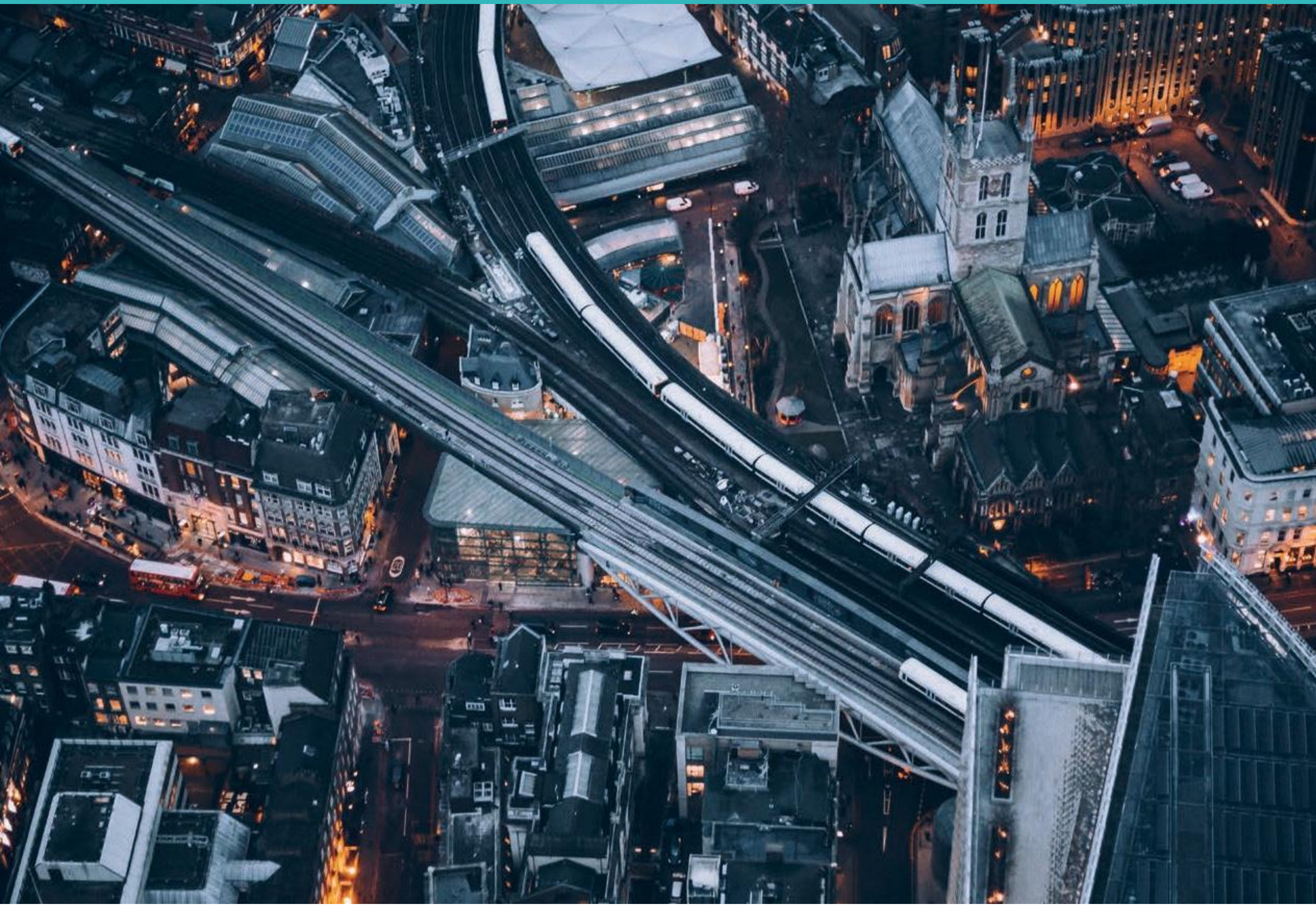

REPORT

SILVERSMITH Functional Requirements

Prepared for: National Grid Electricity Distribution

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EA Technology Limited, Capenhurst Technology Park, Capenhurst, Chester, CH1 6ES;
Tel: 0151 339 4181 Fax: 0151 347 2404

http://www.eatechnology.com

Registered in England number 2566313

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. Utilising the Transform models, analysis in this report focuses on the Business as Usual (BaU) and novel solutions that get deployed in order to resolve the network constraints identified in the EA16141-TR1 SILVERSMITH Network Study Results report, and on what time frame. This is further broken down to report on the BaU and novel solutions that were selected to be specifically deployed on each different LV network archetype.

This study utilises Transform to perform a broad study of the BaU and novel solution deployed across National Grid's electricity distribution network. A similar study utilising PowerFactory has been conducted to provide insight into how specific novel solutions may be utilised to resolve network constraints on three different case study networks. Findings from the PowerFactory study will be presented in a separate report, EA16141–TR5 SILVERSMITH PowerFactory Functional Requirements report. Findings from the two methodologies will be compared in the future EA16141-TR7 Technology Witnessing report that will be produced later in this project.

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

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. Solutions that release voltage rise headroom, and solutions that release thermal (transformer and thermal cable) headroom are required in order to resolve the forecast network constraints across the LV network.

C2. Increasing volumes of solutions are required in later years as more LCTs are connected to the network. Increasingly, solutions that deliver significant headroom release are necessary to keep pace with high levels of LCT installation.

C3. Practicalities of deploying specific solutions should be considered. For example, Manual Phase Balancing is commonly selected by Transform. Practically this could be difficult to implement particularly in the case of underground networks. It is likely to only prove a temporary solution since a small number of further LCTs deployments is likely to leave the feeder unbalanced once more.

C4. Novel technologies offer alternative solutions and get widely deployed in parallel with BaU technologies across all licence areas and scenarios

C5. In total, more solutions are deployed in the BaU plus Novel solution study than in the BaU solution study only. More solution deployments leads to a lower overall totex spend and wider supply chain diversity but may require additional staffing so careful management of resource will be required when deciding which technologies to deploy.

C6. The most commonly deployed novel solutions are (in descending order of prevalence): Network Data Monitoring, Active Network Management, Active Transformer Cooling, Real Time Thermal Ratings (RTTR) for H/LV transformers

C7. Solutions deployed across each licence area are broadly similar regardless of the DFES scenario. Therefore, the network operator can have confidence that regardless of the uptake rate of LCTs, similar types of solutions will be required. (The quantity of solution deployment will depend on the LCT uptake rates).

C8. Variation in technology uptake prevalence deployed in different licence areas shows that the technology deployment is highly sensitive to LCT uptake rate.

C9. Novel solutions provide a saving of BaU costs through the deferral of investment. Sensitivity studies show that these savings are robust across differing LCT uptake rates and network topologies.

Next Steps

Detailed analysis and case studies showing how novel technologies offer value to specific LV network archetypes will be presented in a subsequent report of this project (EA16141 – TR6 LV Voltage Control Selection Methodology). The LV Voltage Control Selection Methodology report will consider how specific novel technologies offer value to specific LV network archetypes, to allow network planners to easily identify the technologies most likely to provide value when resolving network constraints.

Recommendations

The following recommendations are made based on this report.

R1. National Grid should consider whether to perform a similar study considering constraints on and solutions for the HV network in addition to the LV network.

R2. Managing the LV network utilising flexible solutions should be revisited once understanding of flexible solutions including customer engagement and price point has been developed further.

