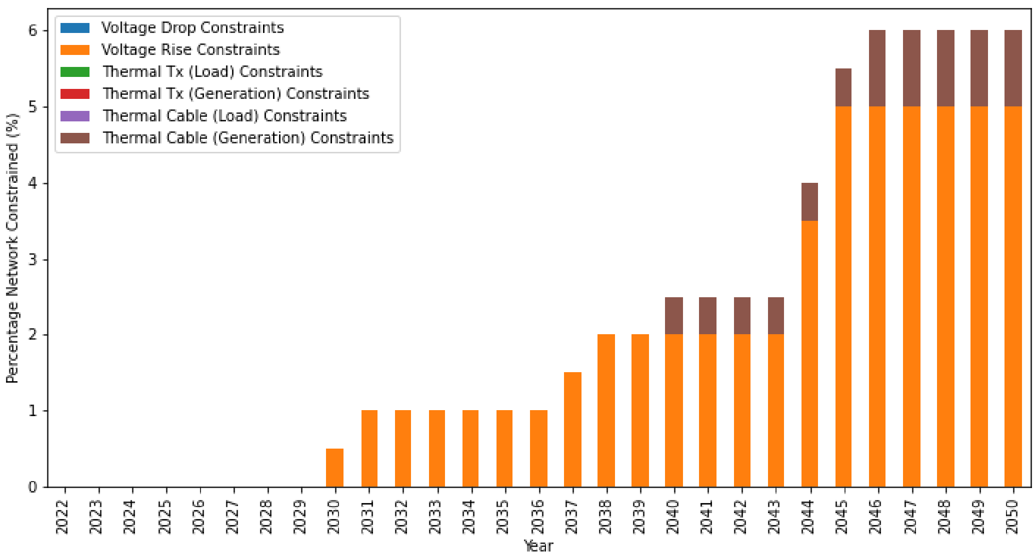


Figure 16 shows the constraint types encountered on LV network archetype LV1, LV3, LV4 and LV5 in the East Midlands, West Midlands, South West and South Wales respectively. The solutions most commonly used to resolve voltage rise constraints are:

- Manual Tapping of HV/LV Tx [Increasing Headroom]
- Switched Capacitors – LV
- Manual Phase Balancing – LV
- Network Data Monitoring
- Permanent Meshing of Networks – LV Urban / Sub-Urban[5]

The solutions commonly deployed to resolve thermal constraints are:

- Active Transformer Cooling – LV
- Active Network Management – LV
- Permanent Meshing of Networks – LV Urban / Sub-Urban
- Network Data Monitoring

The solutions Permanent Meshing of Network – LV Urban / Sub-Urban and Network Data Monitoring get deployed for both thermal and voltage constraints. These solutions should be considered by network planners for feeders that are expected to witness both thermal and voltage constraints at a similar time period. The modelling suggests permanent meshing is a cost-effective solution. However, there are specific challenges with permanent meshing that must be considered on a case by case basis, such as difficulty retrofitting to existing network and implication on substation protection schemes, safety implications and changes required to operational practice. For these reasons, permanent meshing is not necessarily recommended for a wide scale role out, but further investigation into where specific applications (e.g. new build feeders) may be suitable.

Traditionally, the default option for network experiencing both voltage and thermal transformer issues would be the installation of new or upgraded transformers. While the analysis shows that in some cases, the installation of a new Ground Mounted 11kV/LV Transformer is the most cost effective option, in other cases there are solutions available that are able to resolve the constraints more cost effectively over the 5-year solve duration of the Transform modelling. For example, deployment of Manual Tapping in conjunction with Active Transformer Cooling can be used to resolve voltage and thermal constraints on a network with moderate uptake of LCTs, avoiding the need for a new GMT. If LCT growth continues strongly, this may prove only a temporary solution and a new GMT will still be required, but the need for it will be deferred.

[5] Permanent Meshing of Networks - LV Urban used as a solution for urban feeders LV1 and LV3.
Permanent Meshing of Network - LV Sub-Urban used as a solution for sub-urban feeders LV4 and LV5.

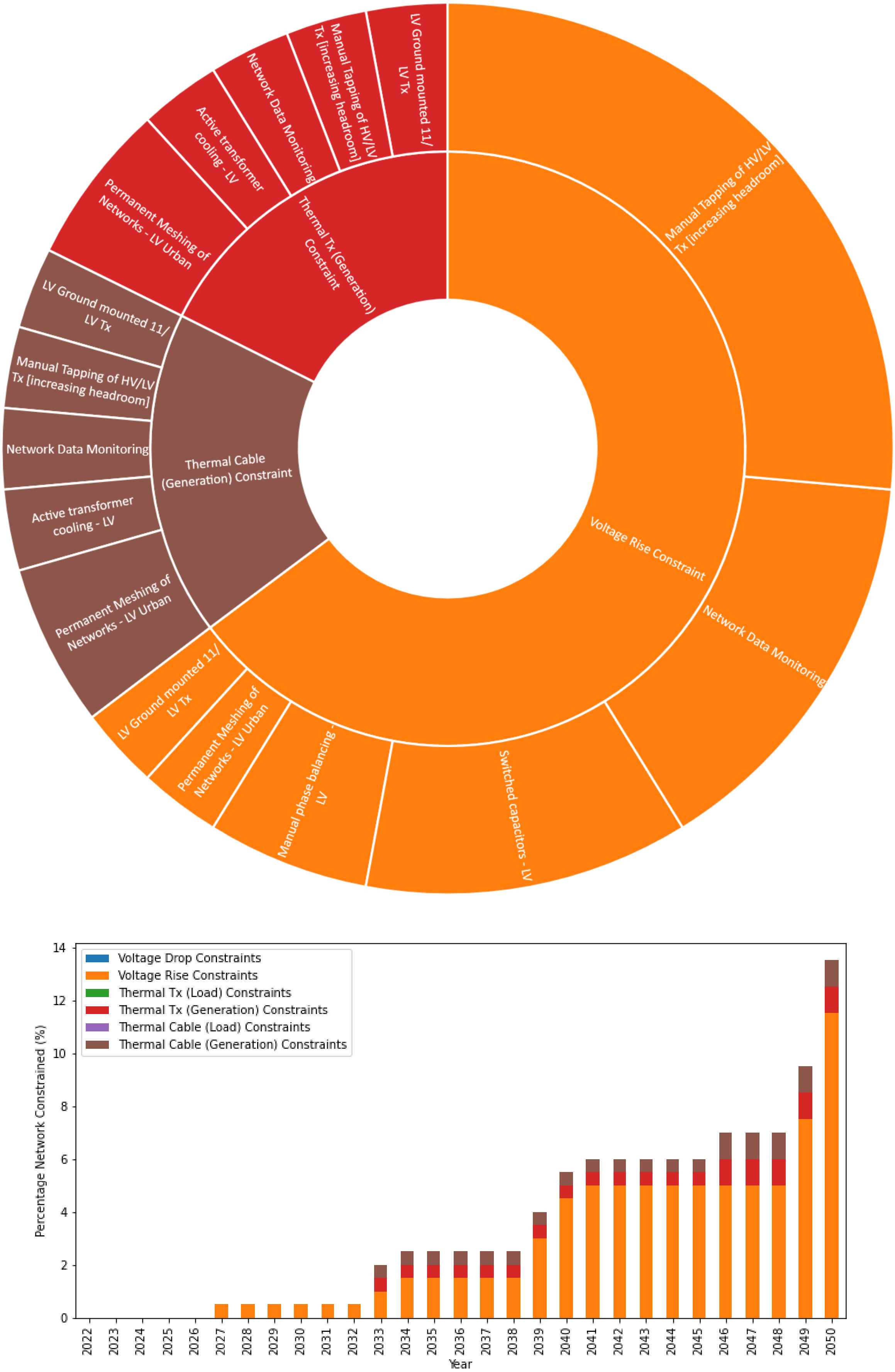


Figure 13: Solutions deployed for constraints on LV1 in East Midlands under BV scenario

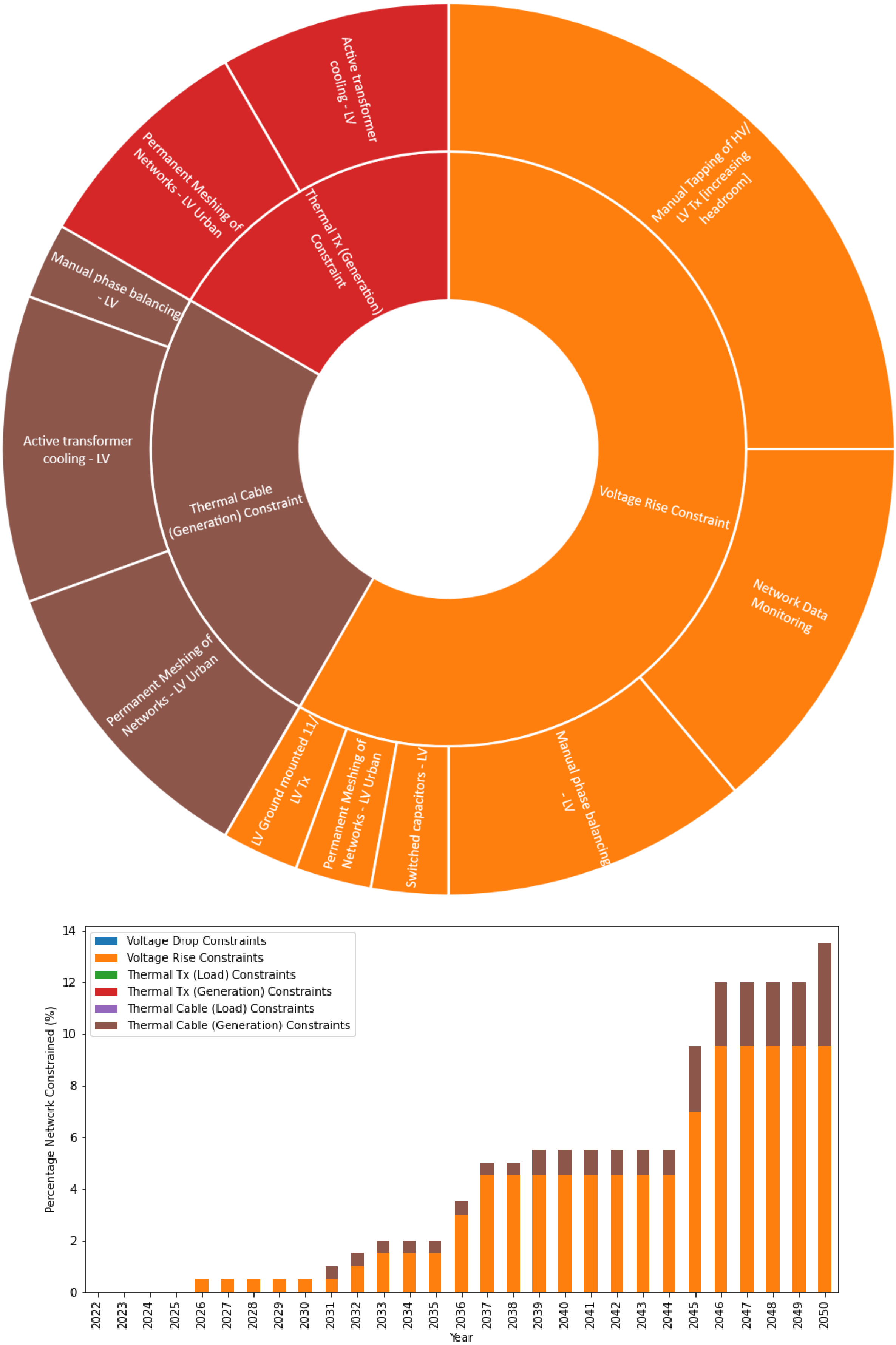


Figure 14: Solutions deployed for constraints on LV3 in East Midlands under BV scenario

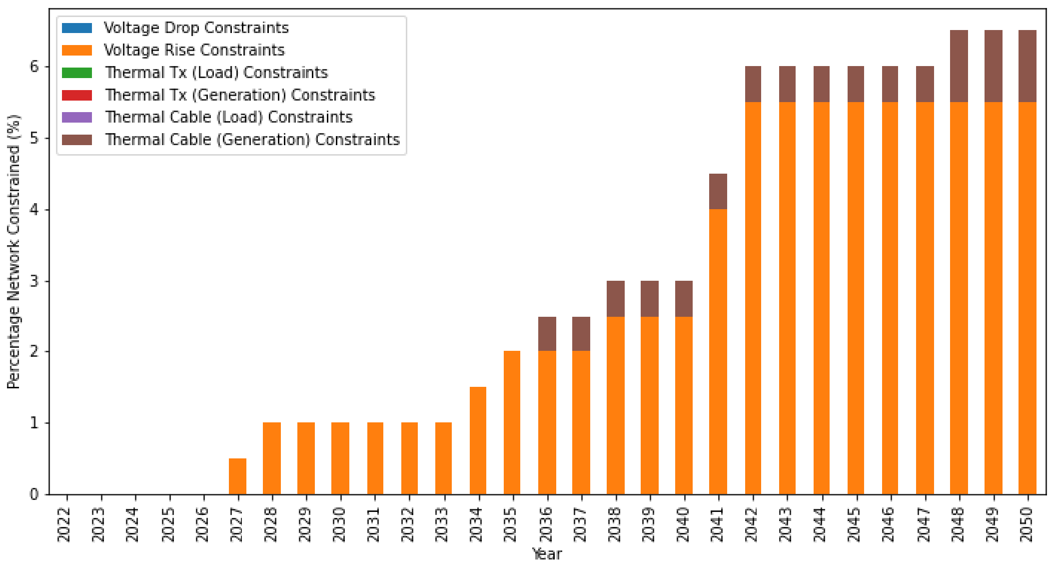


Figure 15: Solutions deployed for constraints on LV4 in South West under BV scenario

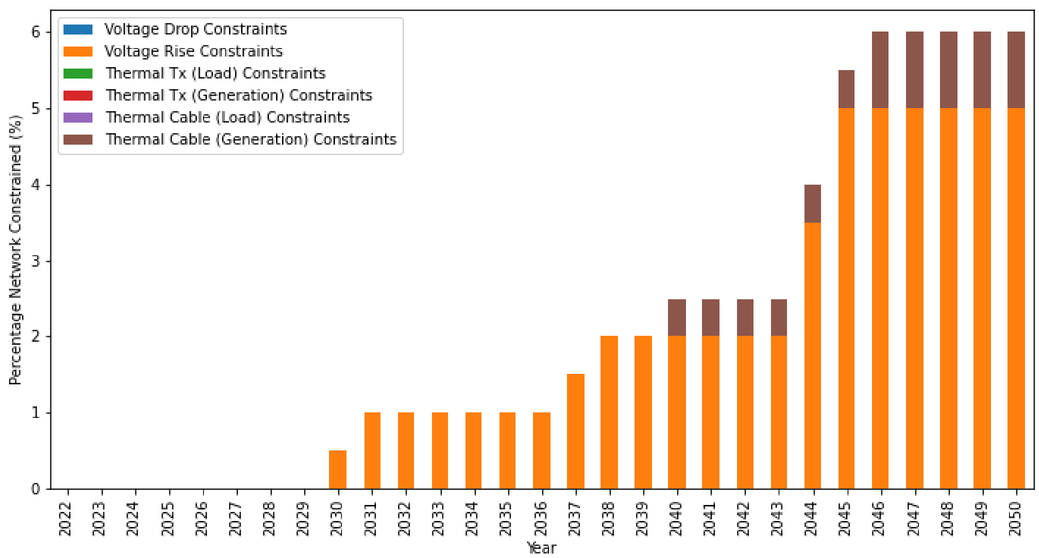


Figure 16: Solutions deployed for constraints on LV5 in West Midlands under BV scenario

4.1.2 LV2 (Dense Urban), LV6 (Sub-Urban Streets), LV7 (New Build Housing Estates) and LV8 (Terraced Streets)

LV network archetypes LV2, LV6, LV7 and LV8 are urban and sub-urban feeders primarily serving domestic customers. The Network Study report [2] showed most common constraint type for LV2, LV6, LV7 and LV8 were thermal constraints under net import due to the uptake of EVs and heat pumps. Some feeders witness voltage rise constraints caused by the uptake of solar PV. The Functional Requirements report [4] showed a wide variety of BaU and novel solutions need to be deployed across LV2, LV6, LV7 and LV8 feeders to cost effectively resolve all network constraints, but that the solutions used between the network archetypes were similar.

The combination of solution selected by Transform as the most cost effective method for resolving the network constraints varies between each LV archetype and licence areas. The most cost effective solution is sensitive to the forecast LCT uptake rate, capacities available and rating of the network's existing assets. Similar solutions are used commonly across the LV archetypes, in differing proportions, to resolve thermal constraints. These solutions commonly deployed include:

- Active Transformer Cooling
- Network Data Monitoring
- Manual Phase Balancing
- LV Underground Network Split Feeder
- LV Ground Mounted 11/LV Tx
- Permanent Meshing of Networks – LV Urban/Sub-Urban
- RTTR for H/LV Transformers
- Active Network Management

Voltage rise constraints occur on these network archetypes less commonly than thermal constraints. Due to Transform's 5-year solve duration, whenever a feeder hits the upper voltage limit, a solution or set of solutions is deployed to most cost effectively resolve the voltage constraint, and any other constraint (e.g. thermal) that occurs in the year the constraint first occurs and over the following five year period. Typically, the most cost-effective solution to resolve a voltage constraint is by deploying Manual Tapping of HV/LV transformer, a solution that releases 2.5% thermal headroom for £2,495 totex expenditure. However, in many instances other solutions such as Network Data Monitoring, LV Ground Mounted 11/LV Transformer, Manual Phase Balancing, LV Underground Network Split Feeder, Active Transformer Cooling and Permanent Meshing of Networks – LV Sub-Urban are utilised. These solutions are assumed to release low levels of voltage headroom (1% at most), but are deployed primarily to resolve thermal constraints; the small amount of voltage headroom release is sufficient to also resolve the voltage rise constraint occurring on the feeders.