R3. Solutions that release 10-20% thermal headroom at relatively low totex cost may prove highly valuable by allowing the network operator to postpone costlier network interventions. These solutions may be particularly valuable if they can later be redeployed elsewhere on the network. National Grid should continue to monitor novel technologies for any that fulfil these requirements as these could provide significant value to the network operator.

Contents

Appendices

1. Definitions

Term	Definition
BaU	Business As Usual
BESS	Battery Energy Storage Systems
BV	Best View
Capex	Capital Expenditure
DFES	Distribution Future Energy Scenarios
DSR	Demand Side Response
EV	Electric Vehicle
GMT	Ground Mounted Transformer
HV	High Voltage
kW	Kilowatt
LCT	Low Carbon Technology
LtW	Leading the Way
LV	Low Voltage
NG	National Grid
Opex	Operation Expenditure
PMT	Pole Mounted Transformer
PV	Photovoltaics
RfI	Request for Information
RIIO-ED2	Revenue Incentives Innovation Outputs – Electricity Distribution 2
RTTR	Real time thermal ratings
SP	Steady Progress
Totex	Total Expenditure
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 area 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 This Report

The purpose of this report is to identify whether novel technological solutions offer value to National Grid by more cost effectively supporting the forecast of LCTs across the LV network. Building from analysis conducted for the Network Study Results report which identified the types of constraints encountered on the network, to understand the necessary quantities of thermal and voltage headroom release, analysis was conducted utilising

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

artificial solutions in the Transform model each releasing differing quantities of a single type of headroom (e.g. voltage rise, thermal cable, thermal transformer). This allowed the necessary levels of each type of headroom release to be identified.

Following this, a counterfactual study utilising an agreed set of traditional solutions, together with their associated parameters (such as Capex and Opex costs and headroom releases) was performed as a baseline. To understand which novel technological solutions offer value to the network operator, analysis from another study utilising a set of novel technological solutions, in addition to the traditional solutions has been conducted. Comparison with the baseline has allowed identification of novel technologies that offer value to National Grid by cost effectively supporting the forecast LCT uptake rates on the LV network. This study has focussed solely on managing the LV network; it has made no consideration for the effect of the forecast uptake of LCTs on the HV network.

R1. National Grid should consider whether to perform a similar study considering constraints on and solutions for the HV network in addition to the LV network.

3. Transform Analysis

The reader is referred to section 3.4 of the Network Study Results report which gives an introduction to Transform, the parametric model of the electricity networks utilised in this study [2]. The reader is also referred to section 3.5 of the Network Study Results report which explains how the Transform models were validated to ensure that they were representative of National Grid's four electricity distribution licence areas.

The analysis conducted for this report has considered three possible future scenarios, taken from National Grid's Distribution Future Energy Scenarios (DFES). The three scenarios considered are:

1. Best View
2. Steady Progress
3. Leading the Way

Each of the three scenarios represent possible future pathways of LCT deployments across National Grid's four licence areas. Best View is considered the most likely scenario, and can be considered therefore as the central scenario. Steady Progress reflects a scenario with slower progress towards Net Zero and thus has slower uptake rates of LCTs. Leading the Way reflects a scenario with faster progress towards Net Zero and has higher uptake rates of LCTs.

The Network Study Results report performed analysis using the Transform model to identify network constraints encountered across National Grid's LV networks. Through detailed analysis of the Transform 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 is hit due to further deployment of LCTs, which requires 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 findings from the constraints analysis is presented in the Network Study Results report, to which the reader is referred to for more detail.

Whereas the Network Study Results report focussed on the network constraints, this report focusses instead on analysis using the Transform model to identify the solutions that resolve those constraints, including identification of novel technologies that may offer high value in helping National Grid manage their LV network in the most cost effective manner.

The Transform model resolves network constraints as they arise by selecting the most cost effective solution or set of solutions to resolve the network constraint in that year and any further constraints that occur in the following 5 year time period[3]. Constraints may be resolved with a single solution or may require multiple solutions. If after the 5 year time period has elapsed another constraint is encountered, Transform is required to deploy another solution or set of solutions. Therefore, any given feeder in the Transform analysis may be subject multiple solutions over the course of the modelled time period (2023 to 2050).

Due to the combined effect of multiple solutions being deployed on feeders when a given constraint occurs, and repeated interventions being required at different points as new constraints are encountered, the figures in this report sometimes suggest network intervention penetration in excess of 100%. This does not mean all feeders require intervention, but rather that multiple interventions are required on many feeders, whereas other feeders may require no interventions at all.

[3] This 5 year time period is selected to reflect regulatory periods and avoid making assessments based on perfect foresight over the complete analysis period.

4. Functional Requirements

To investigate the level of headroom release required on National Grid's electricity distribution networks, a study was conducted utilising a set of artificial solutions instead of real solutions. Each solution in the artificial solutions releases a set quantity of a single type of headroom release. The artificial solution set (limited in resolution by the number of solutions available in the Transform model) contained 10 voltage headroom solutions, 8 voltage legroom solutions, 20 thermal cable solutions, 20 thermal transformer solution. The artificial solution set is listed in Appendix IV with their associated headroom releases.

The artificial solutions were introduced to assess the amount of headroom required to be released in each year to resolve the network constraint. To do this, Transform was configured to solve network constraints on a 1 year basis, and solutions were set to have a lifetime of a single year such that they expire every year. Solutions of the same type were set to be incompatible with one another such that only a single solution could be deployed to resolve each type of network constraint. Solutions were priced such that the solutions releasing the least headroom were cheapest and the solutions releasing the most headroom most expensive. As such in each year Transform deployed the solution that released the least amount of headroom in order to resolve the constraint(s). This allowed analysis to be conducted to assess the level of headroom release required in order to resolve the network constraints.

4.1 Technical Requirements

4.1.1 Best View Time Progression

Figure 1 shows the artificial solutions deployed for each licence area under the Best View scenario in the years 2028, 2033, 2040 and 2050. It shows that the prevalence of solution deployment increases as time progresses. This statement is true of solutions that release voltage headroom (marked by bars with a diamond pattern), solutions that release thermal transformer headroom (marked by bars with a solid colour), and solutions that release thermal cable headroom (marked by bars with a diagonal pattern). These conclusions also apply to the Steady Progress and the Leading the Way scenarios (for brevity these plots are omitted from this report).

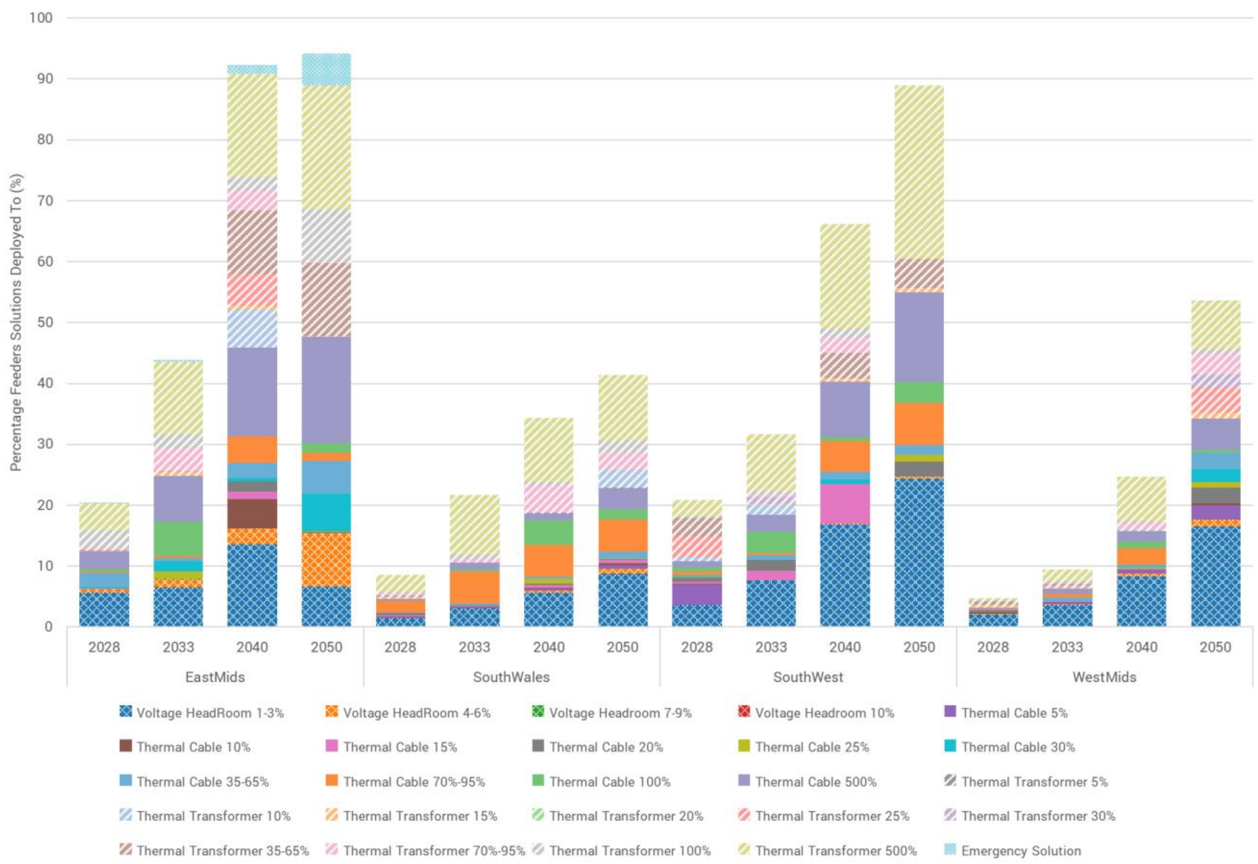

Figure 1: Artificial Solutions deployed in the Best View scenario in 2028, 2033, 2040 and 2050 by licence area

4.1.2 Scenario analysis

Increasing volumes of solutions are required in later years as more LCTs are connected to the network. Increasingly, solutions that deliver significant headroom release are necessary to keep pace with high levels of LCT installation.

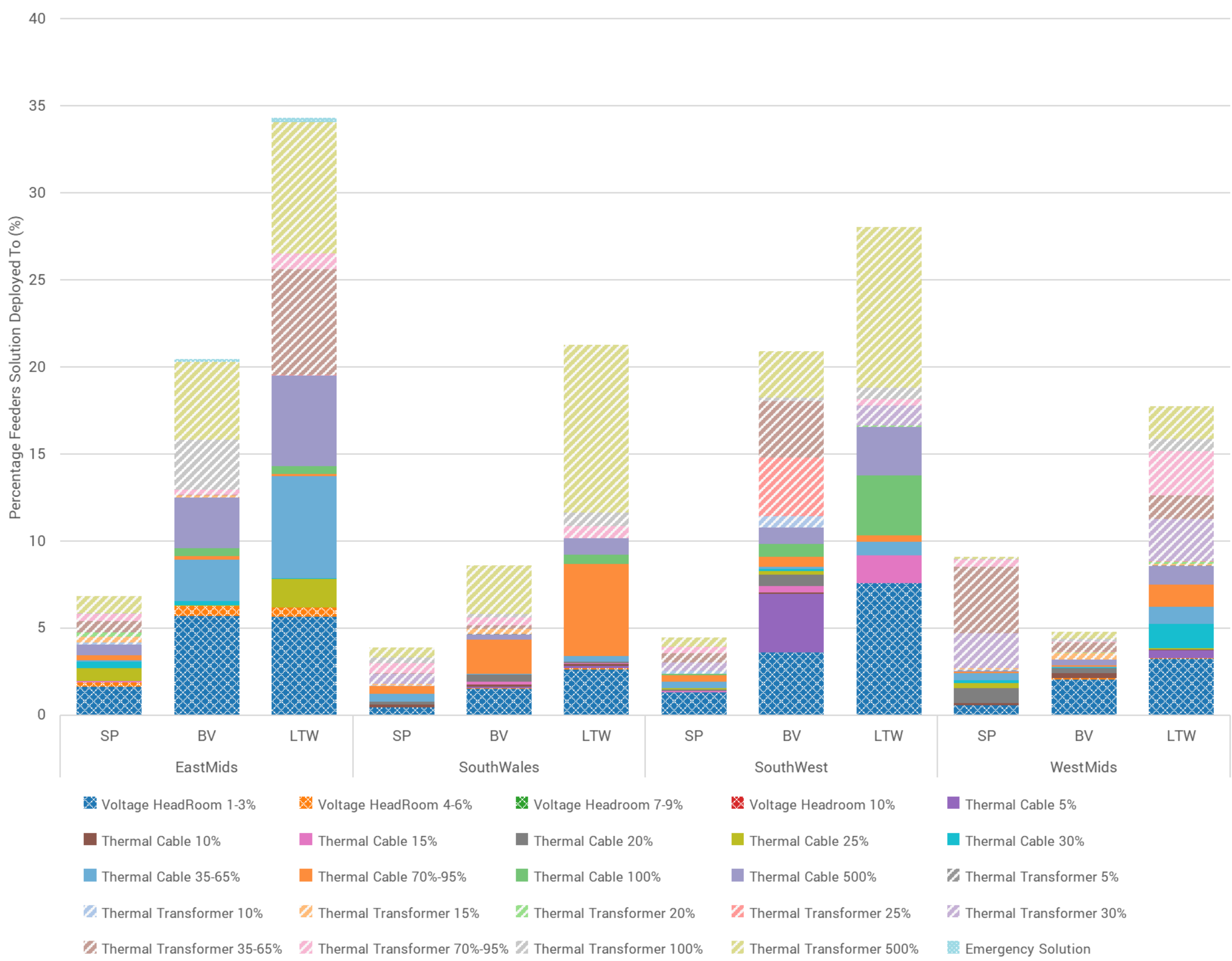

Figure 2 to Figure 5 show the artificial solutions deployed across National Grid's four licence areas in the years 2028, 2033, 2040 and 2050 respectively. Consistent with the finding from Figure 1 that more solutions are required in later years, Figure 2 to Figure 5 also show that in later years more solutions are required for all three scenarios. This is due to the growing levels of LCT deployment that occurs as time progresses.