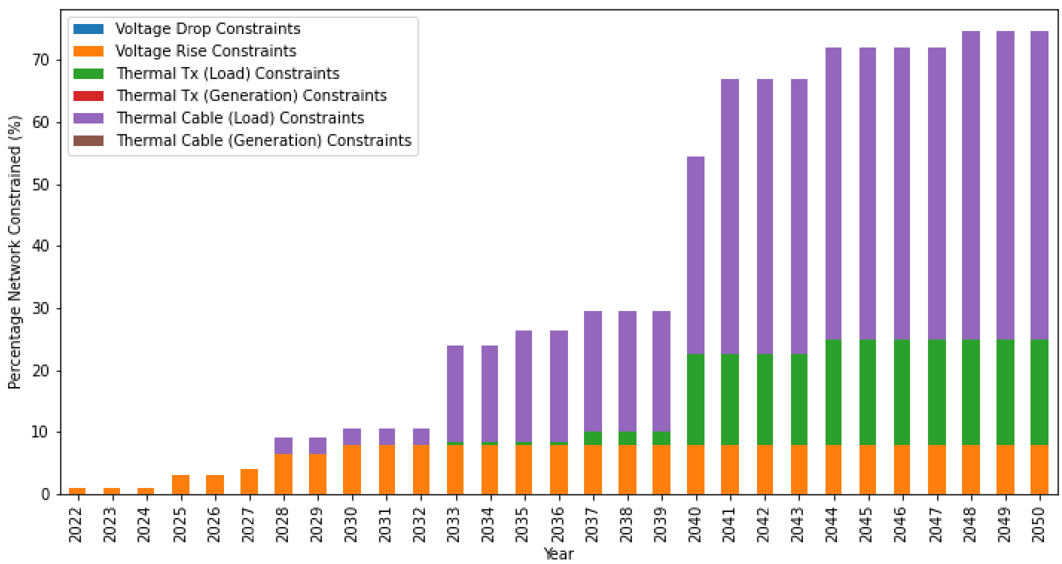


Figure 17: Solutions deployed for constraints on LV2 in East Midlands under BV scenario

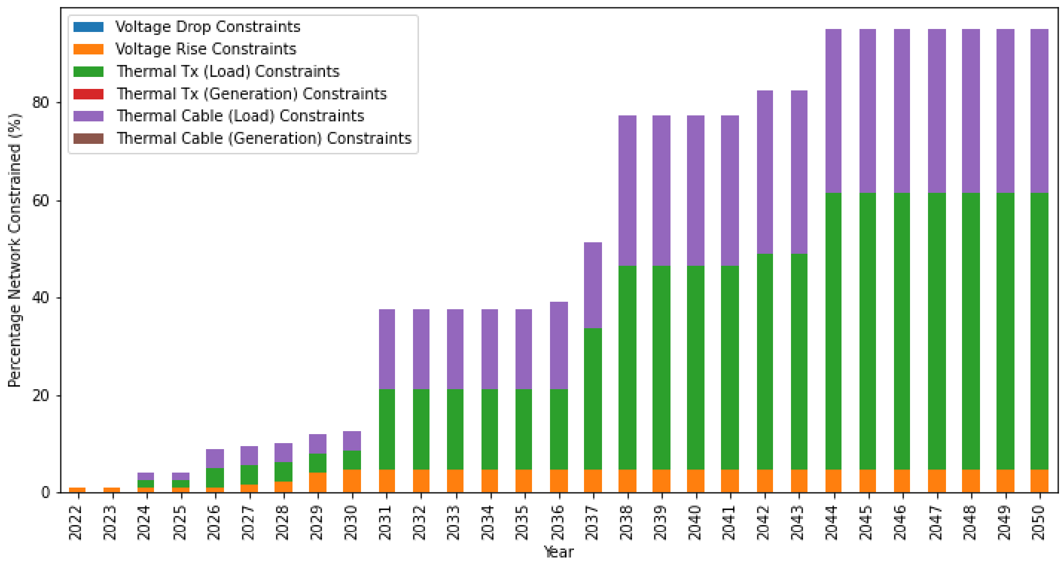


Figure 18: Solutions deployed for constraints on LV6 in East Midlands under BV scenario

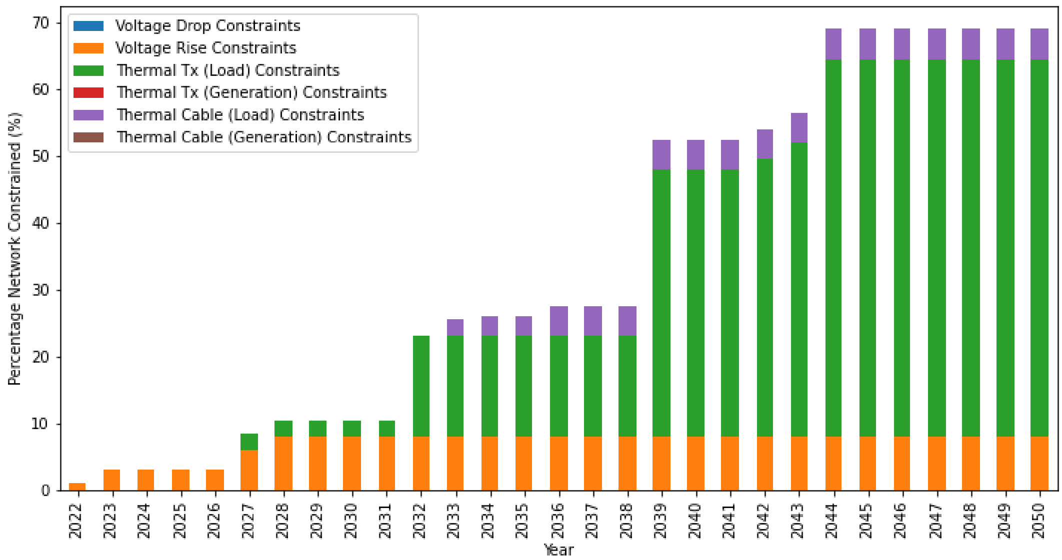


Figure 19: Solutions deployed for constraints on LV7 in East Midlands under BV scenario

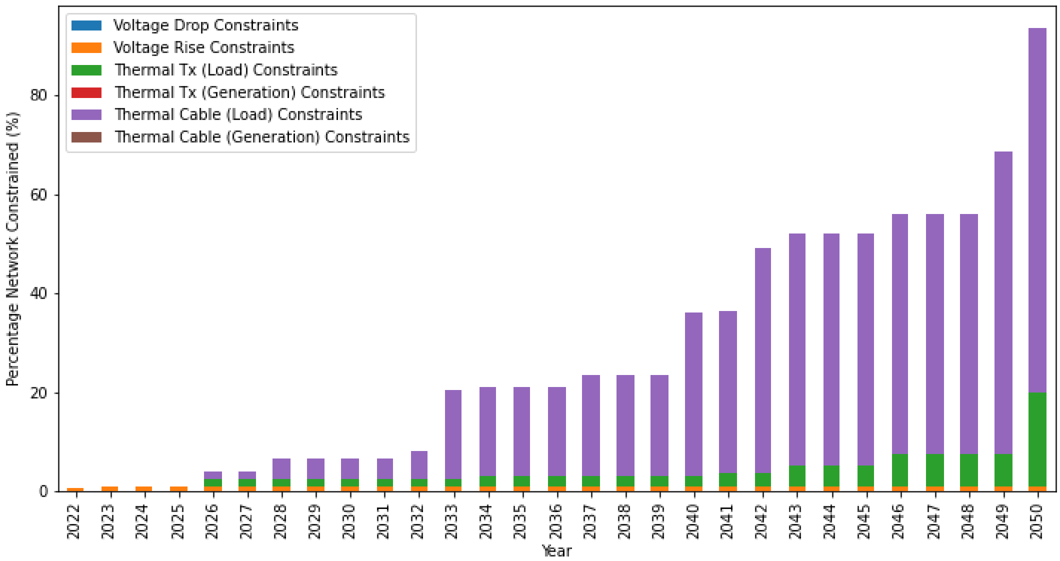


Figure 20: Solutions deployed for constraints on LV8 in South West under BV scenario

4.1.3 LV9 (Rural Villages Overhead construction) and LV11 (Rural Farmsteads)

The Network Study report [2] showed that rural overhead LV archetypes LV9 and LV11 witnessed significant thermal constraints as well as some voltage constraints. The Functional Requirements report [4] showed that similar solutions were utilised to resolve the constraints for LV9 and LV11.

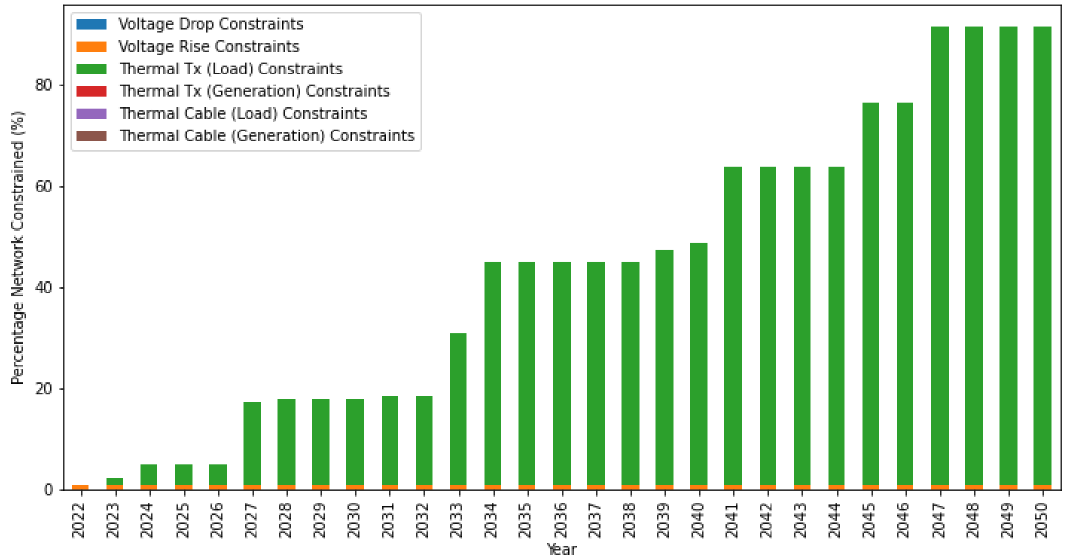


Figure 21 and

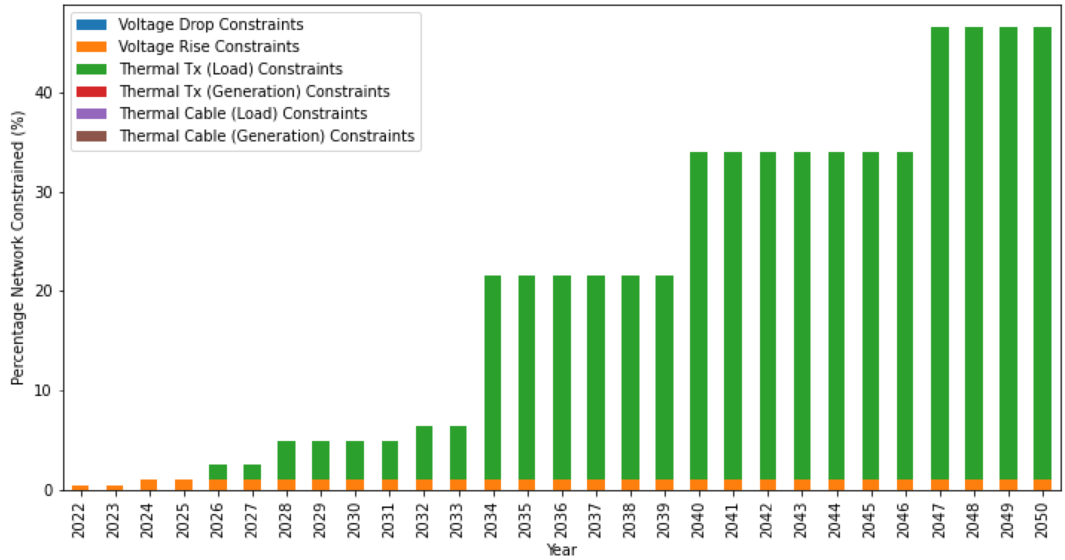


Figure 22 shows the network constraints and the solutions used to resolve those network constraints for LV9 in the South West and West Midlands respectively.

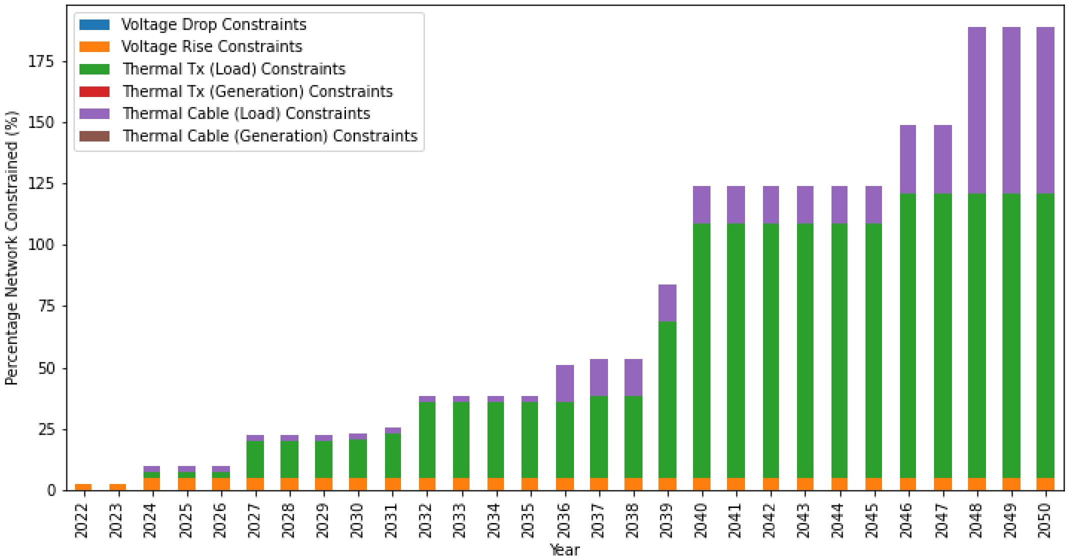
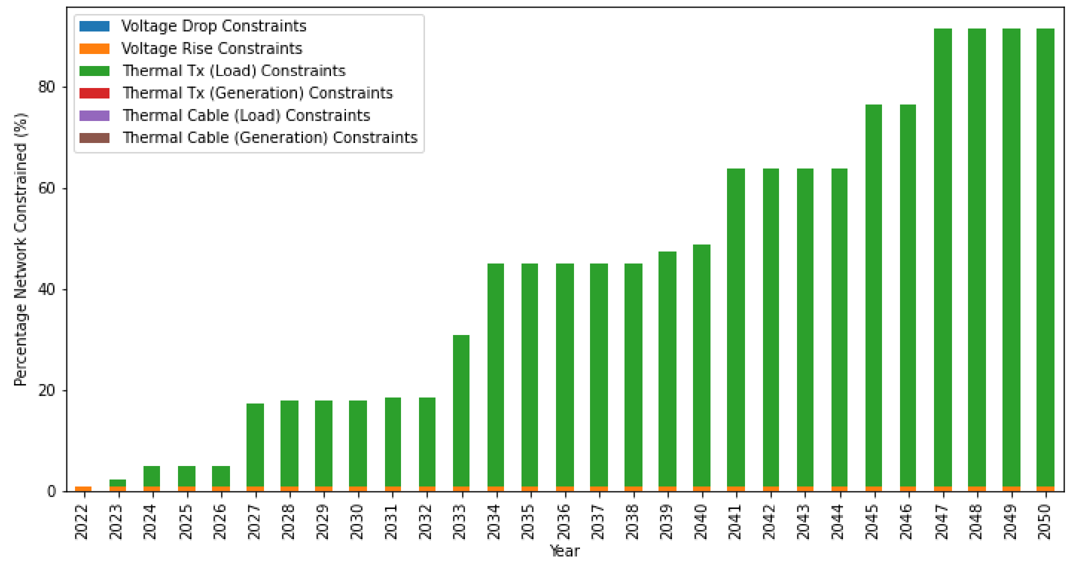


Figure 23 shows the network constraints for LV11 and the solutions used to resolve those constraints for the East Midlands. LV9 and LV11 are dominated by thermal constraints with voltage rise issues caused by solar PV deployment on only a small proportion of LV9 and LV11 feeders.

Thermal constraints on both LV9 and LV11 are significant due to high deployment of EVs and heat pumps on feeders with low levels of thermal headroom. Typically, BaU solutions which release high levels of thermal capacity are deployed:

- LV Pole Mounted 11/LV Tx
- LV Overhead Minor Works

A range of novel solutions get deployed across LV9 and LV11 feeders, delaying the need for one of the BaU solutions, providing National Grid with savings through deferral of investment. Novel solution selected to defer investment are sensitive to the LCT uptake rate, since the most cost effective viable solution set is a function of the level of capacity release required.



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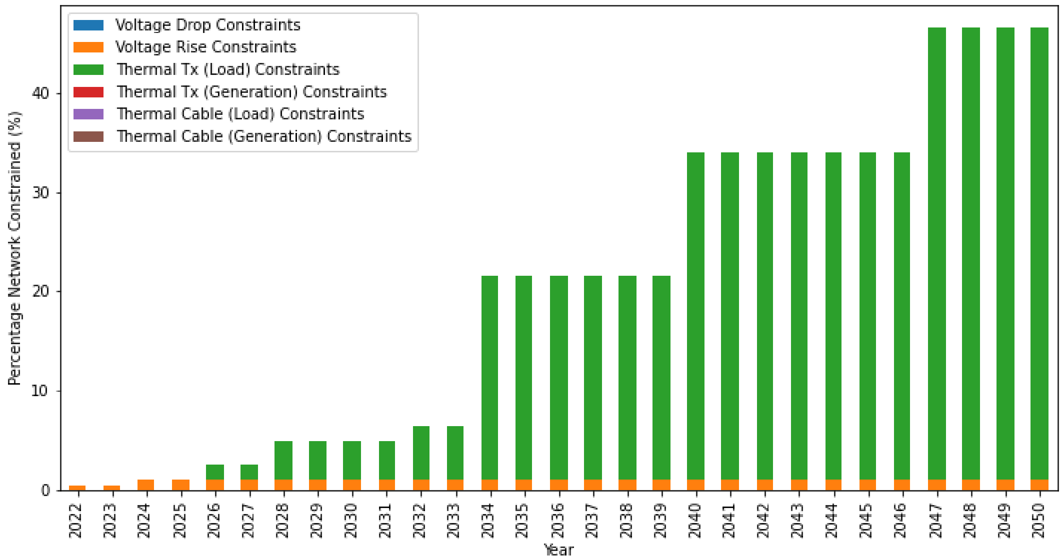


Figure 22 show this sensitivity as different novel solutions are deployed in the South West and West Midlands. Novel solutions that often get deployed include:

- Network Data Monitoring
- Manual Phase Balancing[6]
- Active Network Management – LV
- RTTR for H/LV Transformers

Voltage rise constraint occur infrequently across LV9 and LV11 feeders. When voltage rise issues do occur, Transform solves for all constraints over a 5-year solve duration, in which time thermal constraints occur which must also be resolved by the solution set deployed. Since thermal constraints are typically the bigger issue, solutions such as LV Pole Mounted 11/LV Tx and LV Overhead Minor Works which release small amounts of voltage headroom get deployed as they also release significant levels of thermal headroom to resolve the thermal constraints. If thermal constraints were not forecast on the feeder, then Manual Tapping of HV/LV Tx [Increasing Headroom] would be the first solution deployed due its 2.5% voltage headroom release at low totex cost of £2,495.

[6] A BaU solution but Manual Phase Balancing is also deployed to defer investment costly BaU solutions so has been included in this list.

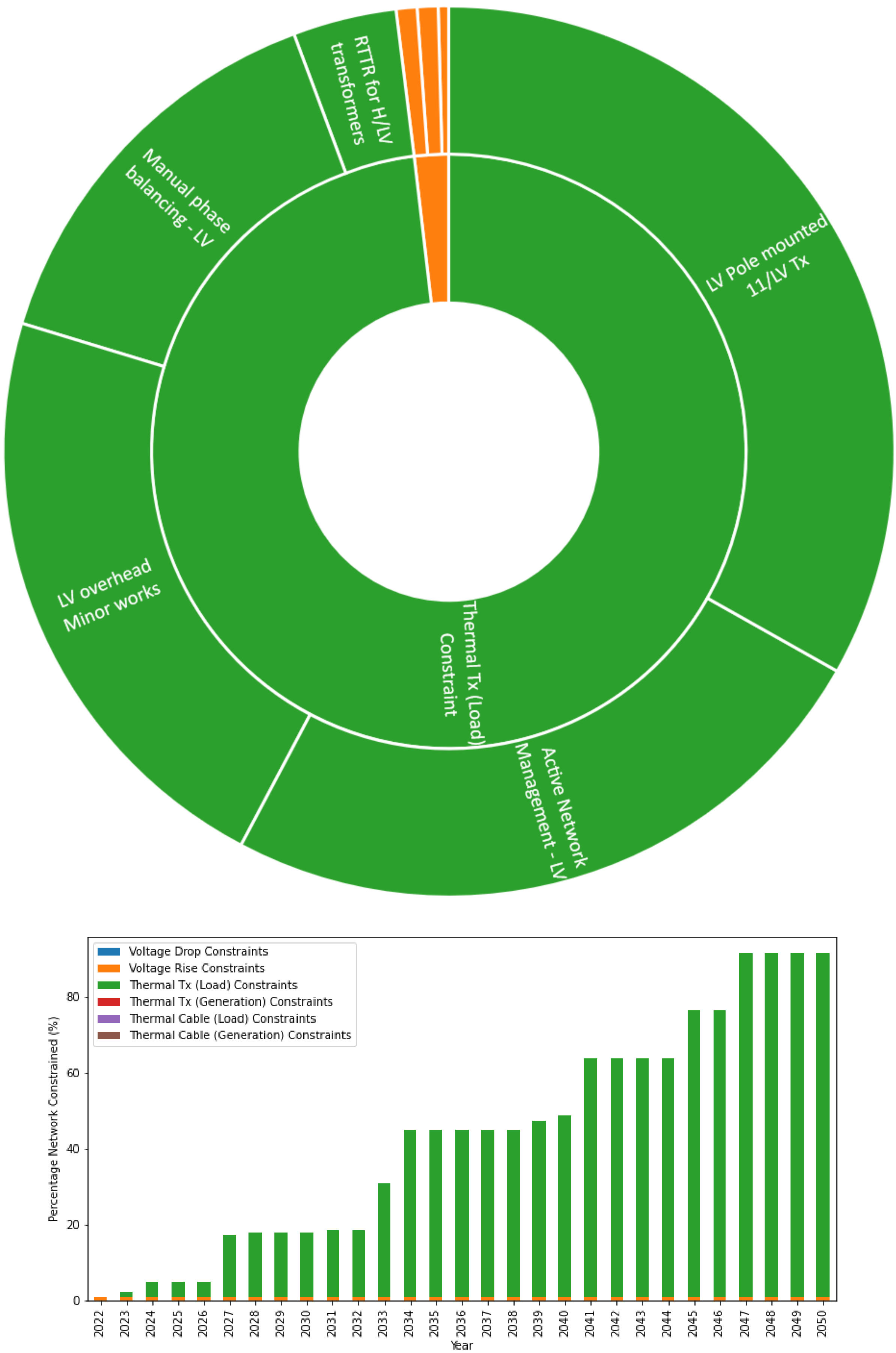
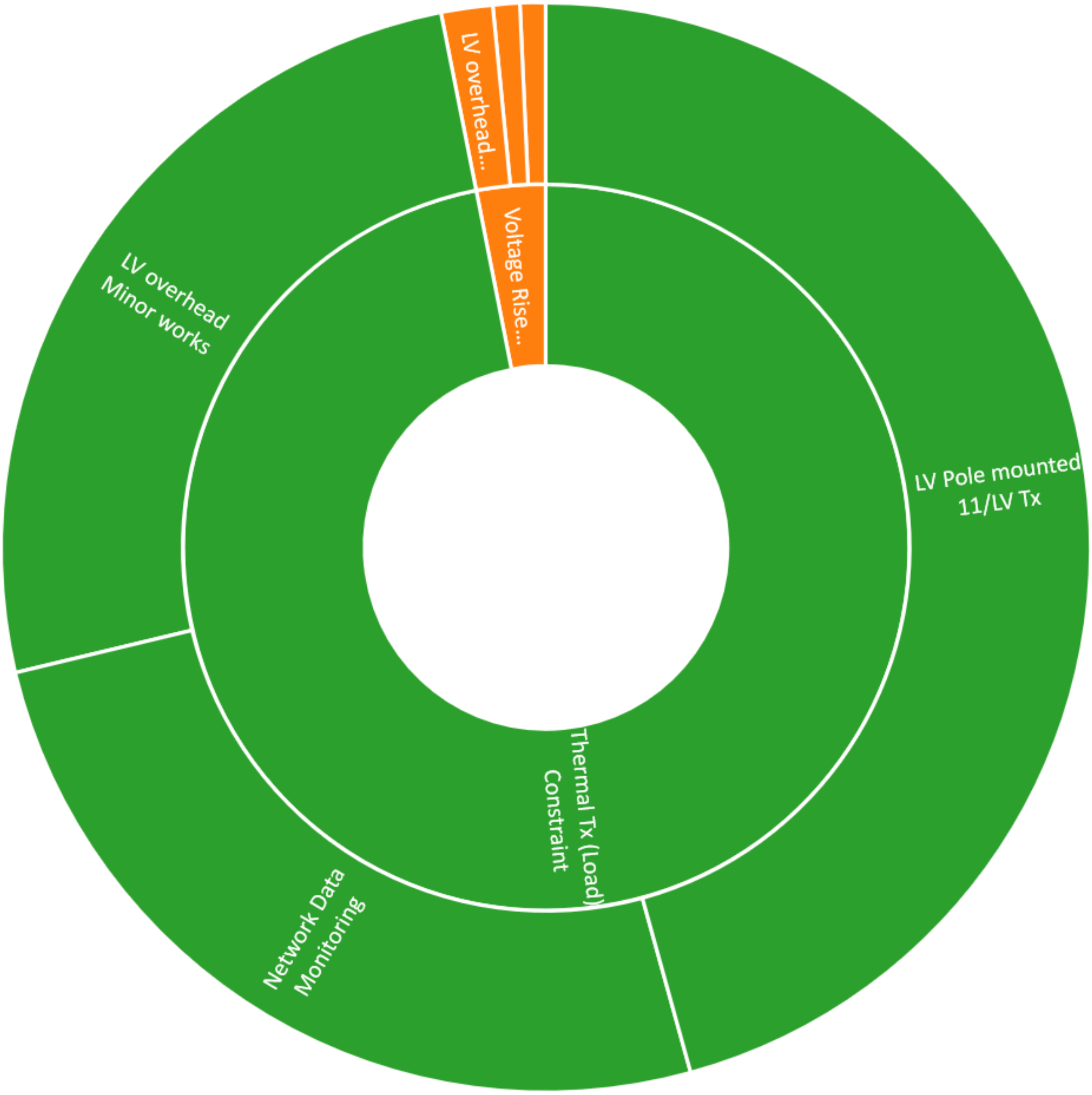


Figure 21: Solutions deployed for constraints on LV9 in South West under BV scenario



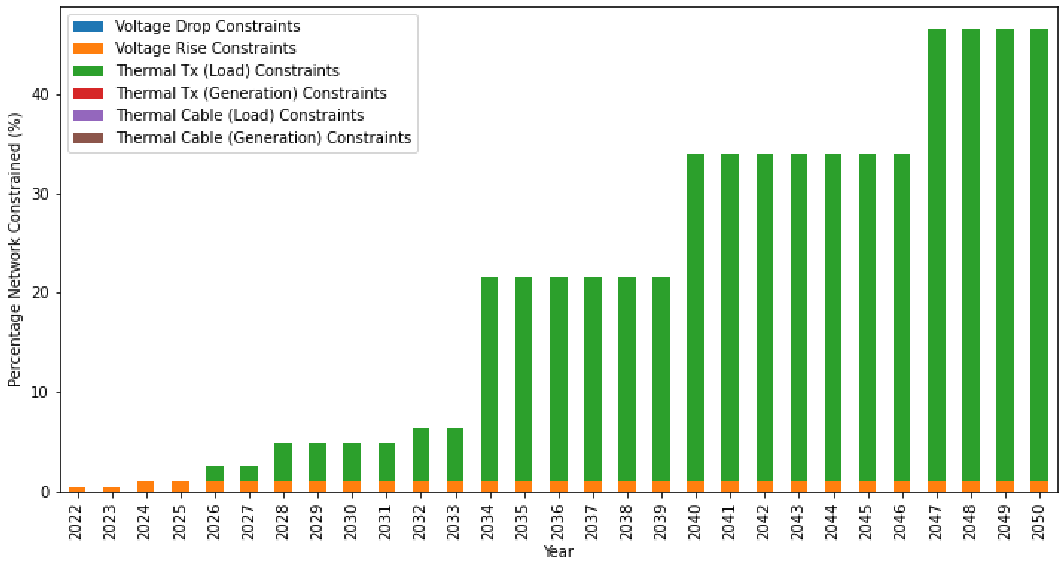


Figure 22: Solutions deployed for constraints on LV9 in West Midlands under BV scenario

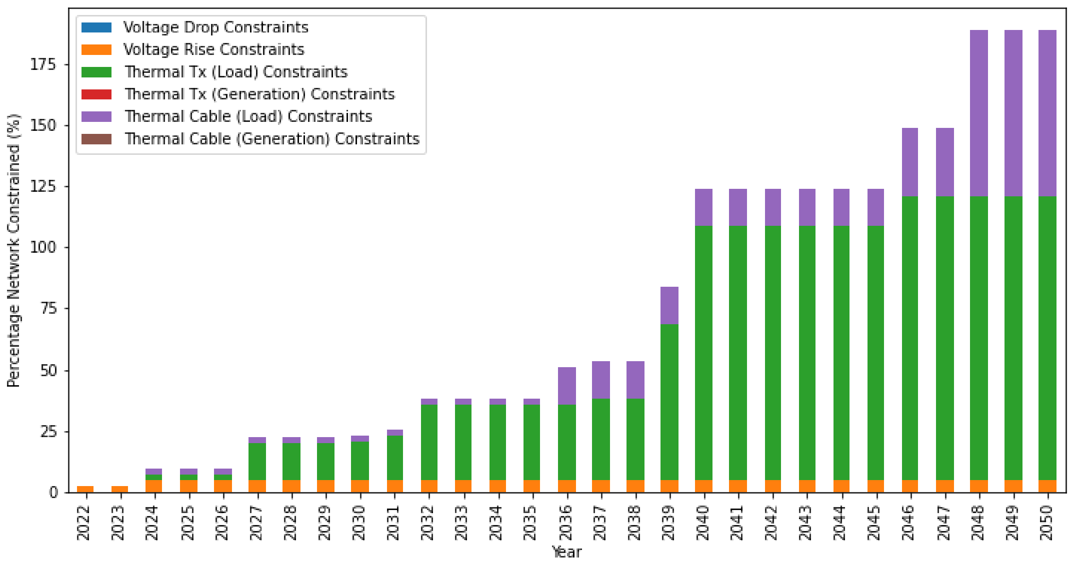


Figure 23: Solutions deployed for constraints on LV11 in East Midlands under BV scenario

4.1.4 LV10 (Rural Village Underground construction)

LV10 feeders are predominantly underground feeders that are located in rural villages, supplying domestic properties. The most common constraint type witnessed on this type of feeder is thermal constraints under net import. Voltage rise constraints under net export due to PV installation occurs less commonly.

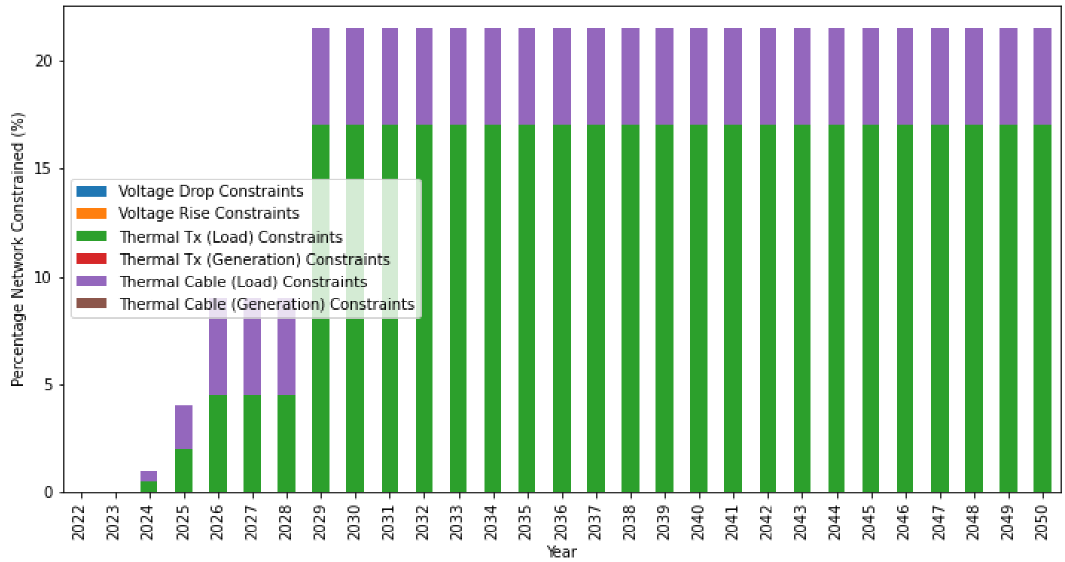


Figure 24 and

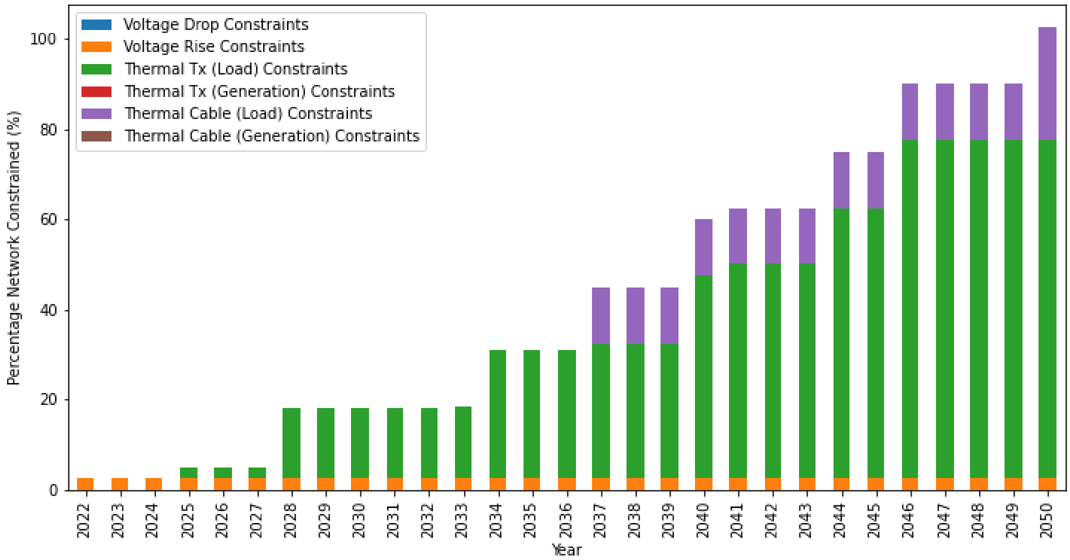


Figure 25 show the constraint types witnessed in South Wales and South West respectively, together with the solutions utilised to resolve each constraint type. Some variation is observed between the licence areas in terms of proportion of solutions deployed to resolve each constraint type. However, for thermal constraints, the following solutions are used across the licence areas:

- Active Transformer Cooling
- Active Network Management
- LV Underground Network Split Feeder
- LV Ground Mounted 11/LV Tx
- LV Underground Minor Works
- Network Data Monitoring

Typically, without novel solutions, the BaU solutions LV Ground Mounted 11/LV Tx, LV Underground Network Split Feeder and LV Underground Minor works get deployed in order to resolve thermal constraints that arise due to the deployment of EVs and heat pumps. BaU solutions get paired with novel solutions to reduce the number of the most costly solutions required (the effect of this is clearly shown in South Wales where very costly LV underground Minor works is deployed far less commonly than other solutions LV Ground Mounted 11/LV Tx and LV Underground Network Split Feeder. This occurs because the novel solutions Active transformer cooling LV and Active Network Management – LV release sufficient capacity across much of the network to avoid the need for LV Underground Minor Works). In other cases, novel solutions get deployed to delay the need for costly solutions such as LV Underground Minor Works, releasing deferral savings to the network operator.

While thermal constraints are the most common form of constraint on this feeder type, voltage rise constraints are forecast to occur due to high levels of PV installation causing net export. Voltage rise constraints often occur at the same time as thermal constraints, which results in similar solutions deployed to resolve both voltage and thermal constraints. Solutions such as LV Underground Minor Works, LV Ground Mounted and LV Underground Network Split feeder are modelled to release a small amount of voltage rise capacity, while at the same time releasing high levels of thermal capacity required to resolve the more dominant thermal constraint. For some feeders, voltage rise issues occur before thermal constraints. In these instances, the solution favoured to resolve the constraint is Manual Tapping of the HV/LV Tx [increasing Headroom]

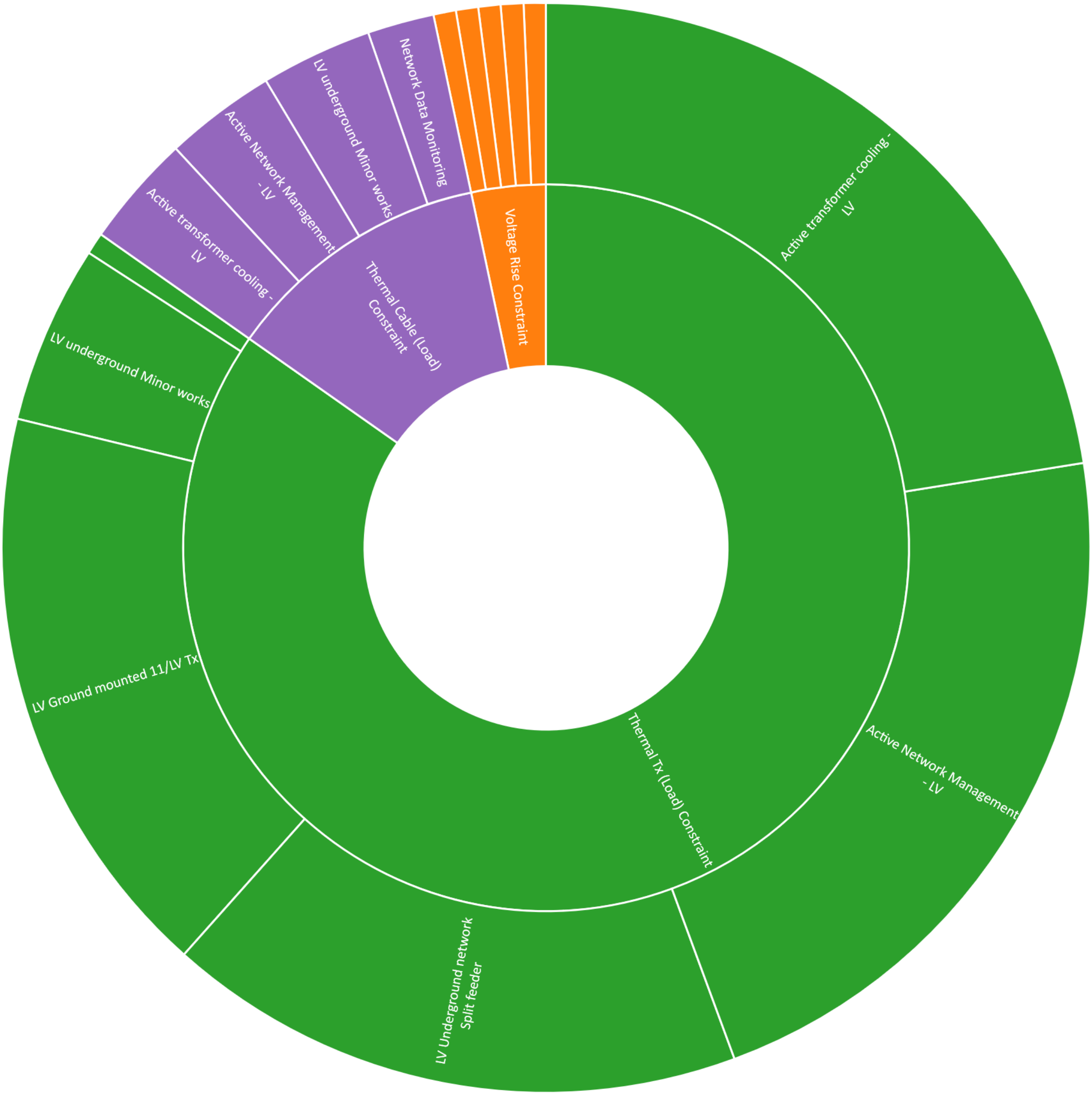
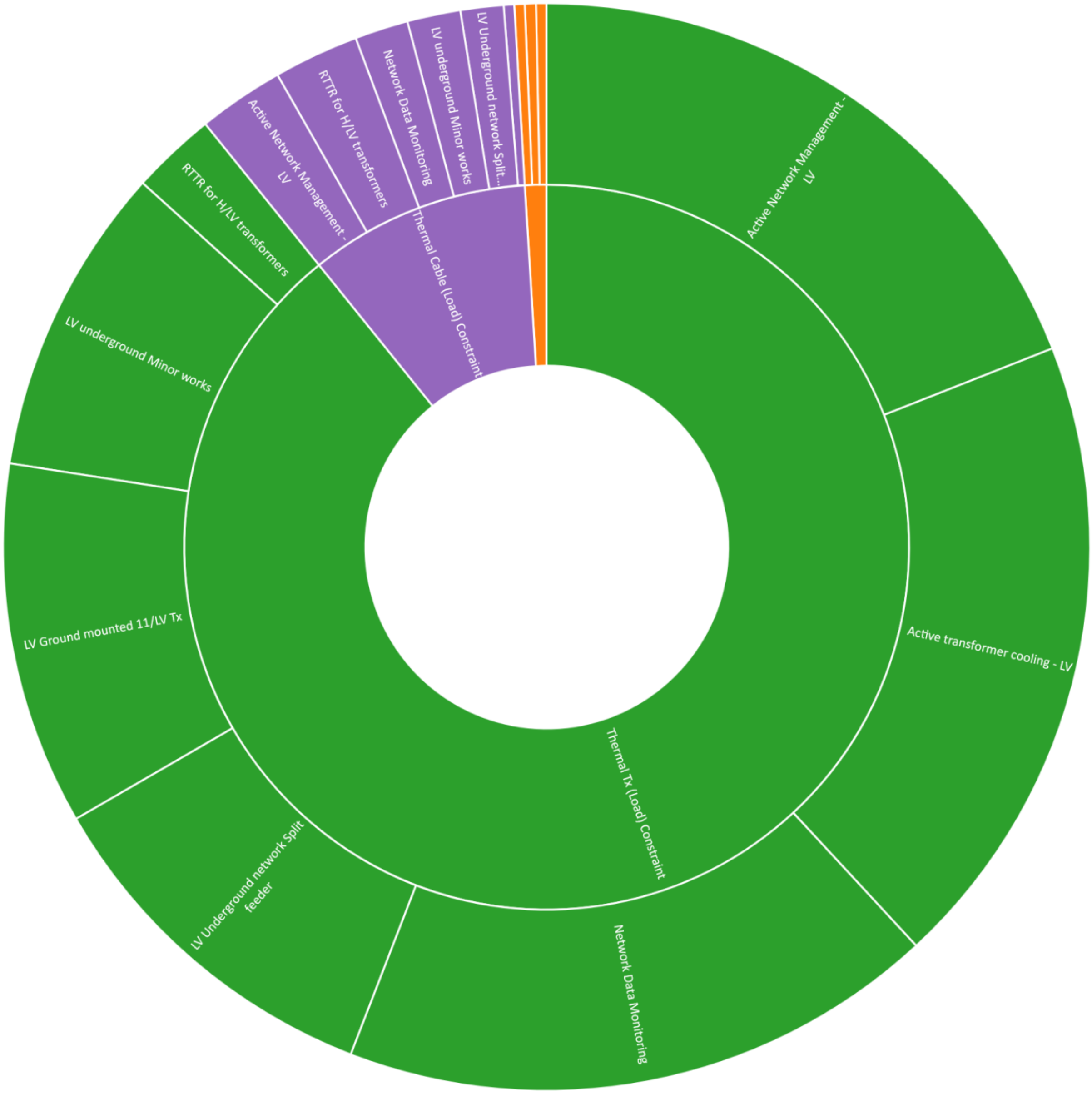


Figure 24: Solutions deployed for constraints on LV10 for South Wales in BV scenario



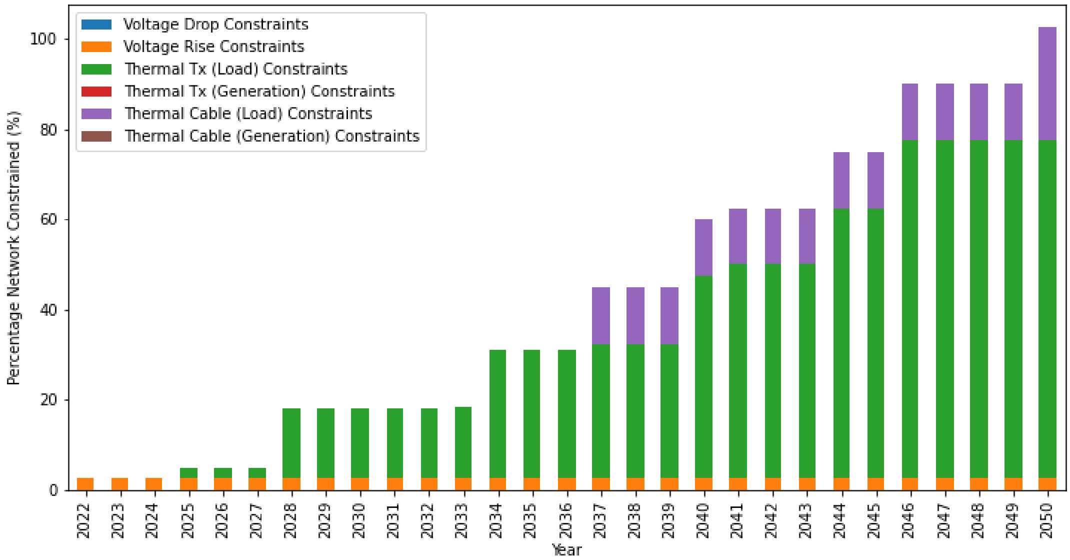


Figure 25: Solutions deployed for constraints on LV10 for South West in BV scenario

4.2 Indicative Timelines

Analysis has been conducted on the Transform outputs to produce indicative timelines showing the necessary timing for intervention on an archetypal basis. This analysis has been performed on the West Midlands licence area, however technologies deployed across licence areas are broadly similar. The analysis has been performed on National Grid's Best View scenario, since it is deemed the most likely outcome. If LCTs are deployed faster or slower in the real world, then the technologies will be required earlier or later respectively. Transform utilises clustering to reflect that real world deployment of LCTs varies from feeder to feeder. This analysis is based upon the 95th percentile feeder for LCT uptake (the feeder with faster LCT deployment than 95% of the feeders of each archetype). This was chosen to ensure the indicative timelines show novel technology deployment far enough into the future that there is a realistic possibility for trials to be completed before they are required, but early enough such that the technology can be deployed across a significant majority of the feeders of each archetype to deliver the maximum benefit to the network operator. The timelines presented in this section are indicative only, where LCTs are very highly clustered technologies will need to be deployed earlier, and where LCT deployment is lower technologies will not be required until later, if indeed they are required at all.