For all licence areas, the following patterns occur:

- For every year, as expected more solutions are deployed in scenarios with aggressive uptake rates of LCTs (the most aggressive scenario Leading the Way has the most solutions deployed, whereas the least aggressive scenario Steady Progress has the least solutions deployed). The additional PV deployment in Leading the Way compared to Steady Progress is responsible for the higher number of voltage constraints which occur due to voltage rise under net export conditions. The additional heat pump and EV uptake drives higher thermal constraints.
- Solutions that release higher levels of headroom release are deployed more prevalently in more aggressive uptake scenarios, whereas solutions which release less headroom tend to make up a smaller proportion of the total solutions deployed in Steady Progress and Best View compared to Leading the Way. The higher uptake rates of LCTs results in more LCTs being deployed to each feeder. The higher levels of LCT uptake result in more LCTs being deployed on all feeders. The feeders with the most densely clustered LCTs require solutions that release significant amounts of headroom to resolve the network constraints that occur.
- Each scenario and licence area requires voltage headroom (represented by bars with diamonds patterns), thermal cable headroom (represented by solid bars) and thermal transformer headroom capacity release (represented by bars with diagonal pattern).

C1. Solutions that release voltage rise headroom, and solutions that release thermal (transformer and thermal cable) headroom are required in order to resolve the forecast network constraints across the LV network.

C2. Increasing volumes of solutions are required in later years as more LCTs are connected to the network. Increasingly, solutions that deliver significant headroom release are necessary to keep pace with high levels of LCT installation.

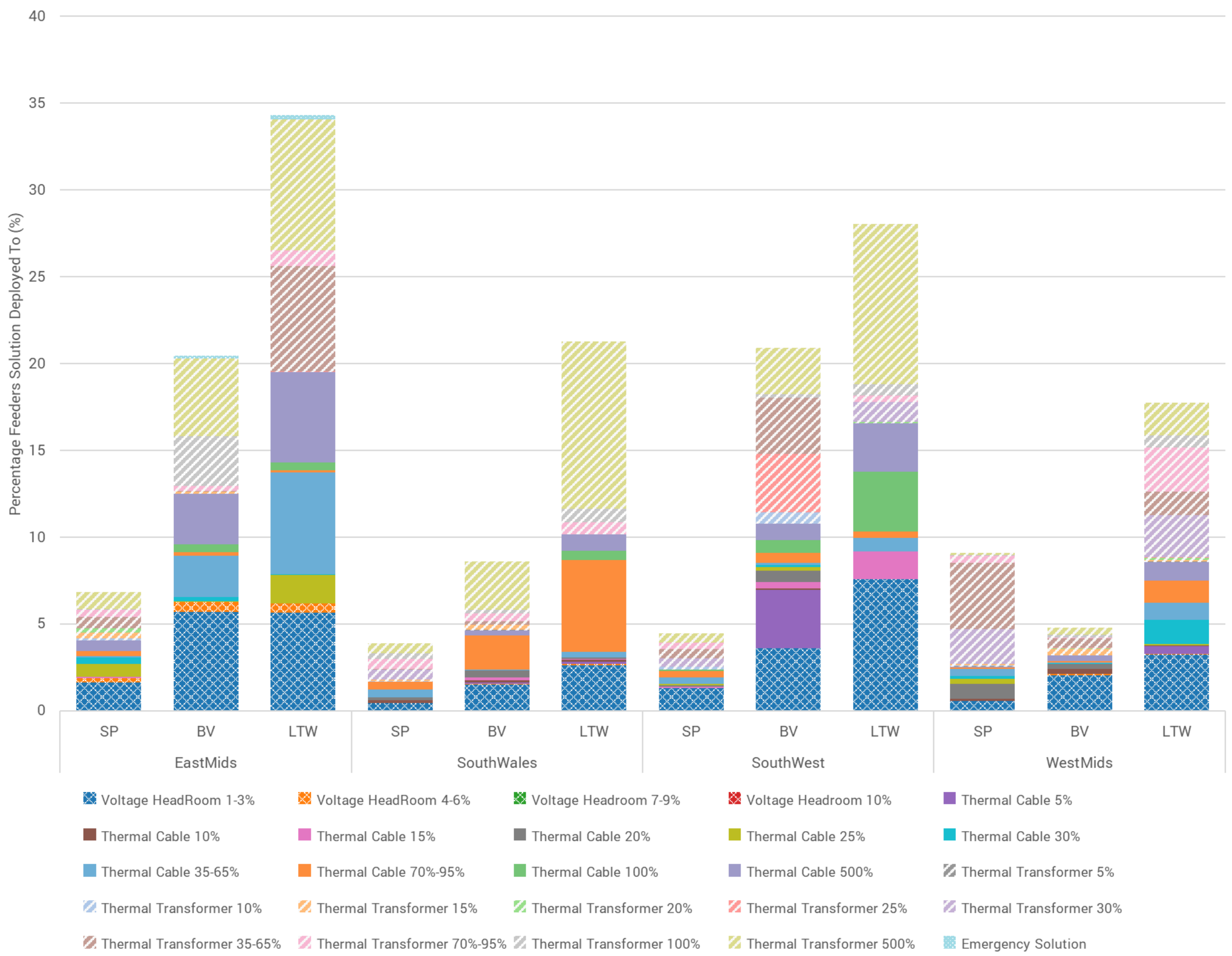

Figure 2: Solutions deployed in 2028 for each DFES scenario.

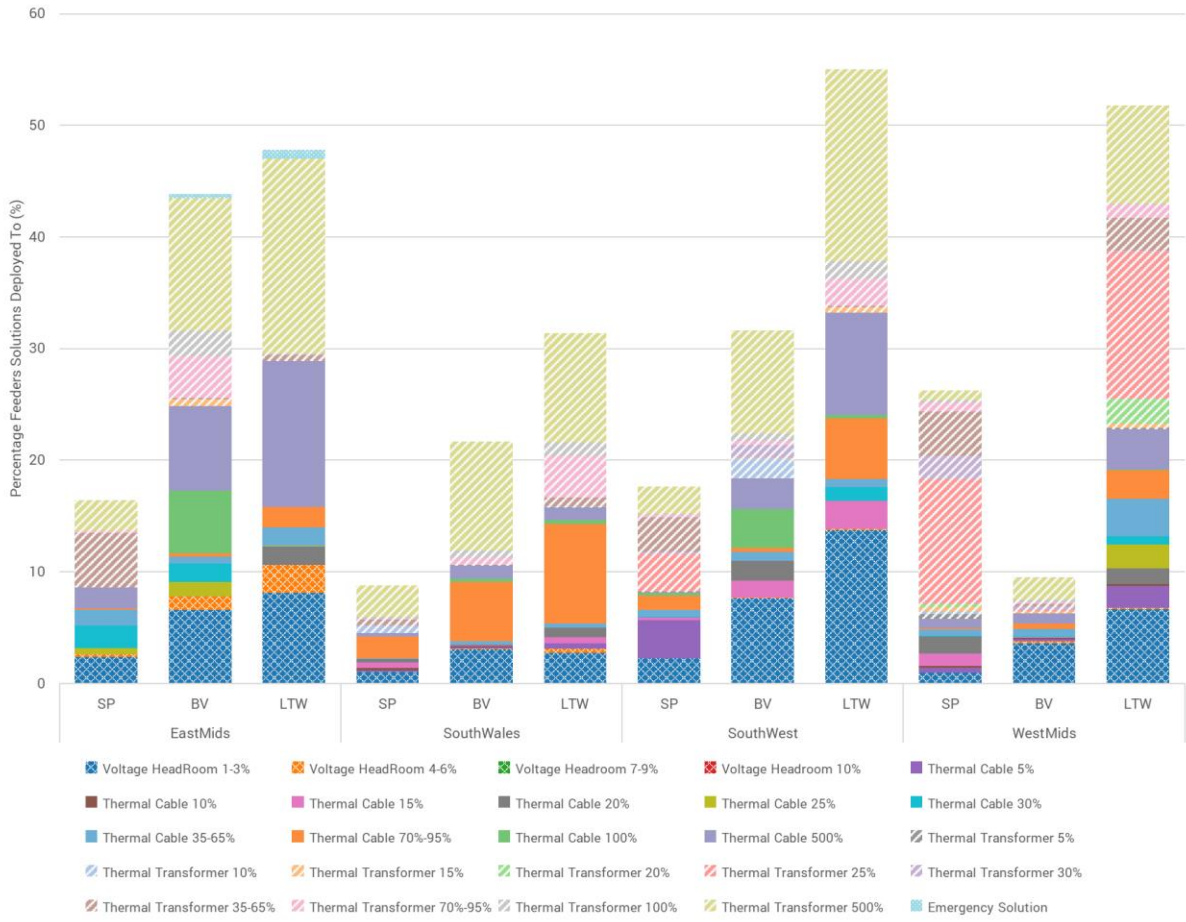

Figure 3: Solutions deployed in 2033 for each DFES scenario.