The figures below show the net import and net export through each network archetype over time as LCTs are increasingly installed across the network. In some figures, the power through the network plateaus; this corresponds to feeders that reach LCT deployment saturation (e.g. no more PV can be added to rooves, each household has 2EVs and a heat pump). In addition, the figures show the thermal and voltage rise limits of the feeder. Where there are step changes in the network limits, the figures indicate the solutions that are deployed to increase capacity, together with their totex cost and capacity they release. Details of the assumed totex costs and capacity releases for BaU and novel solutions are available in Appendix III and Appendix IV respectively.

Flexibility is a key option available to network operators as a method for deferring necessary network investment, Section 4.2.5 explores the necessary flexibility requirement that would need to be procured in order to defer network investment for a 5-year period from the point that otherwise network investment would be required. Since the indicative timelines are based on the 95th percentile feeder for LCT uptake, the flexibility need calculated is suitable for 95% of feeders. If less flexibility is procured than calculated, flexibility may still be viable option for feeders with slower uptake rates of LCTs.

4.2.1 LV1 (Central Business Districts), LV3 (Town Centres), LV4 (Business Parks) and LV5 (Retail Parks)

LCTs are not deployed at sufficient scale to cause constraints for the 95th percentile feeder in the West Midlands for LV1, LV3, LV4 and LV5. This would likely change if a commercial heat pump profile was modelled. A greater understanding of commercial heat pumps is recommended (see Recommendation 1 in the Transform Network Study report [2]) before accurate commercial heat pump modelling can be conducted.

4.2.2 LV2 (Dense Urban), LV6 (Sub-Urban Streets), LV7 (New Build Housing Estates) and LV8 (Terraced Streets)

LV2

In the mid 2030s, BaU solution Manual Tapping is deployed to resolve the voltage rise constraint caused by the uptake of PV. Continued uptake of LCTs drive thermal constraints by the late 2030s, which are resolved by combining BaU solution Manual Phase Balancing with novel solution Network Data Monitoring. Network Data Monitoring is a solution widely deployed across National Grid's licence areas and therefore no trial is required.

To avoid the need to deploy manual phase balancing and network data monitoring, 54kW of flexibility would be required[7], equating to 1.3kW per customer (peak after diversity maximum demand (ADMD) per customer is 5.4kW), representing a 24% decrease in load throughout the feeder. There is uncertainty over whether this high level of flexibility required per customer will be able to be procured, particularly on an ongoing basis and there is a risk that if a flexibility strategy is pursued but insufficient flexibility is procured the network operator would have insufficient time to deliver a technological solution.

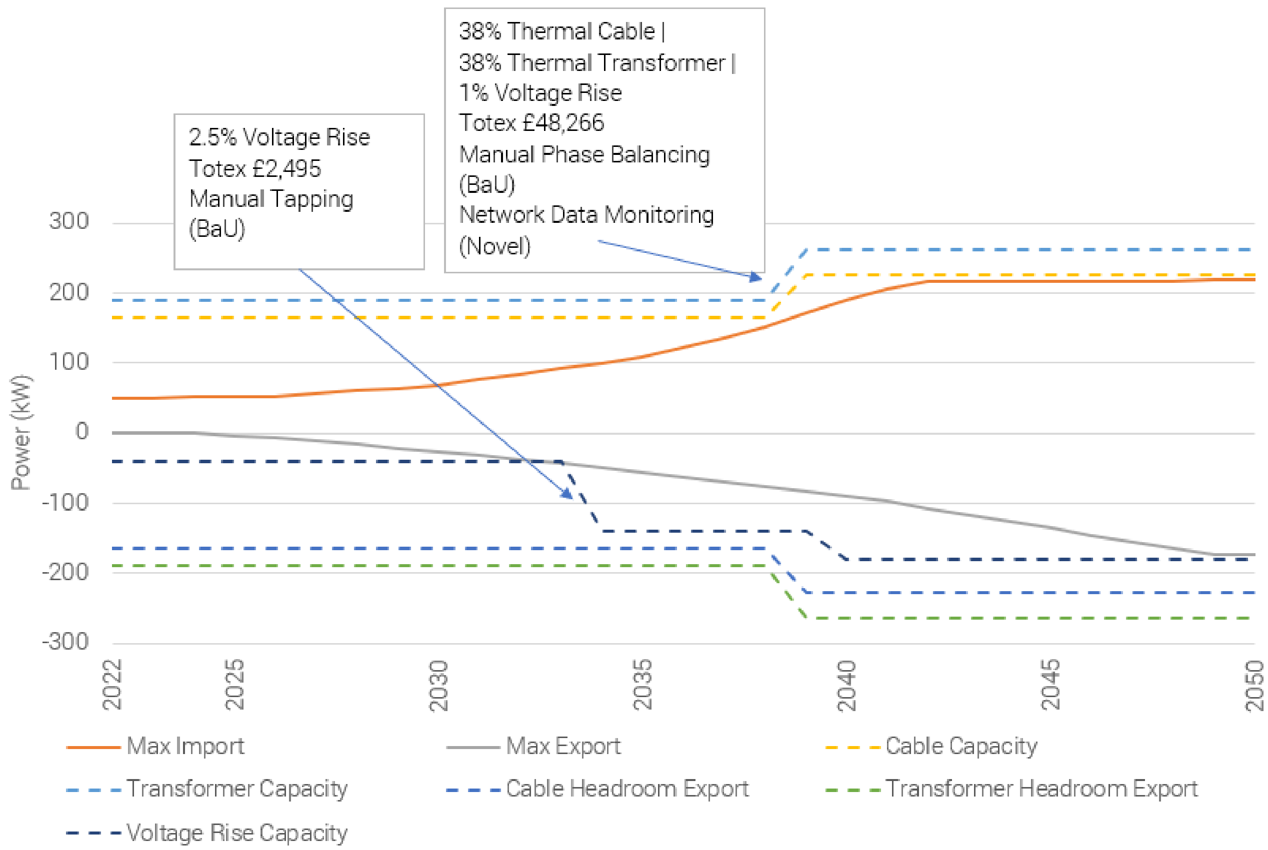


Figure 26: LV2 West Midlands Best View[8]

[7] Flexibility associated with EV chargers has already been partially accounted for. The assumed EV profile used throughout the analysis can be found in the Network Study report [2].

[8] Totex costs for each solution come either from the RfI process, or from collaboration between the network operators during development of the Transform model. Appendix II and Appendix III present the individual totex costs for BaU and novel solutions respectively, including the source for their modelled totex costs.

LV6

The novel technologies Permanent Meshing of LV Network (Sub-Urban), Network Data Monitoring and Active Transformer Cooling are deployed in the early 2030s to resolve thermal constraints, together with BaU solution Manual Tapping used to resolve a voltage constraint. While Network Data Monitoring is widely deployed across National Grid's licence areas, Permanent Meshing of LV Network (Sub-Urban) and Active Transformer Cooling are not currently deployed at low voltage. Therefore, it is recommended that the following technologies are trialled on a subset of National Grid's heavily loaded LV6 feeders in the late 2020s:

- Active Transformer Cooling

The modelling shows Permanent Meshing of LV Networks also being required for deployment in the early 2030s. However, in practice, permanent meshing is a complex solution to deploy due to difficulties retrofitting to existing networks, implications on substation protection schemes, safety implications and changes required to operational practice. Due to these challenges, Permanent Meshing is not necessarily recommended for wide scale role out, but rather further investigation into where specific applications (i.e. on new build feeders) that it may be suitable; its suitability will need to be assessed carefully on a case by case basis.

In the late 2030s, BaU solutions LV Underground Network Split Feeder and LV Ground Mounted Transformer are required to release further thermal capacity. Subsequently, Network Data Monitoring and Active Transformer Cooling will reach the end of their lifetime, with Network Data Monitoring being redeployed when Active Transformer Cooling reaches its end of life.

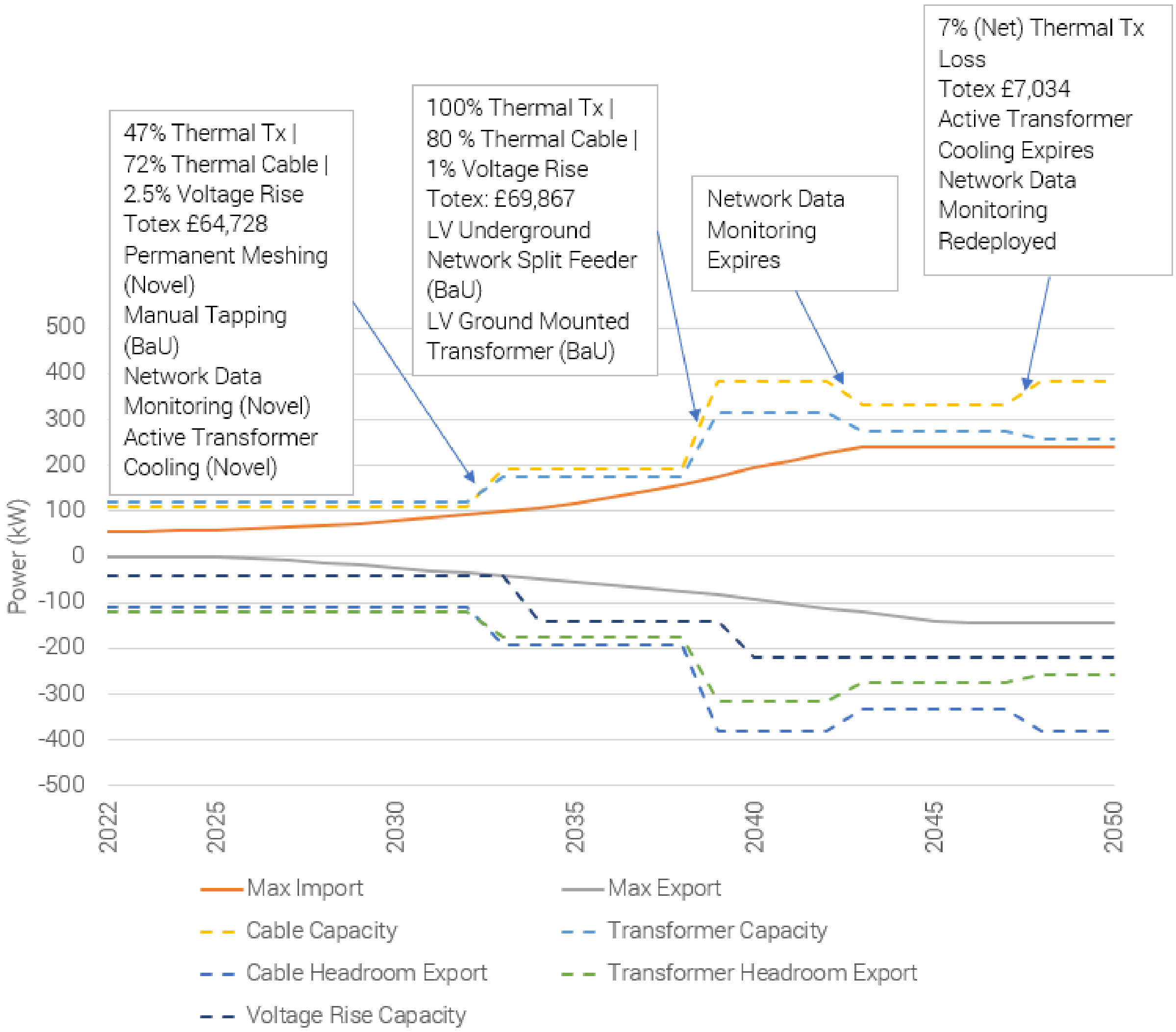


Figure 27: LV6 West Midlands Best View

LV7

Around 2030 BaU solution Manual Tapping and novel solution Network Data Monitoring are deployed to relieve voltage and thermal constraints. Network Data Monitoring is already widely deployed across National Grid's licence areas so no trial is necessary. In the late 2030, further thermal capacity release is required and provided by novel technology Permanent Meshing of LV Network (Sub-urban) and BaU solution LV Ground Mounted Transformer. Permanent Meshing of LV Network (Sub-urban) is an untested solution, which in practice is a complex solution to deploy due to difficulties retrofitting to existing networks, implications on substation protection, safety implications and changes required to operating practice. I Due to these challenges, Permanent Meshing is not recommended for wide scale role out, however it may be suitable for specific applications; its suitability needs to be carefully assessed on a case by case basis.

In the early 2040s, Network Data Monitoring expires, but after a few years is redeployed to release the necessary thermal transformer capacity to support continued uptake of LCTs. By 2050, the previous thermal transformer limit is exceeded by 13kW (6% transformer overload), equivalent to approximately 0.5kW per customer. If 0.5kW flexibility per customer on average can be procured, then flexibility could avoid the need to invest in Network Data Monitoring. This would be cost effective if procuring flexibility could be done cheaper than the Network Data Monitoring totex cost of £7,034 over its 10 year lifetime. By 2050, peak load per customer is 7.8kW, therefore 0.5kW of flexibility would only require a 6% reduction in peak load per customer.

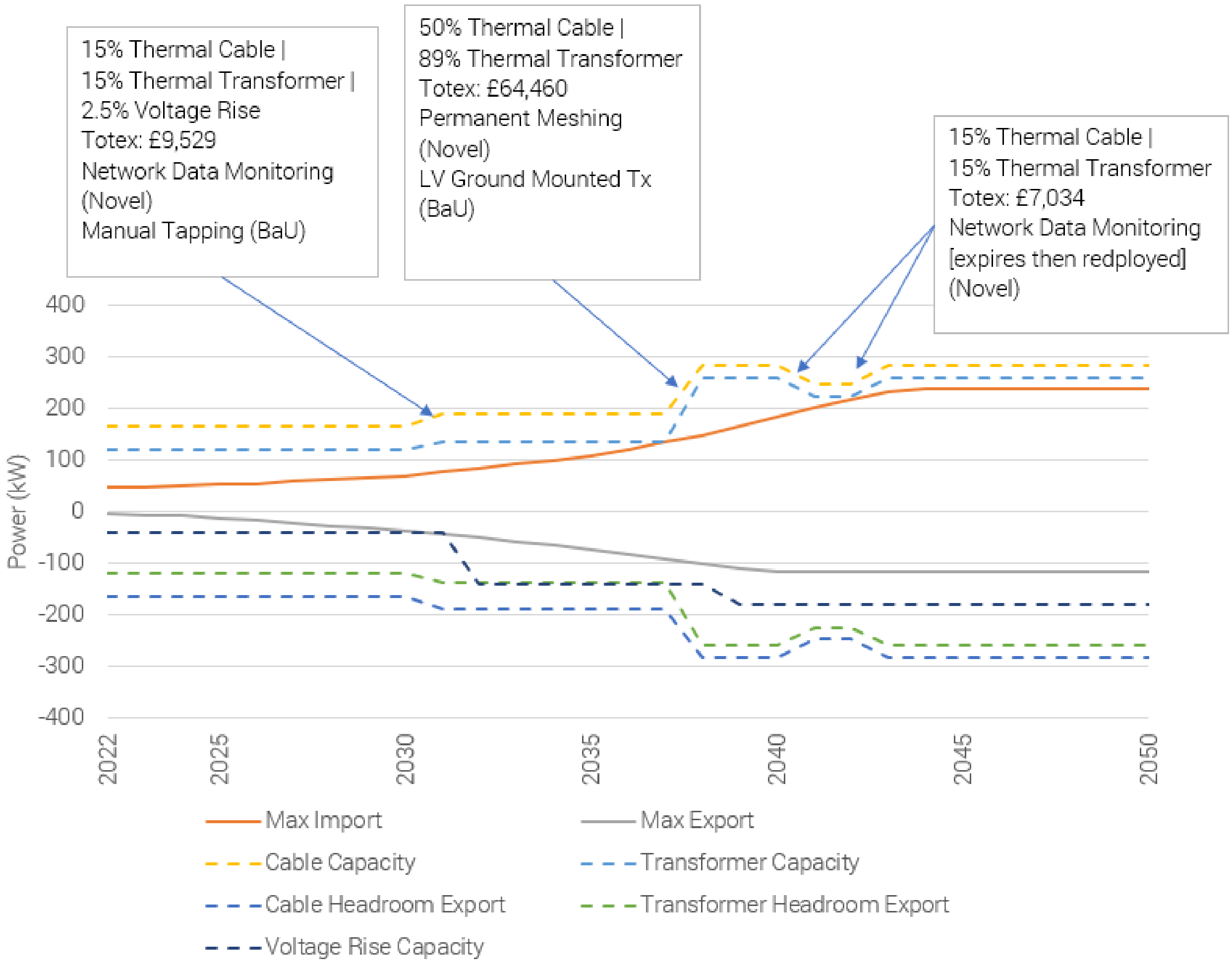


Figure 28: LV7 West Midlands Best View

LV8

The following novel technologies are deployed to LV8 by the mid 2030s:

- Permanent Meshing of LV Network – Sub-Urban
- Network Data Monitoring
- Active Transformer Cooling

Permanent meshing and active transformer cooling are not in use across National Grid's LV network. Network data monitoring is widely deployed across National Grid's LV network. It is therefore recommended that trials are conducted of the following technologies installed on heavily loaded LV8 feeders to be completed by the early 2030s:

- Permanent Meshing of LV Network – Sub-Urban
- Active Transformer Cooling

In the mid 2040s, the thermal transformer limit is marginally exceeded by 1kW. The only technology available that has not already been deployed to resolve the constraint is the installation of new Ground Mounted Transformers. This could be instead resolved by a flexible solution, requiring a response of less than 0.05kW per customer on the feeder. The installation of Network Data Monitoring would allow the network operator visibility of the network assets, and such the network operator would be able to make an informed decision regarding whether to take no action, procure flexibility or install a technological solution.

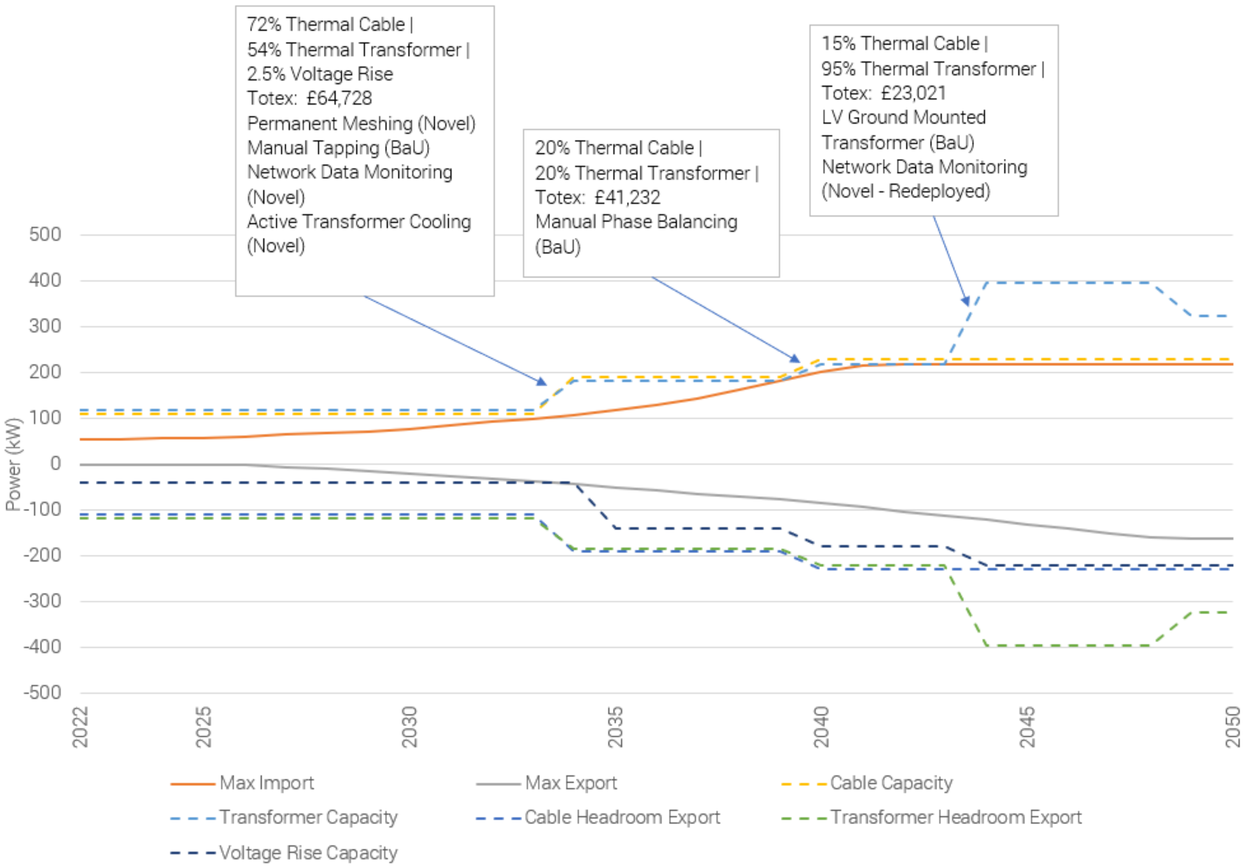


Figure 29: LV8 West Midlands Best View

4.2.3 LV9 (Rural Villages Overhead construction) and LV11 (Rural Farmsteads)

LV9

The only novel technology deployed across LV9 is Network Data Monitoring in the mid 2020s. Network Data Monitoring is widely deployed across National Grid's LV network, therefore no trials are required of this technology. Network Data Monitoring is deployed in conjunction with LV Pole Mounted Transformers since it is the cheapest method of resolving constraints over Transform's five year solve duration. However, by bringing forward the later investment in LV Overhead Minor Works, the need for Network Data Monitoring can be avoided. Network data monitoring therefore acts to defer investment in the more disruptive LV Overhead Minor Works, Flexibility may act as an alternative means to defer investment, but the enduring solution for this network archetype is investing in significant network upgrades due to the rapid deployment of LCTs.

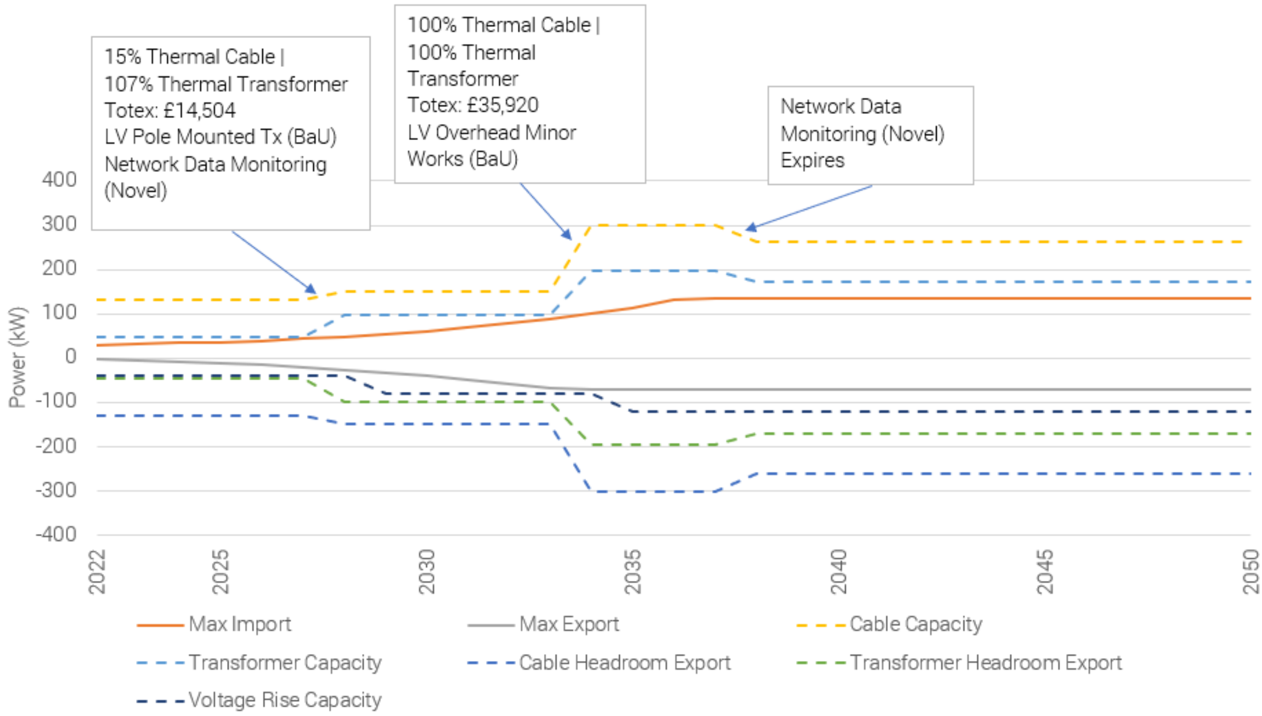


Figure 30: LV9 West Midlands Best View

LV11

The only novel technology required for LV11 is Network Data Monitoring from the mid 2030s. Network Data Monitoring is routinely deployed across National Grid's distribution network, and therefore no trials are required.

Network Data Monitoring is deployed in the mid 2030s to alleviate a thermal cable constraint. This constraint is minor and its magnitude is only 1kW equating to 0.1kW per customer, indicating that flexibility is likely be a good option for alleviating thermal cable network constraint, which would remove the need to deploy Network Data Monitoring. To avoid the need to deploy the new Pole Mounted Transformer (as well as Network Data Monitoring), 19kW of flexibility would be required, equating to 1.75kW per customer on the feeder. The peak demand per customer by 2050 on this archetype is expected to be 10.5kW per customer, therefore 1.75kW of flexibility would require a 17% decrease in peak demand.

In the second set of interventions, thermal transformer capacity is significantly over-procured. The deployment of a PMT is the most cost effective option for resolving the thermal transformer constraint, but the capacity it releases is surplus to what is required. While this example is for overhead feeders supplied by PMTs, this can also happen for underground feeder supplied by GMTs. Innovative technologies that could release between 20% and 80% thermal transformer capacity for less than the per feeder cost of a PMT (approximately £7,500 for overhead feeders) or a GMT (approximately £16,000 for underground feeders) would provide significant value to the network operator by offering an cheaper solution that releases less excess capacity.

R2. Development of innovative technologies that could offer between 20% and 80% thermal transformer capacity at less than £16,000 per feeder (for underground feeders supplied by GMTs) or £7,500 per feeder (for overhead feeders supplied by PMTs) would offer significant value to the network operator and reduce unnecessary capacity overprocurement.

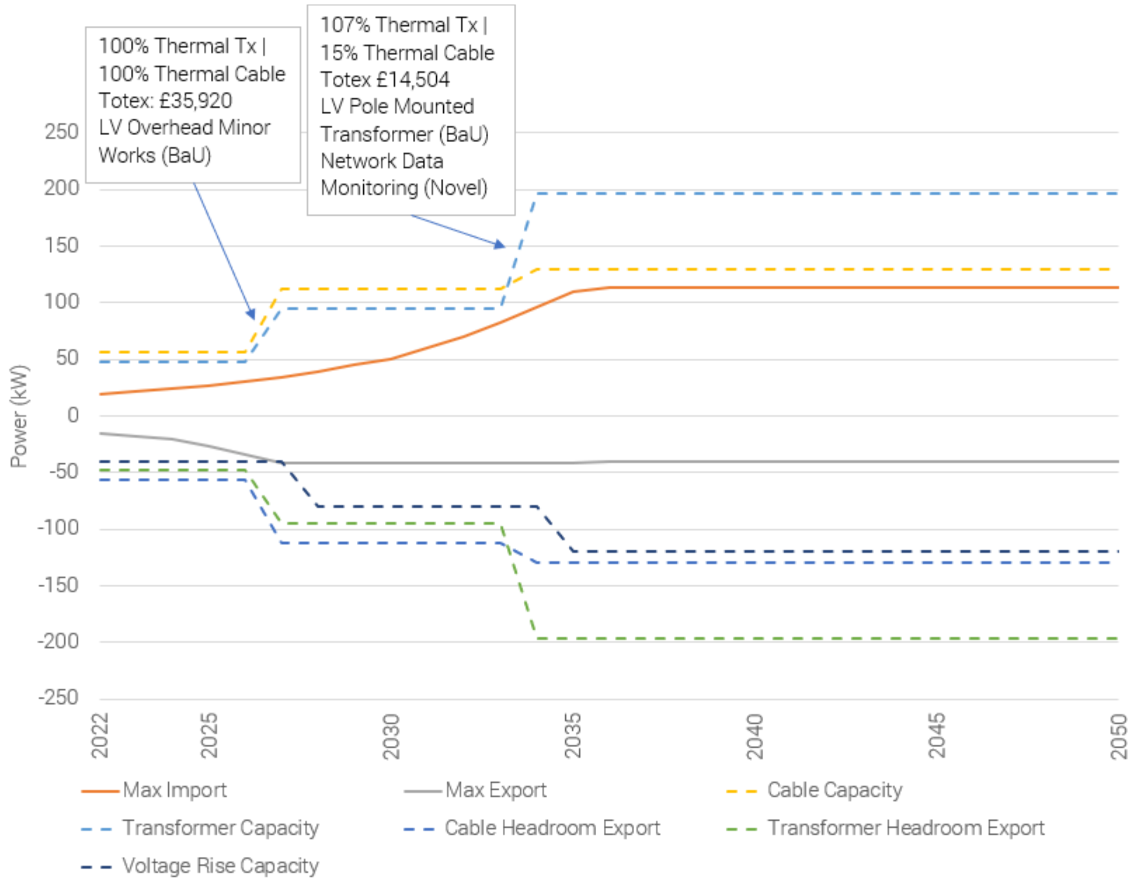


Figure 31: LV11 West Midlands Best View

4.2.4 LV10 (Rural Village Underground construction)

Novel technologies are not required for LV10 until around 2040, where Network Data Monitoring, Active Network Management and Active Transformer Cooling are deployed in parallel to increase thermal and voltage rise limits sufficiently to facilitate continued LCT uptake. Network Data Monitoring is already deployed across National Grid's LV network. Therefore, by the mid 2030s trial of the following technologies should be underway on LV10 feeders:

- Active Network Management
- Active Transformer Cooling

90kW of flexibility would be required to avoid the deployment of novel technologies, which equates to 2.9kW per property, this would represent very significant flexibility requirement which is not likely available as an enduring solution.

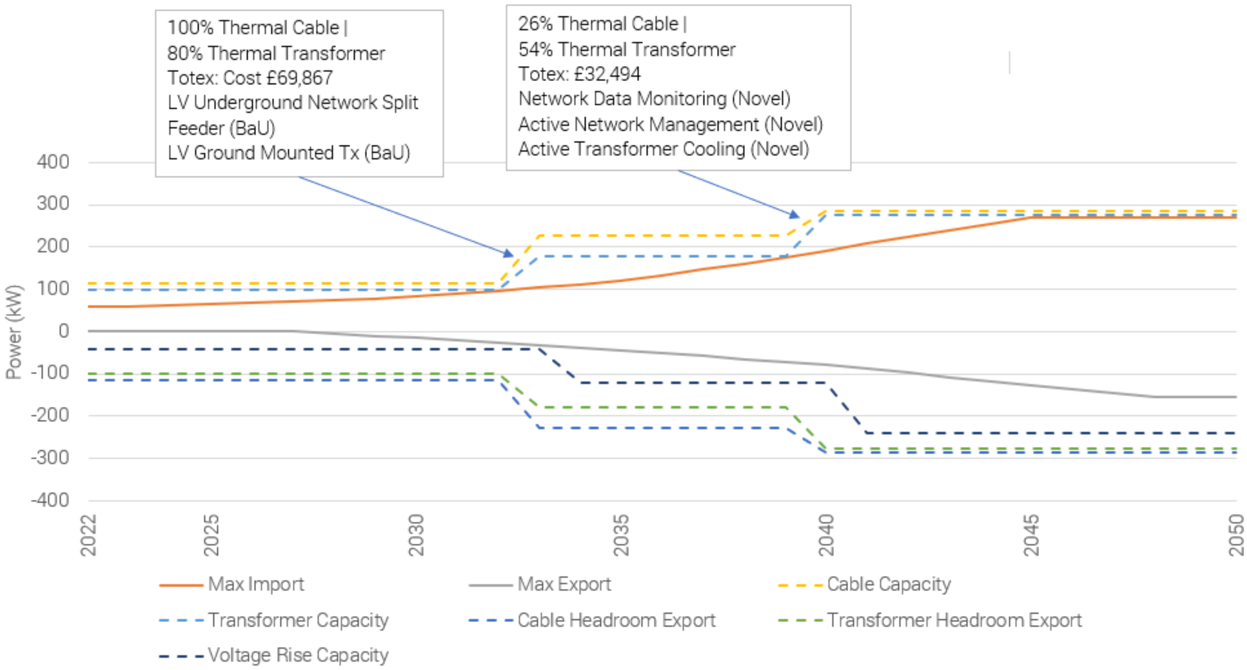


Figure 32: LV10 West Midlands Best View

4.2.5 Flexibility to Defer Investment

Table 1 and Table 2 detail the first and second interventions respectively applied by Transform to resolve network constraints encountered across each LV network archetype. Flexibility services offer benefits to network operators by providing an alternative option to defer investment in the LV network. The tables below indicates the level of flexibility that the network operator would need to procure across each network archetype in order to defer investment in the network for 5 years, based on the above analysis for the 95th percentile feeders. If less flexibility can be procured than that calculated, flexibility may still be a viable solution for feeders with slower LCT uptake rates. Flexibility is potentially a powerful option at the network operator's disposal, for it can be deployed as a standalone solution to postpone necessary network investment, or in conjunction with technological solutions to reduce the necessary up front capital expenditure required. Flexibility can only be utilised as a solution where sufficient flexibility volume can be procured to resolve the network constraints. The consequences of requesting flexibility should also be considered, such as the potential to create further constraints such as secondary peaks. Additionally, the willingness of consumers to participate in flexibility services must also be considered. Whether flexibility is a cost effective method of managing the network depends on a number of factors including:

- Energy demand shifted through flexibility procurement
- Price per unit of energy shifted
- Cost of alternative, technological solution to relieve network constraint.

C3. To defer network reinforcement for a 5-year period from time of first network constraint, between 0.7kW and 2.1kW per customer are required depending upon the network archetype.

Table 1 Table showing first interventions applied across the LV archetypes, and flexibility requirement to defer investment for 5 years

LV Archetype	Year of Intervention	First Intervention(s)	Headroom Release	Totex Cost	Flexibility Required to defer for 5 years (kW)	Flexibility Required per customer to defer for 5 years (kW)[9]
LV1	N/A					
LV2	2033	Manual Tapping of HV/LV Tx	2.5% Voltage Rise	£2,495	29	0.7
LV3	N/A					
LV4	N/A					
LV5	N/A					
LV6	2033	Permanent Meshing of Networks - LV Sub-Urban, Manual Tapping of HV/LV Tx, Network Data Monitoring, Active transformer cooling - LV	47% Thermal Transformer, 72% Thermal Cable, 2.5% Voltage Rise	£64,728	33	1.0
LV7	2031	Network Data Monitoring, Manual Tapping	15% Thermal Transformer, 15% Thermal Cable, 2.5% Voltage Rise	£9,529	33	1.1
LV8	2033	Permanent Meshing, Manual Tapping, Network Data Monitoring, Active Transformer Cooling	54% Thermal Transformer, 72% Thermal Cable, 2.5% Voltage Rise	£64,728	34	0.9
LV9	2028	LV Pole Mounted Tx, Network Data Monitoring	15% Thermal Cable, 107% Thermal Transformer	£14,504	31	2.1
LV10	2033	LV Underground Network Split Feeder, LV Ground Mounted Tx	100% Thermal Cable, 80% Thermal Transformer	£69,867	47	1.6
LV11	2027	LV Overhead Minor Works	100% Thermal Transformer, 100% Thermal Cable	£35,920	12	1.1

[9] Flexibility that would be required to be procured to defer the need for network investment for 5 years after the network constraint first occurs, stated as the required power turn down per customer on the archetype (on average) in the 5th year of the deferral period.

Table 2 Table showing second interventions applied across the LV archetypes, and flexibility requirement to defer investment for 5 years. Assumes no flexibility in placed for first set of interventions.

LV Archetype	Year of Intervention	Second Intervention(s)	Headroom Release	Totex Cost	Flexibility Required to defer for 5 years (kW)	Flexibility Required per customer to defer for 5 years (kW)[10]
LV1	N/A					
LV2	2039	Manual phase balancing – LV, Network Data Monitoring	38% Thermal Transformer, 38% Thermal Cable	£48,266	54	1.0
LV3	N/A					
LV4	N/A					
LV5	N/A					
LV6	2039	LV Underground network Split feeder, LV Ground mounted 11/LV Tx	100% Thermal Transformer, 80% Thermal Cable, 1% Voltage Rise	£69,867	63	2.0
LV7	2038	Permanent Meshing of Networks - LV Sub-Urban, LV Ground mounted 11/LV Tx	89% Thermal Transformer, 50% Thermal Cable	£64,460	80	2.6
LV8	2040	Manual phase balancing – LV	20% Thermal Transformer, 20% Thermal Cable	£41,232	36	1.0
LV9	2034	LV overhead Minor works	100% Thermal Transformer, 100% Thermal Cable	£35,920	35	2.4
LV10	2040	Network Data Monitoring, Active Network Management – LV, Active transformer cooling - LV	54% Thermal Transformer, 26% Thermal Cable	£32,494	76	2.4
LV11	2034	LV Pole mounted 11/LV Tx, Network Data Monitoring	107% Thermal Transformer, 15% Thermal Cable	£14,504	19	1.7

[10] Flexibility that would be required to be procured to defer the need for network investment for 5 years after the network constraint first occurs, stated as the required power turn down per customer on the archetype (on average) in the 5th year of the deferral period.

4.3 Case Studies from PowerFactory Analysis

The PowerFactory analysis presented in the previous load flow analysis report [6] assessed the impact of novel technologies on case study feeders, and whether they could be used to resolve network constraints. This section summarises which novel technologies were found to be capable of resolving particular network constraint types, on which types of network. This PowerFactory analysis focussed purely on a technical assessment with the cost effectiveness of solutions covered as part of the Transform study. For this reason, the flow charts in Appendix II are based primarily on the Transform analysis, but they acknowledge the importance of using PowerFactory or similar assessment tool to investigate the impact of solutions chosen on the network.

4.3.1 Solutions that address Voltage Rise

The following solutions were shown to increase voltage rise capacity.

Smart Transformer

Smart transformers offer fine control of the busbar voltage, avoiding larger step changes associated with manual tapping and on-load tap changers and can effectively be used to manage voltage, increasing voltage rise capacity along a feeder by decreasing the voltage at the transformer. Smart transformer also offer wider benefits as they can offer a degree of phase balancing plus harmonic filtering primarily to the HV network, although a degree of harmonic reduction will also be achieved on the LV network. Smart transformers are available for GMTs and are technically suitable solution for feeders requiring voltage rise capacity increases.