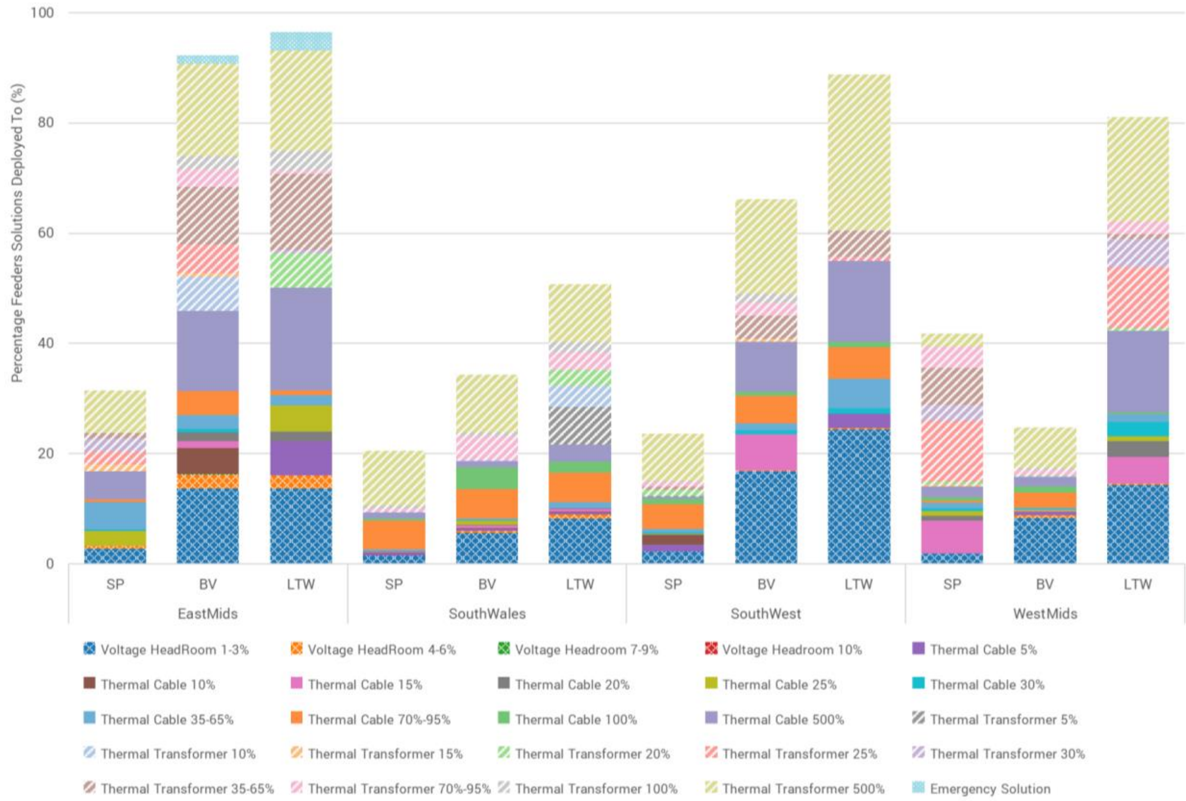

Figure 4: Solutions deployed in 2040 for each DFES scenario.

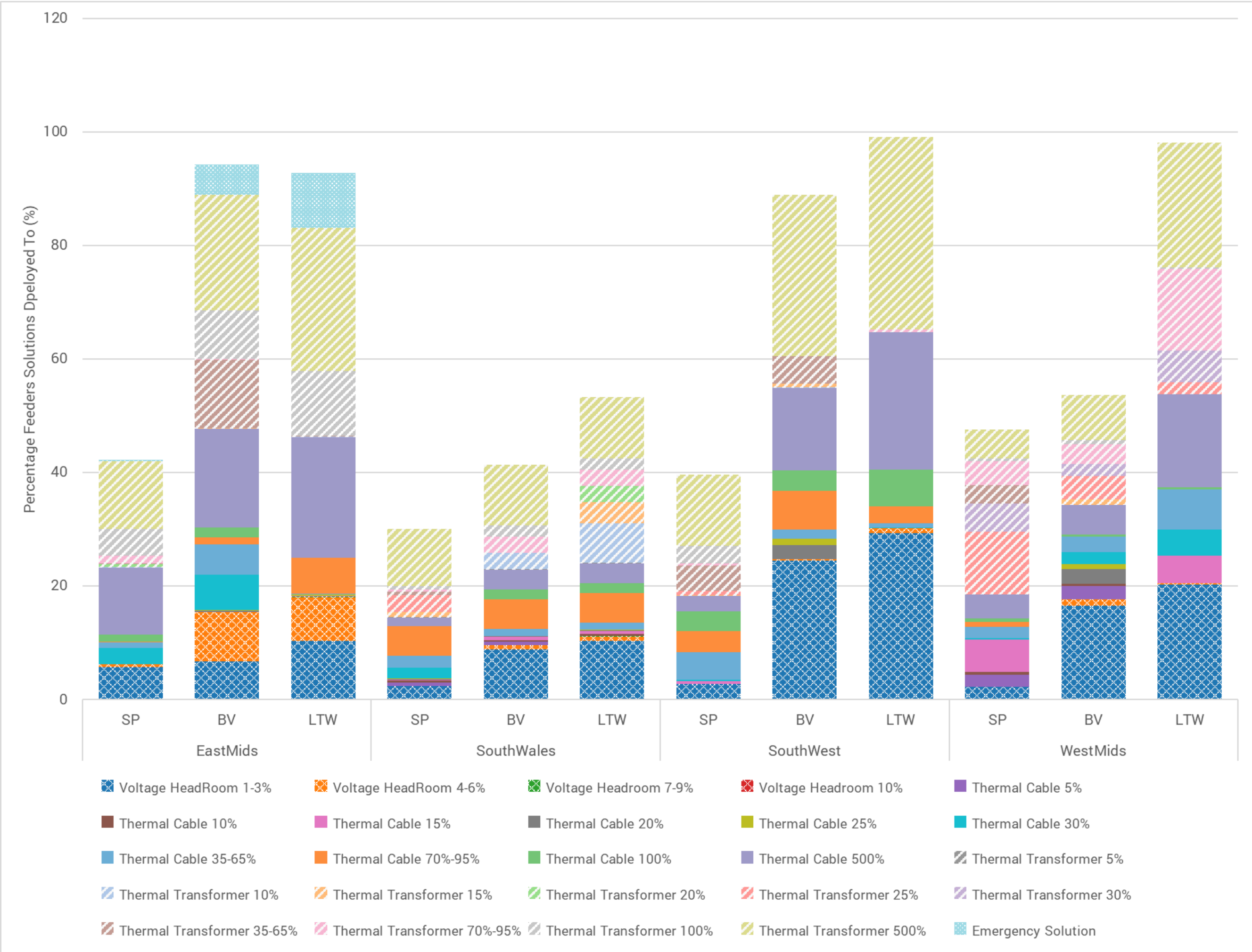

Figure 5: Solutions deployed in 2050 for each DFES scenario.

4.1.3 By LV Network archetype

Figure 6 to Figure 16 show the deployment of artificial solutions for each licence area, under each scenario, for LV archetypes LV1 to LV11 respectively. Key trends that can be picked out from the plots, that are consistent across all network archetypes include:

- When observing the different years, it is possible to note that a greater number of solutions are deployed in the later years such as 2050, when compared to the deployments in 2033. This is a common theme across all DFES scenario due to increase in uptake rates of LCTs throughout years. This could potentially mean that solutions with lower headroom releases could be deployed in the earlier years thus resulting in the deployment of cheaper solutions and delaying costlier solutions with higher headroom releases to a later date.

- In the case of more aggressive scenarios, such as leading the way, the number solutions deployed increases significantly when compared to less aggressive scenarios, such as steady progress. Due to the larger uptake rates of LCTs, solutions releasing more headroom are required. This would mean that the more aggressive scenarios would require solutions that release larger headroom i.e., larger BaU related solutions, which in turn would result in higher costs of solution deployment.

Figure 6 to Figure 16 can also be used to analyse the solution types that are deployed to each LV network archetype. This allows identification of what headroom releases are required from solution in order to be deployed to each LV network archetype. The following conclusions can be drawn from Figure 6 to Figure 16:

- The Network Study results report showed that voltage rise constraints were significant for feeders that primarily serve commercial properties (LV1, LV3, LV4 and LV5) due to PV uptake, together with modest thermal issues. LV network archetypes LV1, LV3, LV4 and LV5 require a modest quantity of interventions that release voltage headroom, sometimes up to as much as 7-9% voltage headroom due to the uptake of PV and its dense clustering on some feeders. Modest quantity of thermal headroom release is required on these LV networks due to the uptake of EVs.
- LV network archetypes LV2, LV6, LV7 and LV8 represent urban and sub-urban feeders serving primarily domestic customers. Solutions that release between 1-3% voltage headroom are sufficient to resolve most of the voltage rise constraints that occur due to solar PV deployment, although some feeders with high levels of PV clustering require solutions releasing 4-6% voltage headroom (primarily in East Midlands in Best View and Leading the Way scenario by year 2050 for LV2, LV6 and LV8 and South West Leading the Way by 2050). Voltage issues typically arise at a network penetration level of 20-30% in the Best View and Leading the Way scenarios (less in Steady Progress). Significant thermal issues are witnessed across LV2, LV6, LV7 and LV8. Thermal transformer 100%, thermal transformer 500%, thermal cable 100% and thermal cable 500% are commonly deployed suggesting high levels of thermal capacity release are required due to the uptake of heat pumps and EVs.
- LV network archetypes LV9 and LV11 representing overhead feeders to rural villages and farmsteads respectively witness moderate voltage rise issues. Solutions releasing 1-3% voltage headroom release are sufficient to resolve voltage rise constraints caused by PV deployment. Significant thermal issues are experienced due to the deployment of heat pumps and EVs. Frequently high thermal headroom release solutions are required to solve network constraints. Solutions commonly deployed by 2050 include thermal transformer 500% (particularly in Best View and Leading the Way scenarios), suggesting there will be cases where to support the anticipated uptake of LCTs it can expected that major works installing new substations and cabling will be required to facilitate the connection of LCTs to the network.
- LV network archetype LV10 representing rural village feeders of an underground construction witness moderate levels of voltage rise constraints due to deployment of solar PV. In most cases solutions releasing voltage headroom between 1-3% are sufficient to resolve the constraint, although more

capacity is required by 2050 in the East Midlands. Significant thermal constraints are witnessed across the LV10 feeders, often requiring major headroom release solution such as commonly thermal cable 500% and thermal transformer 500%. This shows that the network is heavily overloaded and it can therefore be expected the major works are required installing new substations and cabling to facilitate the connection of LCTs to the network.