On-load Tap Changer (OLTC)

Similarly to smart transformers, OLTCs offer control of the transformer voltage which can be performed without taking customers off supply. By lowering the transformer voltage, voltage rise capacity along feeders can be effectively increased. OLTCs do not have the same fine or high speed control of transformer voltage in the way smart transformer do, instead voltage can only be changed in distinct steps. OLTCs offer a technically suitable solution for feeders requiring voltage rise capacity increases but careful consideration of the target voltage is essential.

Statcom

Statcoms connected to the LV busbar control the voltage by absorbing reactive power to lower voltage or injecting reactive power to increase voltage. By decreasing the busbar voltage, statcoms are able to increase the voltage rise capacity of the network. However, the reactive current flowing through the transformer decreases the thermal capacity of the network, limiting the additional PV generation that can be connected to the network and increasing losses. Statcoms can also be connected at remote end of feeders were shown to provide more targeted voltage control and reducing the thermal losses compared to busbar connected statcoms. Statcoms are therefore only effective solutions where there is significant spare thermal capacity on the network, and other solutions that do no increase losses and restrict thermal capacity are likely to be preferable solutions. Statcoms can be deployed to both urban and rural, overhead or underground feeder types.

C4. Both smart transformers and OLTCs offer a potential option to improve voltage management and increase headroom for PV export with the preferred option being dependant on the granularity of control. Statcoms offer some potential, particularly to individual voltage constrained feeders with some spare thermal capacity, with greatest benefit being realised when they can be located at remote end of feeders.

4.3.2 Network Monitoring

While network monitoring itself doesn't increase capacity on the network, it provides network operators with crucial visibility to ensure that appropriate interventions can be made in a timely manner.

The PowerFactory analysis highlighted the importance of network visibility to understand the scale of voltage rise issues, in particular when PV is connected to LV feeders. To ensure that the voltage at all customer connections remains within statutory limits, monitoring is critical to ensure that the set points of voltage control technologies (i.e. smart transformers or OLTCs) can be appropriately set. This can be achieved through either historic smart meter data or near time network data monitoring to provide important insight into voltage magnitude at remote feeder ends.

R3. To effectively manage LV customer voltages using novel solutions, some form of monitoring of feeder voltages through smart meters or network monitoring and feedback loop to establish target set-points will be needed.

4.3.3 Solutions that address Thermal Constraints

The following solutions were shown in the modelling to increase the thermal capacity.

Network Meshing

Network meshing can offer an effective solution to relieve thermal conductor constraints for certain network configurations. Network meshing can be considered as an option to resolve thermal conductor constraints where there are two feeders that can be meshed in conditions where one feeder reaches thermal limits while the other has spare capacity. By meshing the network, load is shared between the feeders, reducing thermal load through the highly loaded feeder and increasing load in the more lightly loaded feeder. However, depending on the source substation of each feeder and protective equipment the impact on fault level and fault clearing times can be significant. A full assessment on fault level implications should be considered before this solution is deployed.

Permanent meshing between feeders traditionally supplied by two feeders is particularly complex as a retrofit solution, due to practical implication, fault level and existing protection schemes. For this reason, permanent meshing is unlikely to be a widely rolled out solution, but there are specific situations where permanent meshing is a valuable solution to the network operator. Careful consideration of whether permanent meshing is suitable is required on a case by case basis. Where permanent meshing is not a suitable solution, there exists a gap in suitable technology to resolve thermal constraints, particularly releasing significant levels of thermal cable capacity. This represents an opportunity for technology providers; a solution that releases thermal cable capacity but is easier and potentially less disruptive to retrofit to the existing network, will provide significant value to the network operator.

C5. Network meshing is an effective solution to increase thermal capacity but consideration around fault levels and protection systems is required on a case-by-case basis. Difficulties associated with retrofitting network meshing to existing networks mean this solution is unlikely to be suitable for wide scale roll out, however it could be valuable for specific cases.

R4. Innovative technology offering significant thermal cable capacity release suitable for retrofit across all feeders, would offer significant value to the network operator.

5. System Cost Benefit Analysis

The Transform models conducted a Cost Benefit Analysis across the LV distribution system for each licence area, as discussed in Section 6 of the Transform Functional Requirements report [4]. The figures below show the totex investment required on a year by year basis across National Grid's four licence areas. The introduction of novel technologies reduces the required total expenditure. The reduction shows some variation between licence areas and scenarios but typically ranges between approximately a 20% to 35% saving in necessary expenditure. This shows that novel technologies offer value to the network operator and thus electricity consumers by helping to provide an overall cheaper set of solutions to resolve the network constraint forecast. Modelling the different scenarios acts as a sensitivity test on the LCT uptake rate, providing confidence that regardless of the observed LCT uptake rate, that novel technologies in conjunction with BaU technologies will provide the network operator a more cost-effective method of managing the LV network than with BaU technologies alone. Similarly, studying National Grid's four licence areas acts as a sensitivity study showing that the novel technologies offer value across a range of differing network topologies.

Table 3 shows the system cost based on the Transform analysis of reinforcing the network to support the anticipated uptake of LCTs across the three scenarios. The scenarios act as a sensitivity study of the actual LCT uptake rate and the licence areas act as a sensitivity study for differing network topologies. In almost all cases, the introduction of novel technologies provides a saving against BaU technologies only.

Figure 36 to Figure 39 show the cumulative savings provided by introducing novel technologies in comparison to utilising BaU solutions only. Savings are offered across the different scenarios and licence areas[11]. Modelling the different scenarios acts as a sensitivity test on the LCT uptake rate, providing confidence that regardless of the future real world LCT uptake rate, across all feasible uptake rates the introduction of novel technologies will provide the network operator with a more cost effective solution set with which to manage the LV network than with BaU technologies alone. Similarly, studying National Grid's four licence areas acts as a sensitivity study that shows novel technologies offer value to the network operator across a range of different network topologies.

C6. Novel solutions offer savings over BaU costs through deferral of investment. Sensitivity studies show that these savings are robust against variations in network topology and LCT uptake rates.

[11] There is very little difference in the costs of when novel technologies are introduced compared to when BaU solutions only are deployed, in the Steady Progress scenario in the South West.

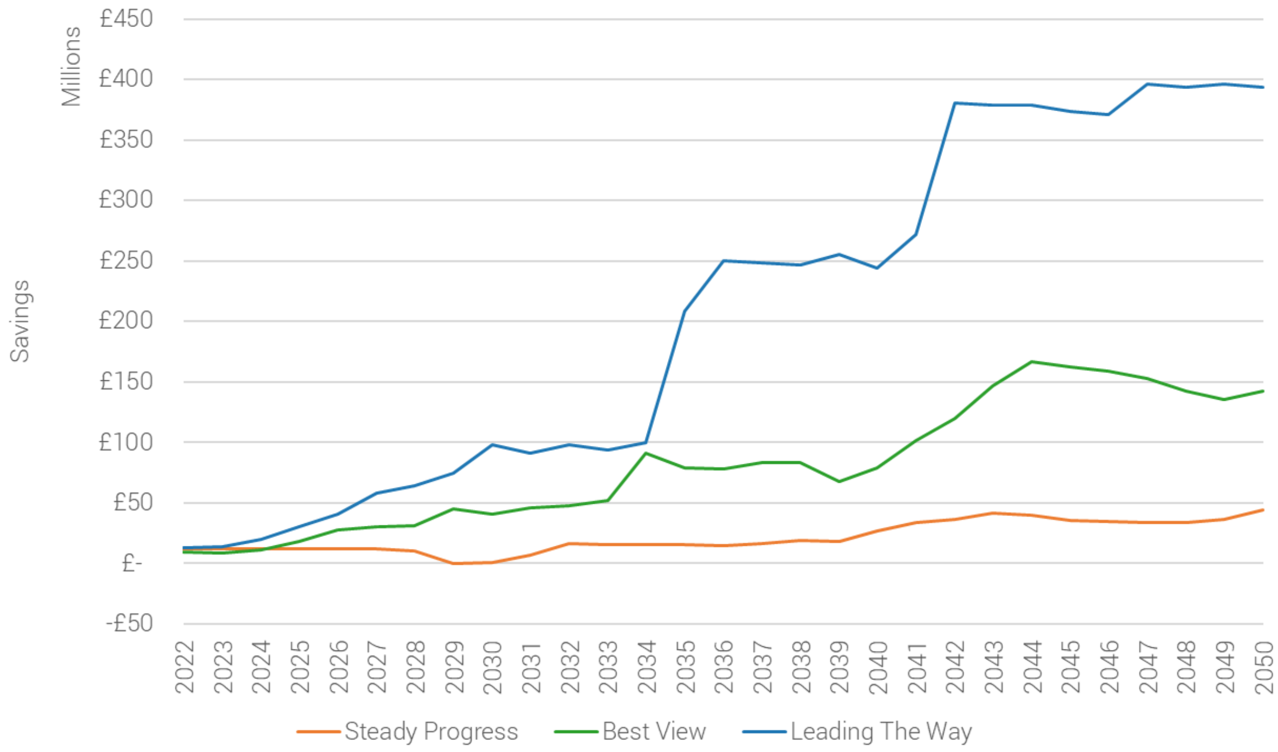


Figure 33: Investment savings in BaU & Novel study compared to BaU study for West Midlands

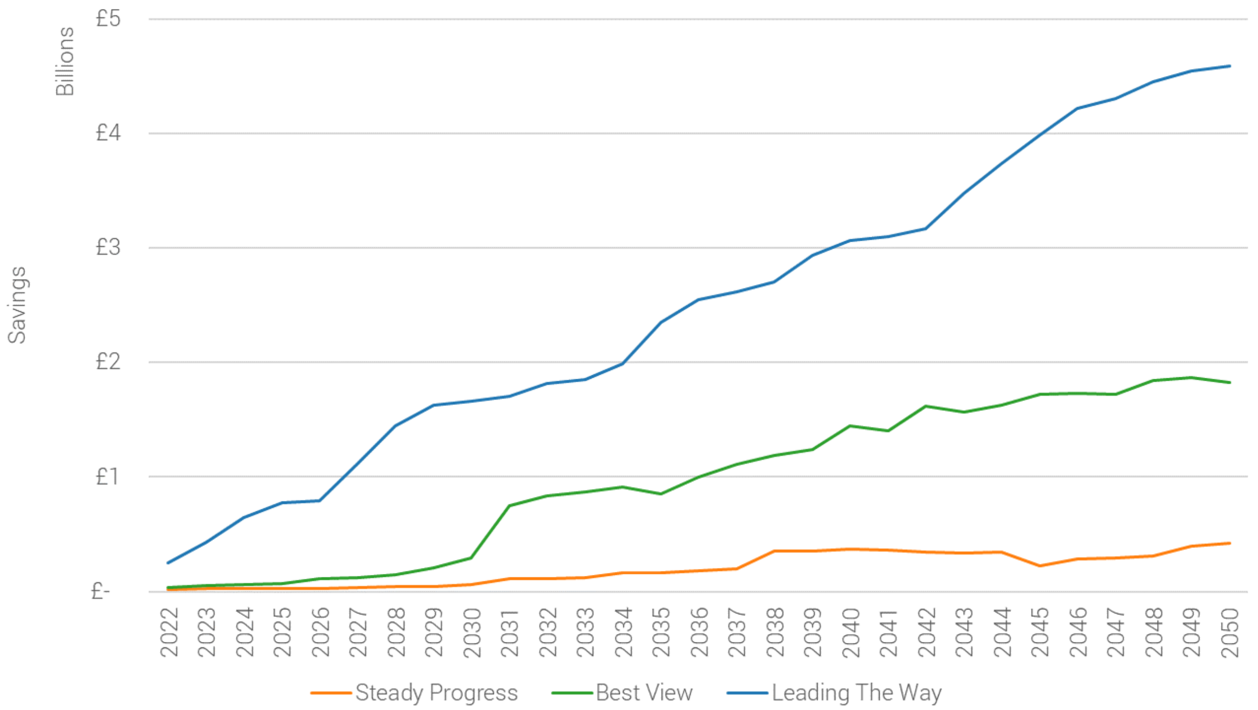


Figure 34: Investment savings in BaU & Novel study compared to BaU study for East Midlands

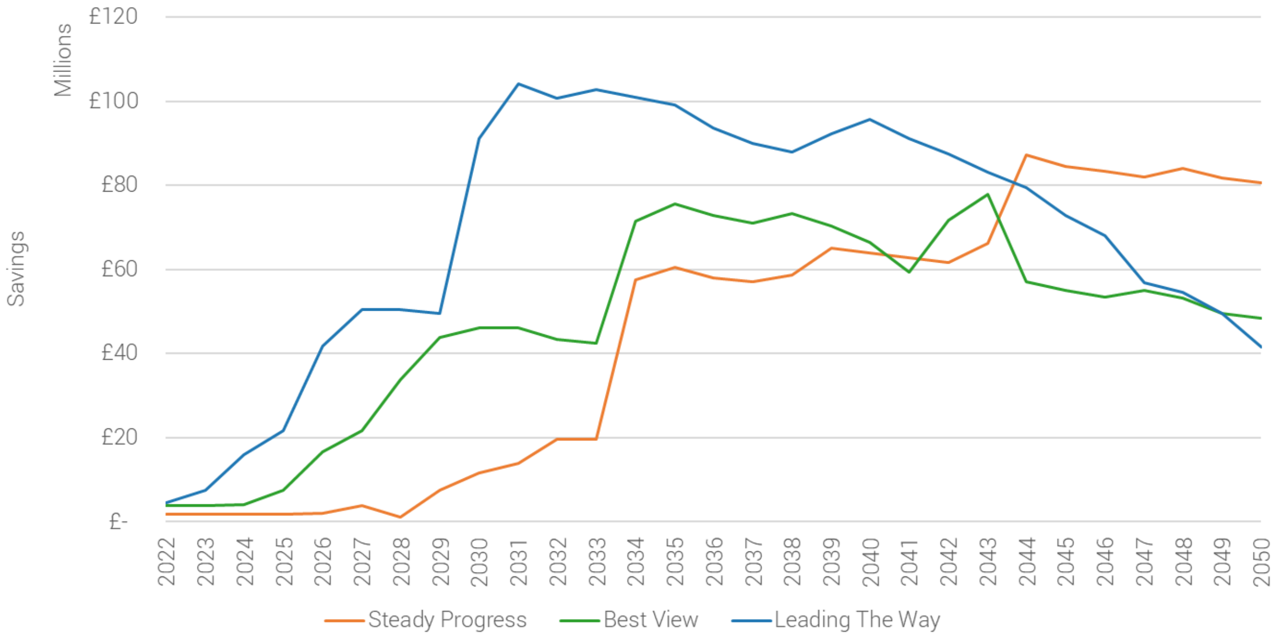


Figure 35: Investment savings in BaU & Novel study compared to BaU study in South Wales

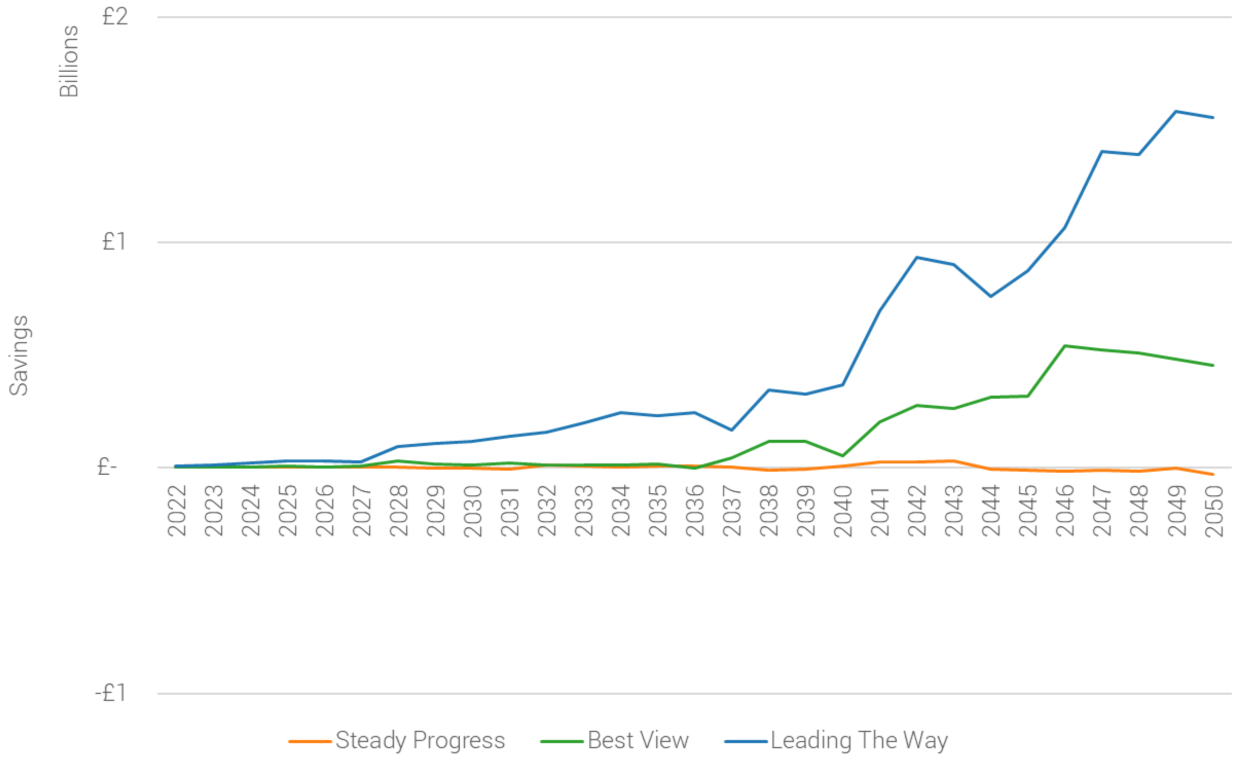


Figure 36: Investment savings in BaU & Novel study compared to BaU study in South West

Table 3 Investment saving across LV network when deploying BaU & Novel technologies compared to BaU technologies alone

	Steady Progress			Best View			Leading the Way		
	BaU	BaU & Novel	% Saving	BaU	BaU & Novel	% Saving	BaU	BaU & Novel	% Saving
East Midlands	£1,438m	£1,016m	29%	£5,200m	£3,376m	35%	£7,101m	£4,593m	35%
West Midlands	£169m	£125m	26%	£764m	£622m	19%	£1,355m	£962m	29%
South Wales	£375m	£291m	21%	£501m	£453m	10%	£587m	£537m	7%
South West	£641m	£668m	-4%[12]	£2,401m	£1,942m	19%	£4,460m	£2,905m	35%

[12] Cost difference between BaU and BaU plus Novel technologies hovers above and below 0% for South West region, in 2049 for example, BaU plus novel offers a 0.1% saving over BaU solutions only. The value of savings offered by deferral of investment in BaU technologies with novel technologies and the additional cost of novel technologies deployed as temporary solutions is closely matched in this instance. In all other licence areas and scenarios, novel technologies offer a clear cost saving.

6. Conclusions, Recommendations and Next Steps

6.1 Conclusions

The analysis conducted for this report has provided a good understanding of the likely best value approaches for resolving particular constraint types:

- For feeders witnessing thermal conductor constraints, the typical first step is to deploy network data monitoring. This provides visibility, allowing operation closer to asset limits and allowing the network operator to make an informed decision whether further action is required. If further action is unavoidable, the constraint is typically best solved through reducing load on the feeder by for example splitting the feeder, or where practicable permanent meshing.
- For thermal transformer constraints in urban areas typically supplied by GMTs, a variety of novel solutions are available to resolve these. The specific solution deployed is highly sensitive to LCT uptake rates. For those with high levels of LCT uptake, novel solutions are viable but may only be able to defer for a limited period until larger GMTs are required, though allowing time to more closely monitor the load growth.
- For rural overhead feeders, larger PMTs are seen as the most viable solution to resolve thermal transformer constraints. High levels of LCT uptake drive high levels of load growth, requiring significant additional capacity and generally the novel solutions have not been able to provide this more cost effectively than installing larger PMTs.

The following conclusions can be drawn from the detailed analysis carried out in the production of this report and highlight the learning established in this phase of the SILVERSMITH study.

C1. Similar solutions are selected to be deployed across all four of National Grid's electricity distribution licence areas. The proportion of solution deployment is sensitive to the LCT uptake rates on each licence's area feeder set. The solutions chosen by network planners should be based on the network constraint type and extent of constraint witnessed on the specific feeder.

C2. The number and types of distinct solutions required across National's Grid network is independent of the scenario. Regardless of the actual LCT uptake rate, the distinct solutions will be utilised for particular feeders due to the variability in clustering of LCT deployments. Network planners do not need to be concerned about the uptake rate of LCT across the system, instead they should focus on the constraint type and extent caused by LCTs on each individual feeder.

C3. To defer network reinforcement for a 5-year period from time of first network constraint, between 0.7kW and 2.1kW per customer are required depending upon the network archetype.

C4. Both smart transformers and OLTCs offer a potential option to improve voltage management and increase headroom for PV export with the preferred option being dependant on the granularity of control. Statcoms offer some potential, particularly to individual voltage constrained feeders with some spare thermal capacity, with greatest benefit being realised when they can be located at remote end of feeders.

C5. Network meshing is an effective solution to increase thermal capacity but consideration around fault levels and protection systems is required on a case-by-case basis. Difficulties associated with retrofitting network meshing to existing networks mean this solution is unlikely to be suitable for wide scale roll out, however it could be valuable for specific cases.

C6. Novel solutions offer savings over BaU costs through deferral of investment. Sensitivity studies show that these savings are robust against variations in network topology and LCT uptake rates.

6.2 Recommendations

The following recommendations are made based on the analysis carried out and documented in this report.

R1. Review data from flexible interventions as flexibility markets develop, to consider how cost effective flexible solutions could be for resolving network constraints.

R2. Development of innovative technologies that could offer between 20% and 80% thermal transformer capacity at less than £16,000 per feeder (for underground feeders supplied by GMTs) or £7,500 per feeder (for overhead feeders supplied by PMTs) would offer significant value to the network operator and reduce unnecessary capacity overprocurement.

R3. To effectively manage LV customer voltages using novel solutions, some form of monitoring of feeder voltages through smart meters or network monitoring and feedback loop to establish target set-points will be needed.

R4. Innovative technology offering significant thermal cable capacity release suitable for retrofit across all feeders, would offer significant value to the network operator.

6.3 Next Steps

The final stage of this project is the production of a Technology Witnessing Report. This report will summarise the technologies studied over the course of the SILVERSMITH project, categorising them as either technologies that meet or exceed the functional requirements and that offer the network operator value today or as technologies currently unable to provide the specification required to be of value to the network operator. The report will issue final recommendations to the network operator including which technologies offering immediate value to the network operator should be progressed to trial stage or network deployment. Additionally, the requirements of any gaps where technologies currently do not exist but would offer value to the network operator in controlling the LV network. Finally, the report will consider where changes to either regulatory or commercial models may be required to enable the use of innovative technologies, including mentioning the role flexibility (not considered throughout this project) could have in controlling the LV network. The report will acts to summarise the findings from the course of the SILVERSMITH project and provide a clear and concise summary of key conclusions and recommendations for National Grid to consider.

7. References

[1] S. Lindmark and T. Stone, “EA16141-TR2 SILVERSMITH Literature Review,” 2022.

[2] T. Stone, “EA16141-TR1 SILVERSMITH Network Study Results,” 2022.

[3] National Grid, “National Grid,” 2021. [Online]. Available: https://www.nationalgrid.co.uk/distribution-future-energy-scenarios-application. [Accessed 16 11 2022].

[4] T. Stone and K. Gebremichael, “EA16141-TR4 SILVERSMITH Functional Requirements Report,” 2022.

[5] A. Bower and T. Stone, “EA16141-TR5 SILVERSMITH - Load flow analysis of novel solutions,” 2023.

[6] A. Bower, “EA16141-TR5 SILVERSMITH - Load flow analysis of novel solutions,” 2023.

Appendix I Interactive Sankey Diagrams

Figure 1 to Figure 12 in this report are static images of interactive html plots. To allow the reader to explore the data further, the interactive plots are uploaded online and can be accessed via the following link: Sankey Diagrams

Table AI.1 Summary Table of Sankey Diagrams online uploads

License Area	DFES Scenario	Filename
East Midlands	Best View	EastMids-BV_Sankey.html
East Midlands	Steady Progress	EastMids-SP_Sankey.html
East Midlands	Leading the Way	EastMids-LtW_Sankey.html
South Wales	Best View	SouthWales-BV_Sankey.html
South Wales	Steady Progress	SouthWales-SP_Sankey.html
South Wales	Leading the Way	SouthWales-LtW_Sankey.html
South West	Best View	SouthWest-BV_Sankey.html
South West	Steady Progress	SouthWest-SP_Sankey.html
South West	Leading the Way	SouthWest-LtW_Sankey.html
West Midlands	Best View	WestMids-BV_Sankey.html
West Midlands	Steady Progress	WestMids-SP_Sankey.html
West Midlands	Leading the Way	WestMids-LtW_Sankey.html

Appendix II Flow Charts for Network Planners

Great Britain is undergoing a transition to renewable and distributed energy. Many energy customers are becoming more involved in the energy system, transitioning from simply being electricity consumers to electricity prosumers. This is being led through the electrification of transport (i.e. electric vehicles) and heating (i.e. heat pumps) along with the continued growth in distributed generation, most commonly solar photovoltaics (PV). Low Carbon Technologies (LCTs) such as Electric Vehicles (EVs) and heat pumps are forecast to witness vast uptake rates over the next few decades. The combined effect of these technologies will have a profound effect on the electricity network. Large numbers of these technologies will be deployed on the Low Voltage (LV) networks, which will place significant additional demand on it, in many cases beyond which the network was designed for. National Grid[13] manage the LV network across their licence areas in the East Midlands, West Midlands, South West, and South Wales, and have commissioned the SILVERSMITH study to help increase their understanding of the challenges and opportunities for new technologies across their LV network.

As National Grid transitions towards management of an active LV network, this must be achieved in a manner which enables customers to install LCTs at the foreseeable uptake rates. This has to be achieved while minimising costs to consumers resulting from network augmentation but continuing to provide a safe and reliable supply of electricity. Additionally, network management should be fair to all electricity consumers, regardless of whether they own LCTs or not. It is therefore important to maximise value extracted. The SILVERSMITH study was commissioned to identify novel technologies that may assist National Grid manage their LV network, identify the network constraint forecast for National Grid's LV network, and to perform a Cost Benefit Analysis to identify those technologies which offer value to National Grid in managing their LV network.

A Literature Review [1], which included an RfI process, was conducted to identify technologies with the potential to offer value in assisting National Grid to manage their LV network. The Network Study report [2] identified the types of constraint forecast across National Grid's four licence areas. The Functional Requirements report [4] presented the results of a Cost Benefit Analysis to determine which solutions were most cost effective at resolving network constraint that arise. The main body of this report links the network constraints to the solutions applied to resolve them. Linking constraints types to the most cost effective solutions allows recommendations to be made regarding which novel (and BaU) technologies to consider when resolving network constraints that arise on the LV network.

Using the results from the analysis presented in the main body of this report, flow charts have been produced to help network planners identify novel technologies that they should consider when planning reinforcements to the network. To identify which LV archetype the feeder being considered by the network planner corresponds to, the network planner should consult Figure 37. Once the network archetype has been identified, the planner should consult the relevant flowchart for that particular archetype (from Figure 38 to Figure 41) for that particular archetype in order to identify solutions that may be applicable for that particular network type.

[13] National Grid Electricity Distribution, part of the National Grid group, were previously known as Western Power Distribution and renamed in September 2022.

Identifying LV Network Archetype

The Transform model used throughout the SILVERSMITH project uses 11 representative LV feeder archetypes to represent all feeder across National Grid's four licence areas. The 11 LV feeder archetypes are detailed in Table AII.1 below.

Table AII.1 Description of 11 representative LV feeder archetypes

LV Network Archetype	Description
LV1	Central Business District
LV2	Dense Urban (e.g. Apartments)
LV3	Town Centres
LV4	Business Parks
LV5	Retail Parks
LV6	Sub-Urban Streets
LV7	New Build Housing Estates
LV8	Terraced Housing
LV9	Rural Village (Overhead Construction)
LV10	Rural Village (Underground Construction)
LV11	Rural Farmsteads

Discussion and case studies throughout this report have been made on an LV archetypal basis. When planning LV network upgrades, in order to consider the recommendations of this report, the network planner first has to identify which LV network archetype the particular feeder under consideration most closely resembles. It is inefficient to accurately model individual LV feeder types, so the network planner should identify the closest match. Figure 37 is provided to assist the network planner in identification of the LV network archetype each feeder corresponds to.

Once the network archetype has identified, the network planner can utilise the flowcharts in Figure 38 to Figure 41, which provide recommendations concerning which technologies should be considered.

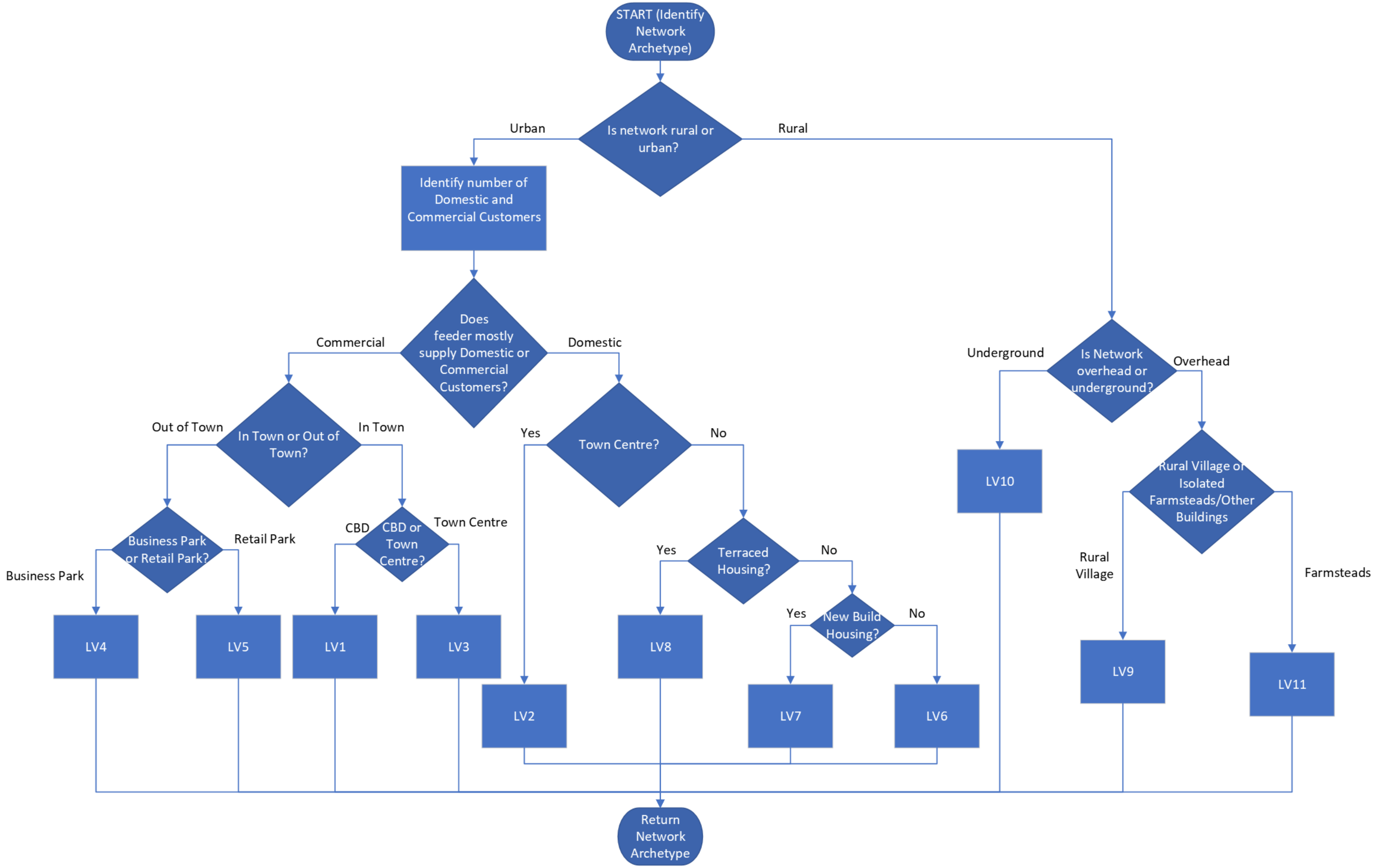


Figure 37: Flowchart for identification of network archetype

Identifying Solutions Based on LV Network Archetype

Once the network archetype has been identified, the following flowcharts aid the network planner to identify which type of novel solution they should consider for that network. The LV network archetypes have been grouped into four distinct groups based on those LV network archetypes that encounter similar constraints and thus require similar solutions sets. In many cases solutions deployed to resolve particular network constraints are highly sensitive to the level of LCT deployment and the optimum solution set will vary from feeder to feeder. For this reason, solutions are often grouped in the flowcharts below, solutions mentioned in the flowcharts should be seen as suggested solutions rather than prescriptive. In some cases a single solution from a set of grouped solutions may be required, in other cases a combination of solutions may be required to resolve the network constraint.

Table AII.2 summarises four flowcharts (Figure 38 to Figure 41) that have been produced to help network planners identify suitable solutions for different type of LV network. The flow charts that have been produced are primarily based upon the Transform analysis, since this provided a cost benefit analysis to select the technologies to deploy to the LV network which solve constraints at the lowest cost to the network operator. However, the Transform methodology considered only voltage and thermal constraints. Other technical parameters such as fault level, power quality and operability need to be considered when planning network upgrades, for example by using load flow analysis software such as PowerFactory. The flowcharts recognise that these additional constraint types should be considered, but are unable to provide details as to which technologies should be deployed when non thermal or voltage limits occur, since the selection methodology is highly specific to the individual network feeder and location.

Table AII.2 Description of Flowcharts

Figure	LV Network Archetypes	Description
Figure 38	LV1 (Central Business Districts) LV3 (Town Centres) LV4 (Business Parks) LV5 (Retail Parks)	Urban feeders with high proportion of commercial customers
Figure 39	LV2 (Dense Urban (e.g. Apartments)) LV6 (Sub-Urban Streets) LV7 (New Build Housing Estates) LV8 (Terraced Housing)	Urban and Sub-Urban feeder with high proportions of domestic customers
Figure 40	LV9 (Rural Village (Overhead Construction)) LV11 (Rural Farmsteads)	Overhead rural feeders
Figure 41	LV10 (Rural Village (Underground Construction))	Underground rural feeders

The network planners should consider that although solutions in the flowchart may be repeated under different branches, it may be impracticable to install duplicate identical solutions on a single feeder. The flowcharts are also non-exhaustive and non-prescriptive, other emerging solutions may offer better value solutions for specific feeders; this analysis has been conducted on representative archetypes where tipping points are often finely balanced. Ultimately, these flowcharts are simply guidance that the network planner is free to use or ignore; the constraints and challenges facing each individual feeder should be carefully considered before implementing solutions.

Flexibility

National Grid's RIIO-ED2 business plan, in common with other GB network operators, identifies flexibility services as a key method for managing their networks in the most cost effective manner for consumers. Flexibility can be provided by a wide range of technologies such as:

- Managed EV Charging
- Battery Energy Storage Systems (BESS)
- Commercial and domestic Demand Side Response (DSR)
- Vehicle to Grid (V2G)

Flexible solutions were excluded from the Transform analysis conducted for this project due to uncertainties in the availability of flexibility and the required price to procure it. This project focuses on understanding the counterfactual to flexibility, namely network operators reinforcing the network to resolve constraints as they occur. Therefore, this project focuses on technological solutions that comprise of assets that the network operator owns and operates.

However, flexibility remains an important option for manging the LV network. Should flexibility solutions offer an alternative method of managing the LV network at a lower cost than the technological solutions, flexibility should be strongly considered in the first instance. As the flexibility markets develop, a clearer picture will emerge of capacity available from flexibility, the willingness of consumers to engage, and the cost of procuring services. The amount of flexibility required to defer investment in costly network reinforcement, or in some cases use as an enduring solution instead of network reinforcement, has been considered in section 4.2 of this report.

In the following flow charts, flexible solutions are frequently recommended as potential solutions to resolve constraints, if they are cost effective. For a flexible solution to be cost effective, the annual cost of flexibility procurement must total less than the annualised totex cost for deploying and maintaining any technological solution or set of solutions that would otherwise be selected to resolve the network constraint. In many cases flexibility may be a viable option to cost-effectively defer investment in technological solutions until a later date. The assumed totex costs for BaU and novel technologies can be found in Appendix III and Appendix IV respectively. Flexibility may also be considered in times of resource constraint as it can offer a fast method for resolving network constraint until resource becomes available to deploy a suitable technological intervention.

LV1 (Central Business Districts), LV3 (Town Centres), LV4 (Business Parks) and LV5 (Retail Parks)

Flexibility can also be considered in conjunction with technological solutions. When considering solutions to deploy, network designers should consider whether combining flexibility services with a technological solution could lead to a more cost effective overall method for resolving the network constraints.

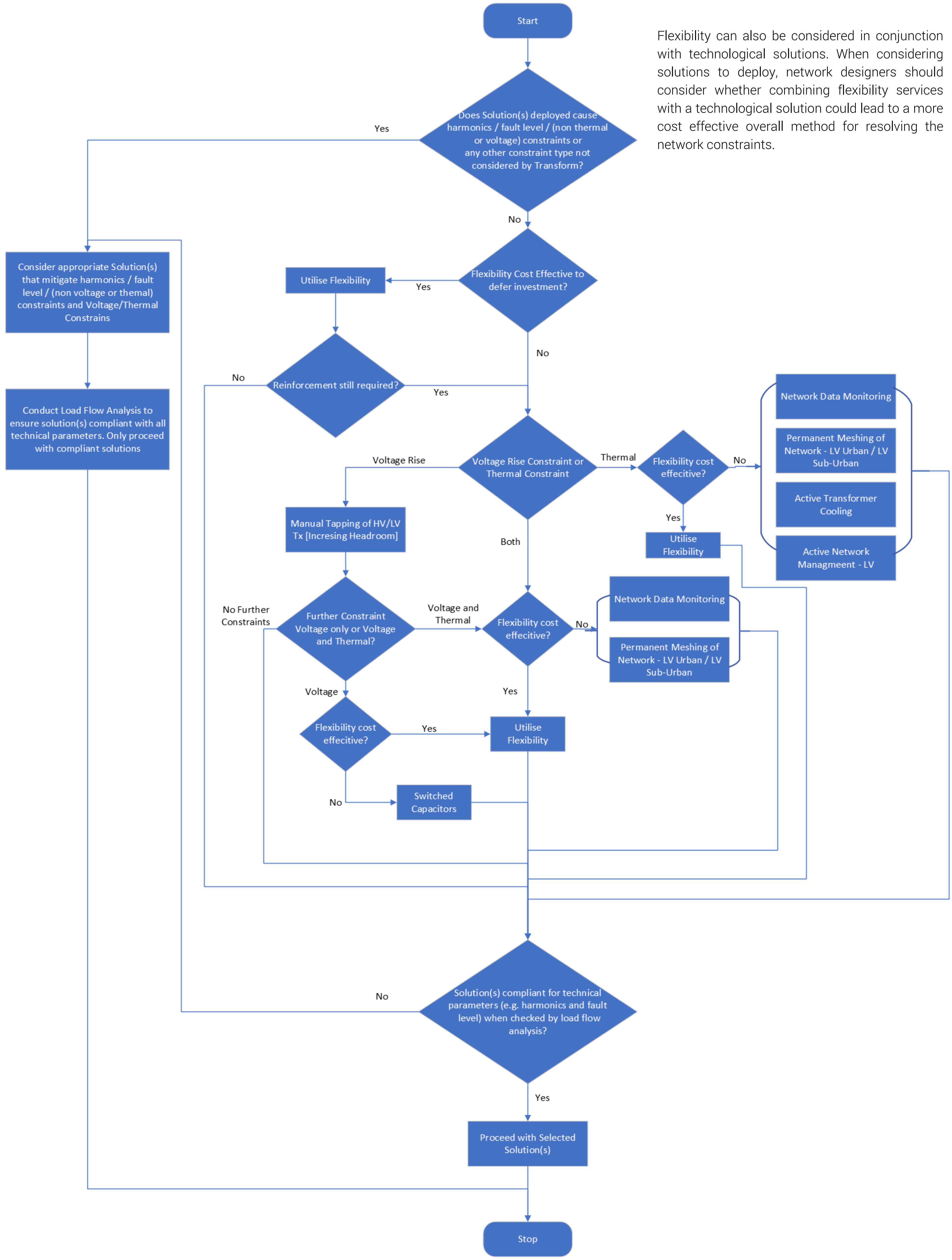
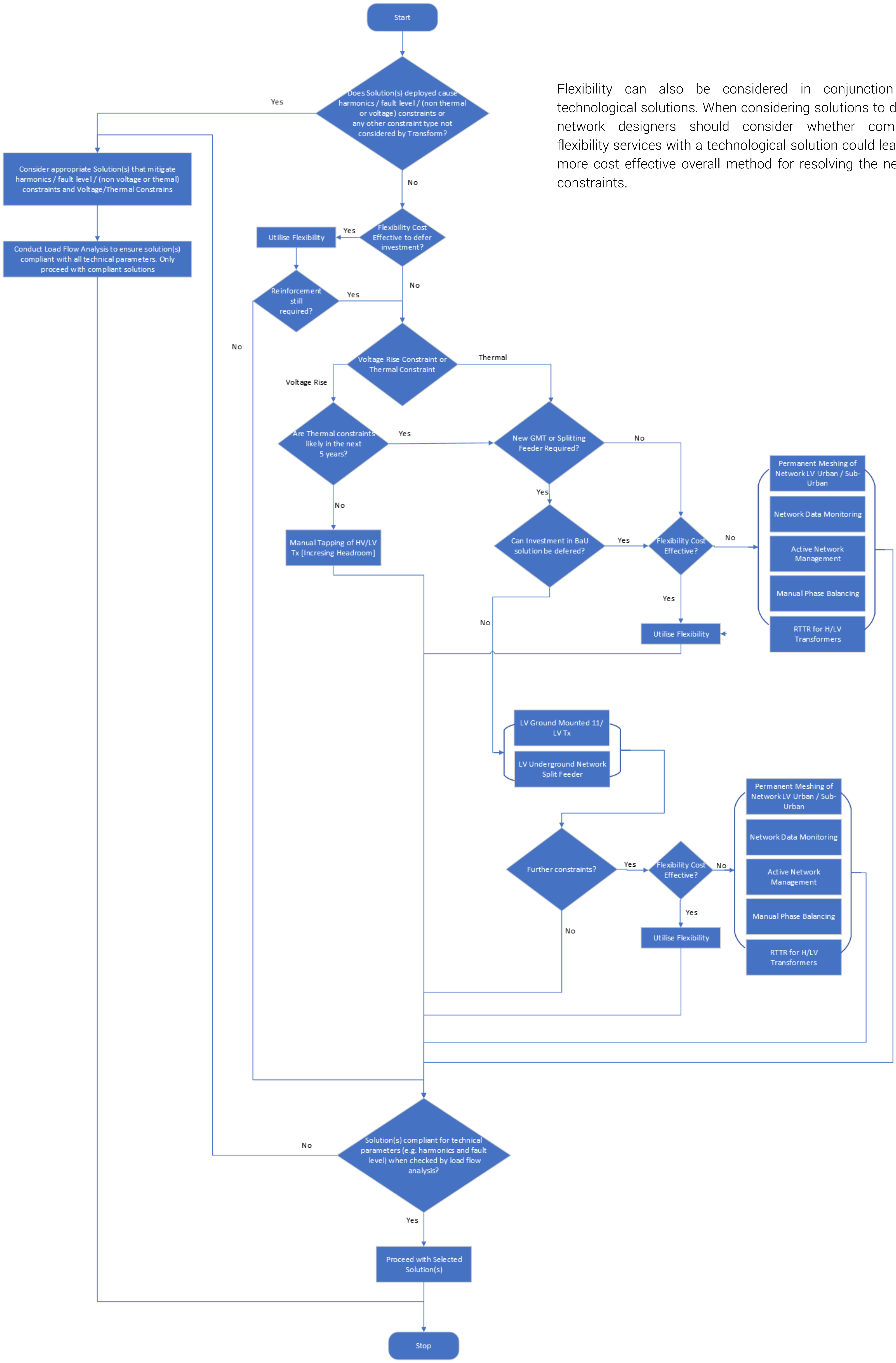


Figure 38: Flowchart for identification of potential suitable solutions for LV1, LV3, LV4 and LV5

LV2 (Dense Urban), LV6 (Sub-Urban Streets), LV7 (New Build Housing Estates) and LV8 (Terraced Streets)



Flexibility can also be considered in conjunction with technological solutions. When considering solutions to deploy, network designers should consider whether combining flexibility services with a technological solution could lead to a more cost effective overall method for resolving the network constraints.