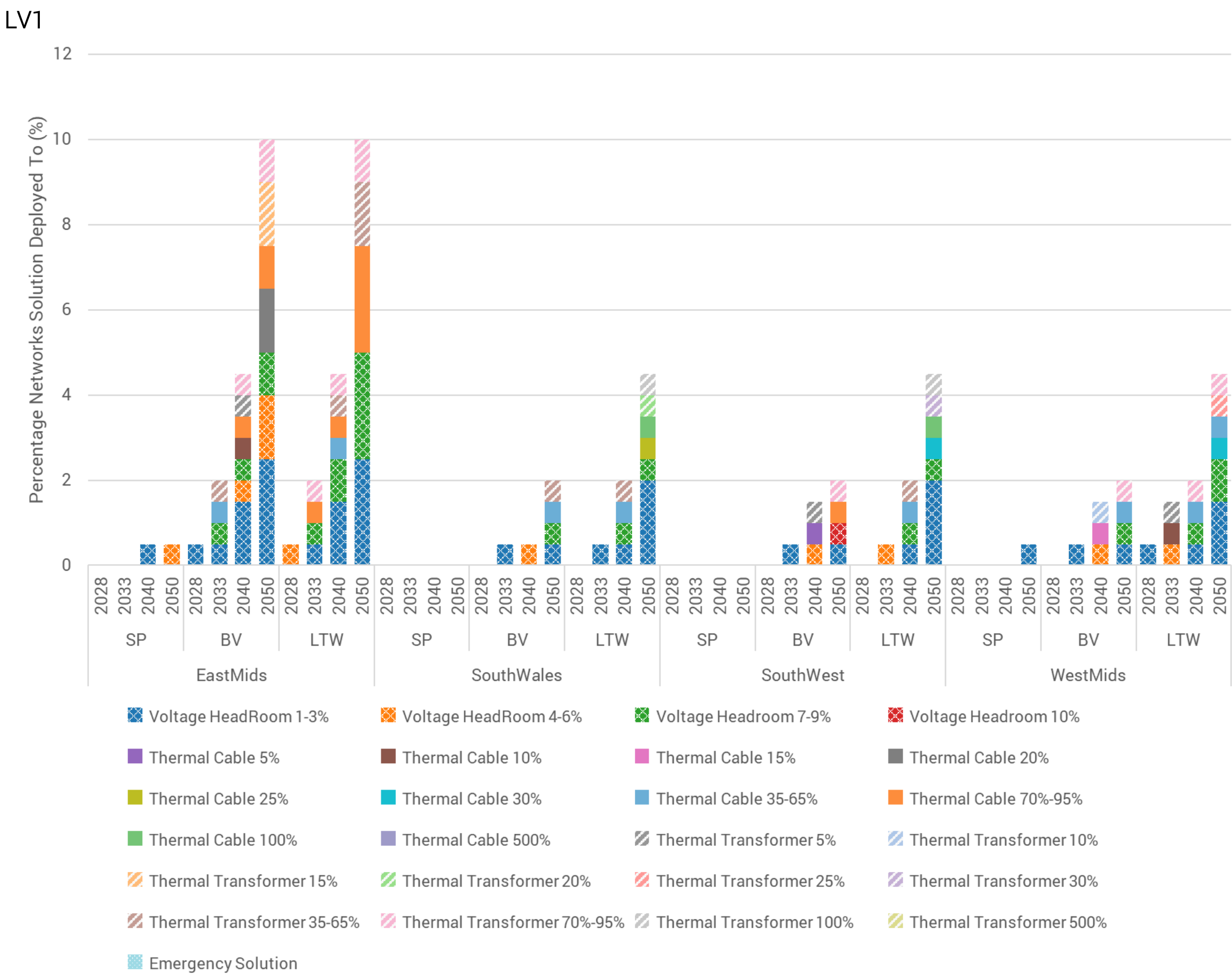

Figure 6: Solutions deployed on LV1

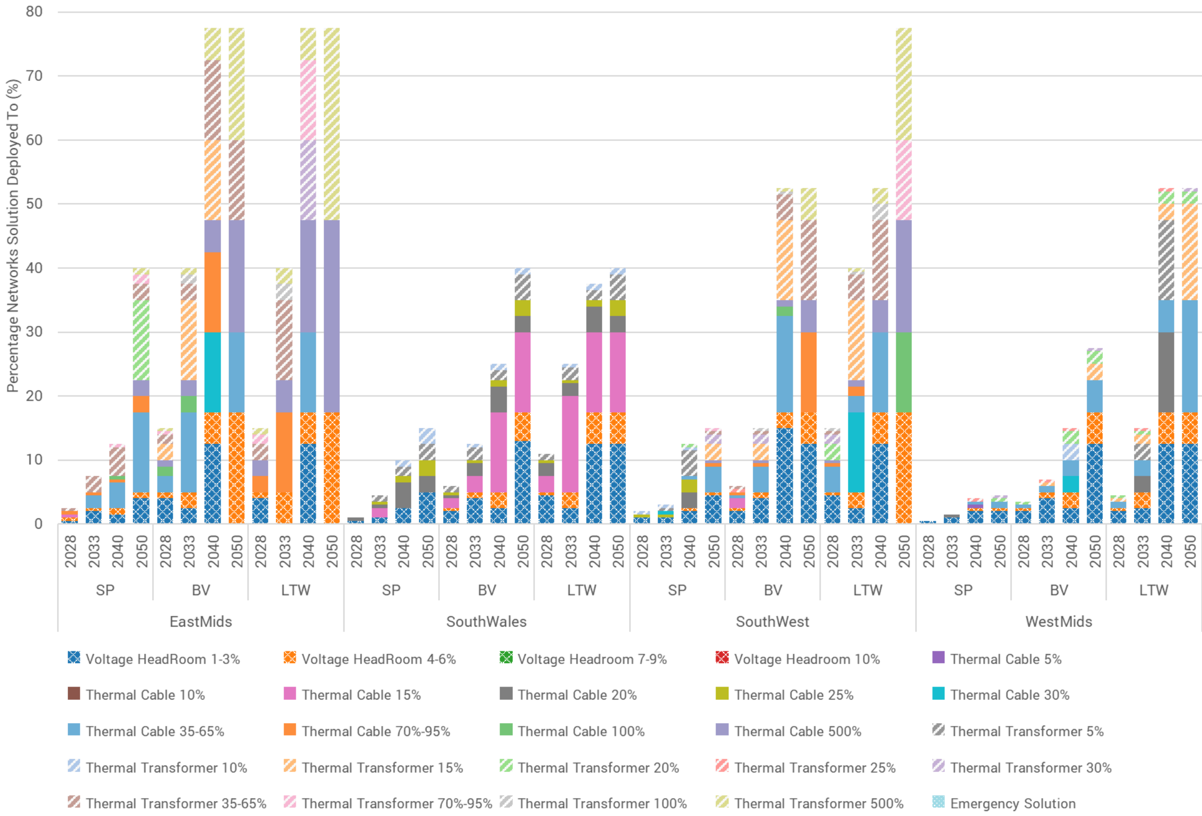

Figure 7: Solutions deployed on LV2

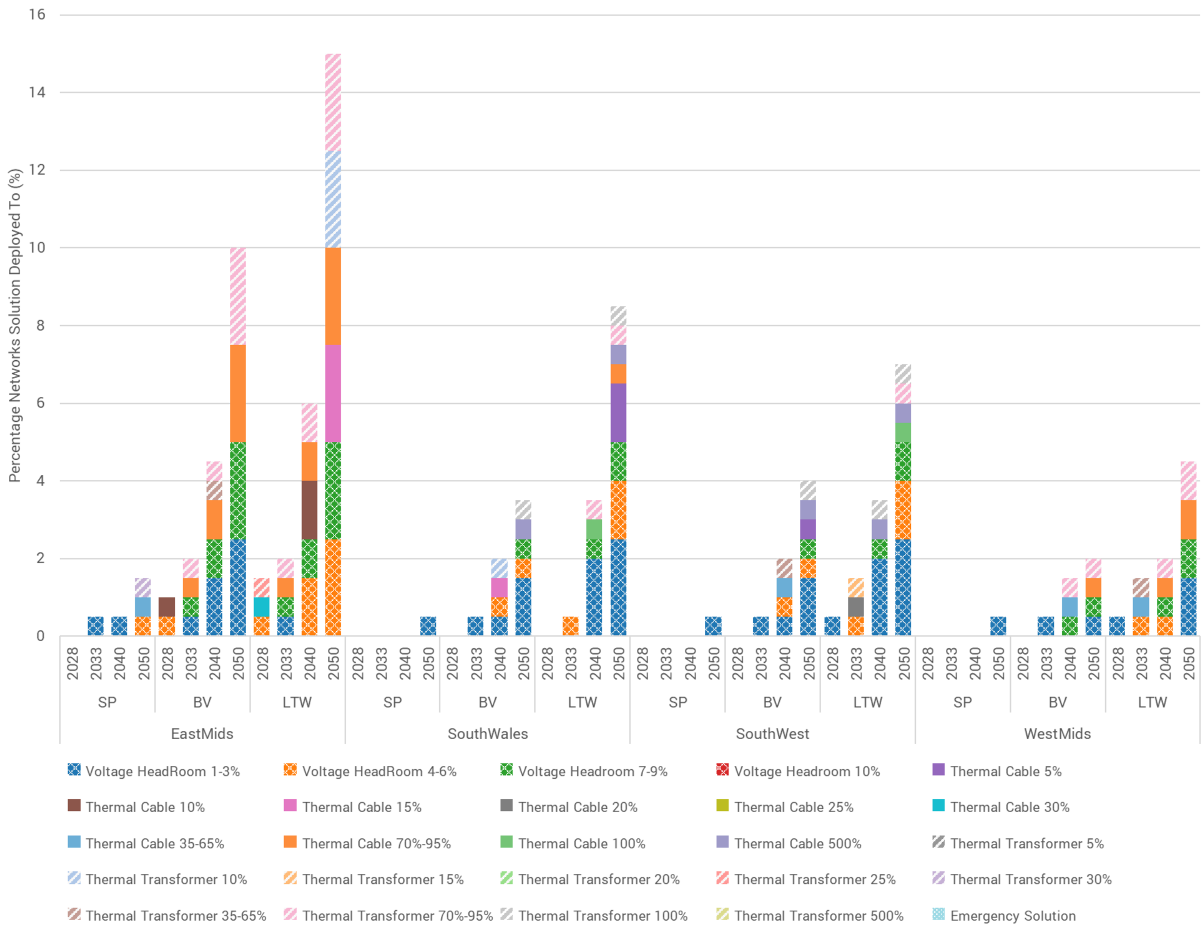