Figure 39: Flowchart for identification of potential suitable solutions for LV2, LV6, LV7 and LV8

LV9 (Rural Villages Overhead construction) and LV11 (Rural Farmsteads)

Flexibility can also be considered in conjunction with technological solutions. When considering solutions to deploy, network designers should consider whether combining flexibility services with a technological solution could lead to a more cost effective overall method for resolving the network constraints.

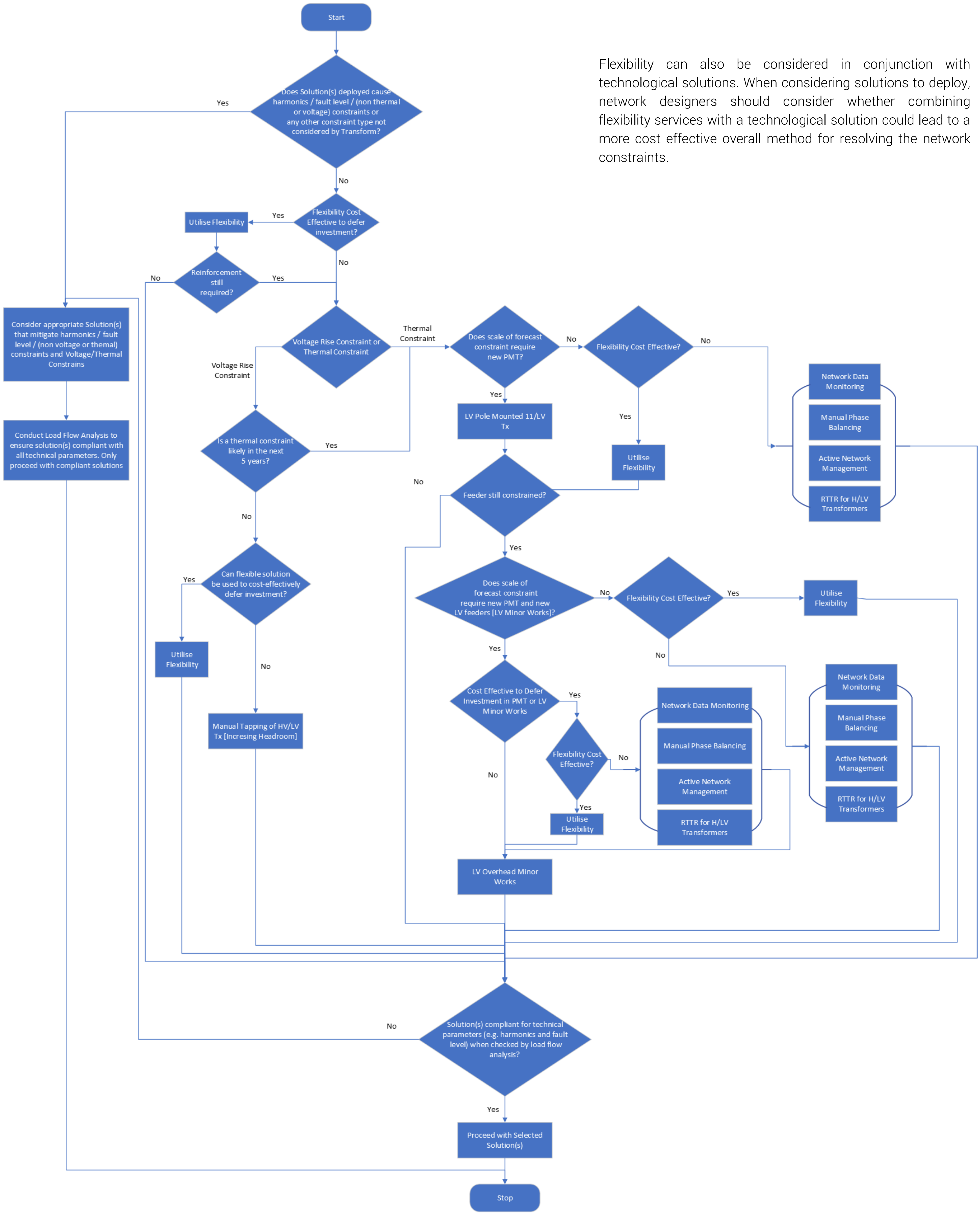
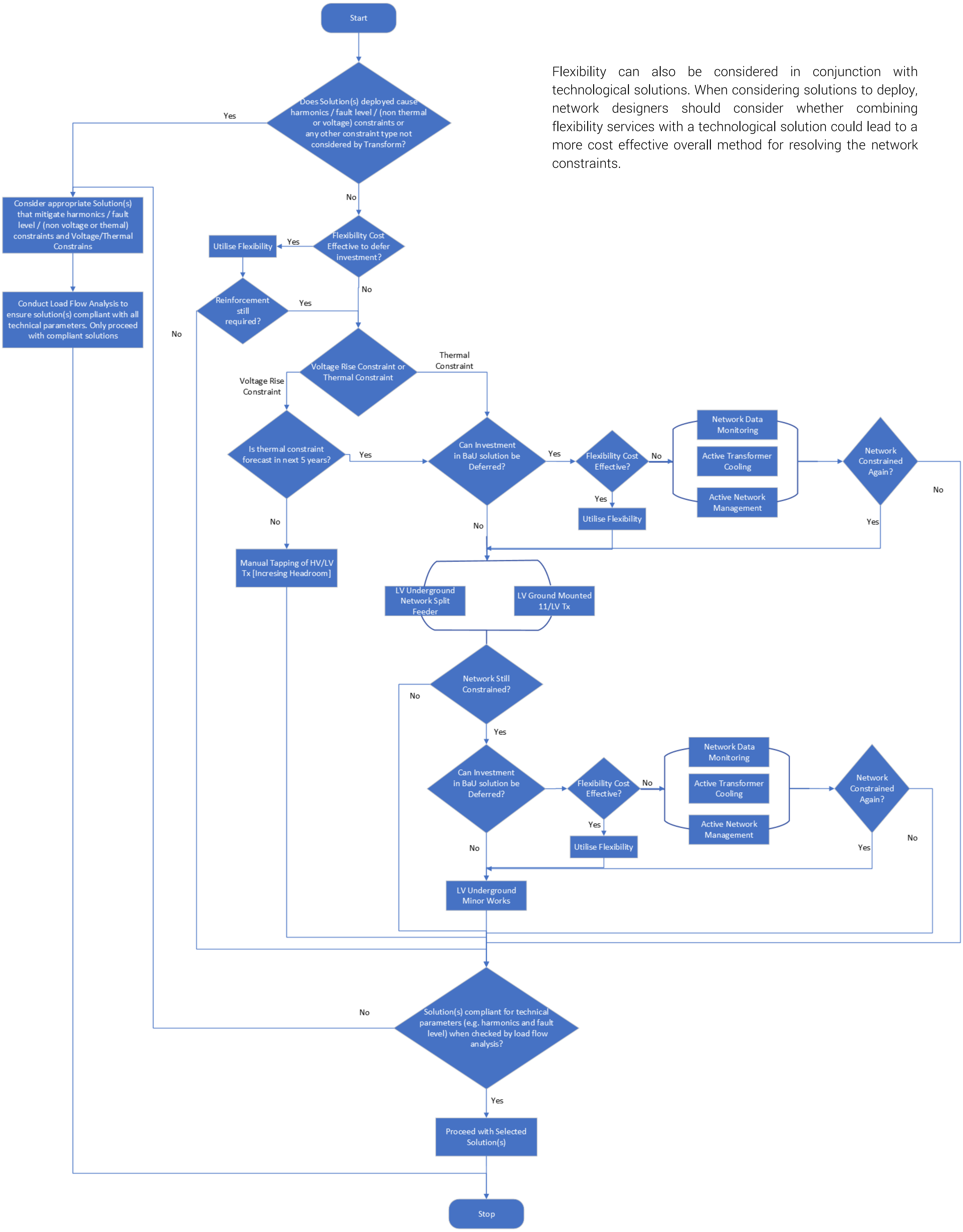


Figure 40: Flowchart for identification of potential suitable solutions for LV9 and LV11

LV10 (Rural Village Underground construction)



Flexibility can also be considered in conjunction with technological solutions. When considering solutions to deploy, network designers should consider whether combining flexibility services with a technological solution could lead to a more cost effective overall method for resolving the network constraints.

Figure 41: Flowchart for identification of potential suitable solutions for LV10

Appendix III Business as Usual Solutions

Headroom releases and costs associated with BaU solutions were agreed by GB network operators during development of the Transform model. These costs have been adjusted for inflation and were agreed by National Grid and EA Technology during the analysis for the Functional Requirements report [4].

Table AIII.1 Business as Usual solutions utilised within the Transform model in the BaU and BaU plus Novel studies.

Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
LV Underground network Split feeder†	Cost based on an assumed average length of 300m for LV underground circuit; therefore 150m of LV cable required, plus some jointing	£39,986	£400	£53,880	45	0%	100%	1%	3%
LV New Split feeder†	Cost based on an assumed average length of 300m for LV underground circuit; therefore 150m of LV cable required, plus some additional crossjointing to allow for the fact that this is the second splitting of the feeder	£43,985	£440	£59,268	45	0%	80%	1%	2%
LV Ground mounted 11/LV Tx†	This cost is based on the cost of a new distribution transformer, split across the average number of LV feeders supplied by that transformer	£13,505	£46	£15,987	45	80%	0%	1%	6%

Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
LV underground Minor works†	The cost is composed of a new ground mounted distribution transformer, 100m of HV cable to supply the new transformer and associated jointing to connect this to the network; 600m of new LV cable to supply two new circuits at an average length of 300m each.	£133,288	£1,333	£179,599	45	100%	100%	1%	10%
LV underground Major works†	The cost is composed of two new ground mounted distribution transformers, 400m of HV cable to supply the new transformers and associated jointing to connect these to the network; 1.8km of new LV cable to supply six new circuits at an average length of 300m each.	£333,220	£3,332	£448,997	45	500%	500%	1%	15%
LV overhead network Split feeder†	Cost based on an assumed average length of 500m for LV overhead circuit; therefore 250m of LV conductor required	£13,329	£133	£17,960	45	0%	100%	1%	3%
LV overhead network New Split feeder†	Cost based on an assumed average length of 500m for LV overhead circuit; therefore 250m of LV conductor required plus some additional cost for	£14,662	£147	£19,756	45	0%	80%	1%	2%

Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
	connecting the new split feeder into the existing network								
LV Pole mounted 11/LV Tx†	This cost is based on the cost of a new distribution transformer, split across the average number of LV feeders supplied by that transformer	£5,892	£40	£7,470	45	80%	0%	1%	6%
LV overhead Minor works†	The cost is composed of a new pole mounted distribution transformer, 100m of HV conductor to supply the new transformer and associated jointing to connect this to the network; 800m of new LV conductor to supply two new circuits at an average length of 400m each.	£26,658	£267	£35,920	45	100%	100%	1%	10%
LV overhead Major works†	The cost is composed of two new pole mounted distribution transformers, 1km of HV cable to supply the new transformers and associated jointing to connect these to the network; 1.8km of new LV conductor to supply six new circuits at an average length of 300m each.	£166,610	£1,666	£224,499	45	500%	500%	1%	15%

Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
Manual phase balancing - LV†	Rebalancing phases by changing which phases customers are connected to	£22,440	£224	£41,232	45	20%	20%	20%	0%
Manual Tapping of HV/LV Tx [increasing headroom] †	Change of tap position to increase voltage headroom	£1,200	£50	£2,495	40	0%	0%	2.5%	-2.5%
Manual Tapping of HV/LV Tx [increasing legroom] †	Change of tap position to increase voltage legroom	£1,200	£50	£2,495	40	0%	0%	-2.5%	2.5%

Appendix IV Novel Solutions

In July 2022, a Request for Information process was conducted where providers of novel technologies were asked for information regarding their technologies, including the expected capacity release, capex and opex costs and expected solution lifetime. This information was used as a basis for the modelling. The solutions where the assumed totex costs calculated from capex, opex and lifetimes provided are marked throughout this appendix with an asterisk (*).

The literature review [1] identified additional novel solutions that the network operator might consider deploying to increase LV network capacity. Headroom releases and costs associated with these technologies were agreed by GB network operators during development of the Transform model. The same methodology has been applied to cost the BaU solutions. These costs have been adjusted for inflation and were agreed by National Grid and EA Technology during the analysis for the Functional Requirements report [4]. These solutions are marked throughout this appendix with a dagger (†).

Table AIV.1 Novel solutions utilised within the Transform model for the BaU plus Novel study.

Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
Dynamic Network Reconfiguration - LV†	The pro-active movement of LV network split (or open) points to align with the null loading points within the network in real time.	£17,385	£1,739	£56,113	15	5%	10%	3%	5%
Distribution Flexible AC Transmission Systems (D-FACTS) - LV†	Series or shunt connected static power electronics as a means to enhance controllability and increase power transfer capability of the LV network	£40,566	£1,623	£82,716	20	4%	8%	8%	8%
Embedded DC Networks_Embedded DC@LV†	The application of point-to-point LV DC circuits to feed specific loads (used in a similar manner to transmission 'HVDC', but for	£144,878	£5,795	£377,194	30	0%	20%	10%	10%

Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
	distribution voltages). A retrofit solution to existing circuits.								
EAVC - HV/LV Transformer Voltage Control†	As the network starts to operate closer to these limits, DNOs may opt to introduce additional automatic voltage control devices over and above those located at the grid and primary transformers. Together these new and existing voltage control devices will constitute an EAVC system.	£42,057	£0	£54,674	40	0%	0%	9%	7%
EAVC - LV circuit voltage regulators†	As the network starts to operate closer to these limits, DNOs may opt to introduce additional automatic voltage control devices over and above those located at the grid and primary transformers. Together these new and existing voltage control devices will constitute an EAVC system	£104,346	£0	£135,650	20	0%	0%	1%	1%
EAVC - LV PoC voltage regulators†	As the network starts to operate closer to these limits, DNOs may opt to introduce additional automatic	£11,590	£464	£22,009	15	0%	0%	2%	2%

Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
	voltage control devices over and above those located at the grid and primary transformers. Together these new and existing voltage control devices will constitute an EAVC system.								
Generator Constraint Management GSR - LV connected generation†	The use of commercial contracts, underpinned with automated signalling, between a DNO and generation customer(s) to ramp down export under certain network conditions. This variant considers larger generators (e.g. supermarkets, commercial buildings) connected to the LV network - it is not deemed to be a residential solution	£23,181	£2,318	£40,376	5	10%	10%	3%	3%
Generator Providing Network Support e.g. Operating in PV Mode - LV†	Contracting with a larger LV 3-phase connected generator for them to operate their sets in PV (Real power and volts) mode rather than the conventional PQ (Real and Reactive power). The generator will draw VARs from the network at certain times, but	£17,391	£1,739	£30,292	5	10%	10%	3%	3%

Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
	ensure that the voltage on the network is not excessively raised at the point of connection.								
Permanent Meshing of Networks - LV Urban†	Converting the operation of the LV network from a radial feeder (with split points) to a solid mesh configuration.	£23,181	£927	£48,443	45	10%	50%	0%	2%
Permanent Meshing of Networks - LV Sub-Urban†	Converting the operation of the LV network from a radial feeder (with split points) to a solid mesh configuration.	£23,181	£927	£48,443	45	5%	50%	0%	2%
RTTR for H/LV transformers†	The use of measurement and ambient forecasting data to predict the rating (and hence current carrying capacity) of assets in a real-time mode. This variant considers RTTR for Secondary distribution transformers	£17,387	£0	£22,602	15	15%	0%	0%	0%
RTTR for LV Overhead Lines†	The use of measurement and ambient forecasting data to predict the rating (and hence current carrying capacity) of assets in a real-time mode. This variant considers RTTR for LV overhead line circuits.	£3,941	£394	£11,023	15	0%	0%	0%	0%

Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
RTTR for LV Underground Cables†	The use of measurement and ambient forecasting data to predict the rating (and hence current carrying capacity) of assets in a real-time mode. This variant considers RTTR for LV underground cable circuits	£29,172	£0	£37,924	15	0%	5%	0%	0%
Switched capacitors - LV†	LV connected mechanically switched devices as a low cost form of reactive power compensation. They are used for voltage control and network stabilisation under heavy load conditions.	£11,590	£116	£15,094	30	0%	0%	5%	5%
Active Network Management - LV†	Active management of the LV network by controlling e.g. Normally Open Points	£5,795	£580	£18,704	15	10%	10%	3%	3%
Active transformer cooling - LV†	Thermal Tx capacity released via active cooling of Tx via e.g. positive or negative pressure systems	£4,344	£74	£6,756	15	22%	0%	0%	5%
Widening of the design voltage tolerance - LV†	Changing voltage limits from +10% / -6% to +/-10%	£78	£0	£117	60	0%	0%	0%	20%
Smart Tx (Power Electronics)*	Smart Tx technology utilising power electronics	£10,000	£100	£12,267	15	8%	0%	8%	8%

Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
Magnetic Power Flow Controller (Tx)*	Smart Tx technology controlling magnetic flux through transformer	£40,000	£800	£54,135	15	20%	0%	10%	10%
Smart Tx (OLTCs)*	Smart transformer using automatic OLTCs	£6,950	£820	£20,465	20	0%	0%	10%	10%
Network Data Monitoring*	Network data monitoring devices release effective headroom by allowing greater utilisation of existing assets	£2,500	£350	£7,034	10	15%	15%	0%	20%
STATCOMS [PMT]*	Network data monitoring devices release effective headroom by allowing greater utilisation of existing assets. Singular STATCOM for PMT application	£9,000	£700	£24,633	20	5%	10%	15%	15%
STATCOMS [GMT]*	Network data monitoring devices release effective headroom by allowing greater utilisation of existing assets. Two STATCOMs stacked for larger GMT application	£18,000	£700	£36,333	20	5%	10%	15%	15%
Emergency HV / EHV Soln	Emergency solution to ensure Transform runs, only available for HV and EHV feeders not studied in this project	£10	£1	£34	40	1000000%	1000000%	1000000%	1000000%

Safer, Stronger, Smarter Networks

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