Figure 8: Solutions deployed on LV3

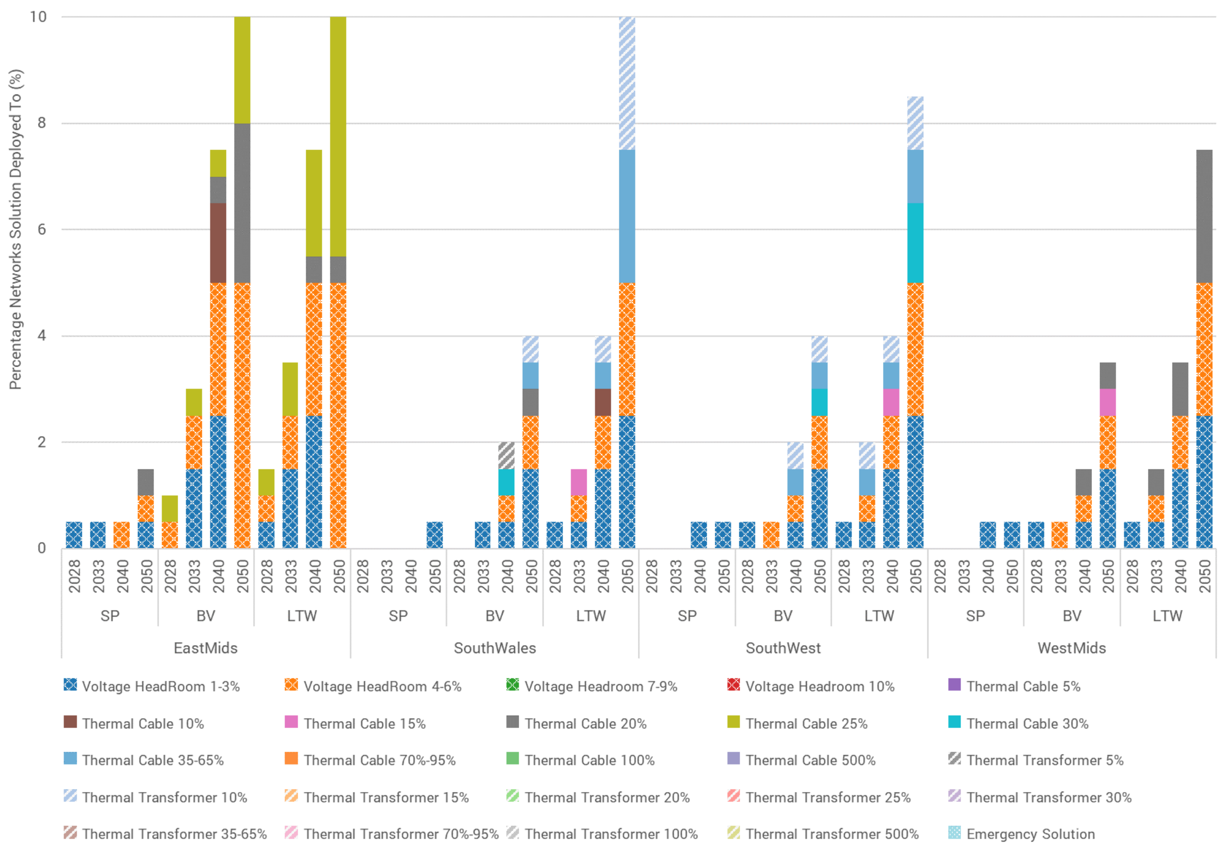

Figure 9: Solutions deployed on LV4

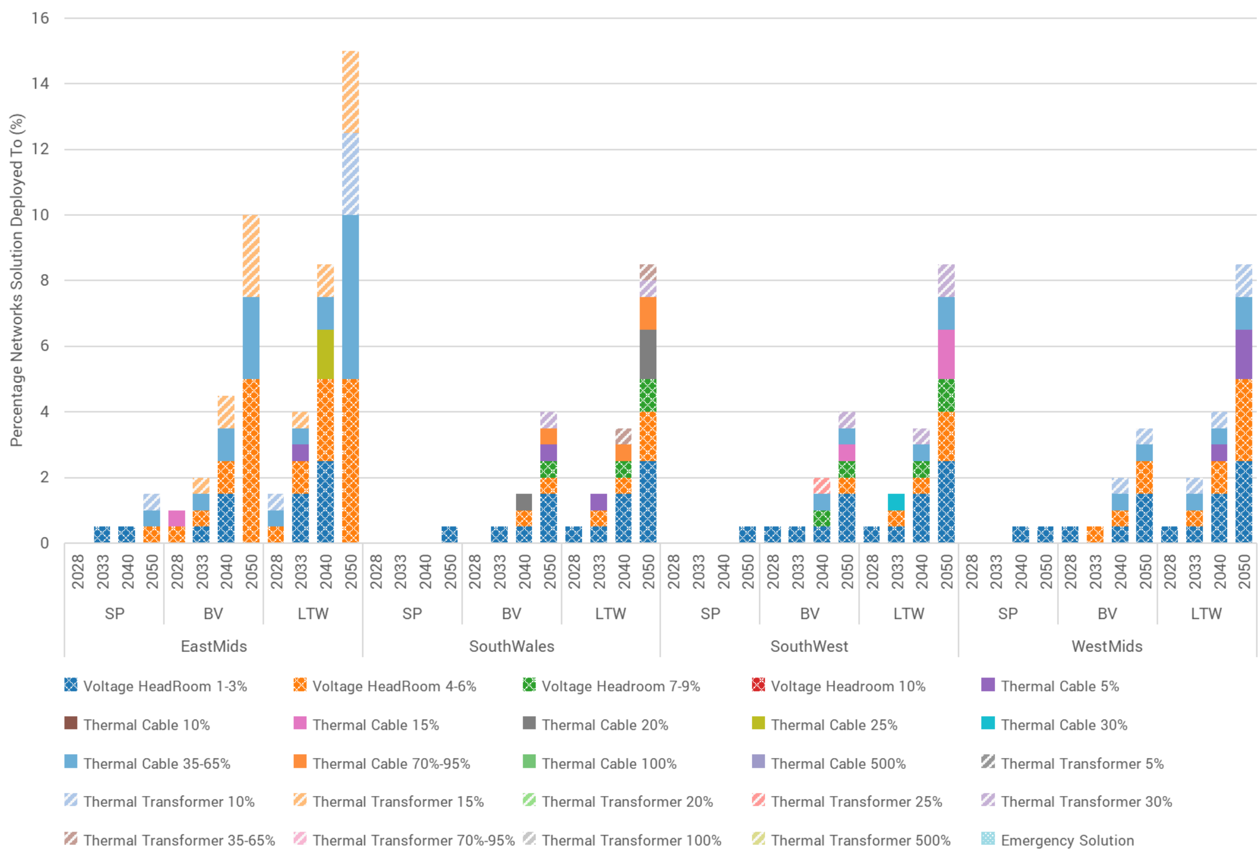

Figure 10: Solutions deployed on LV5

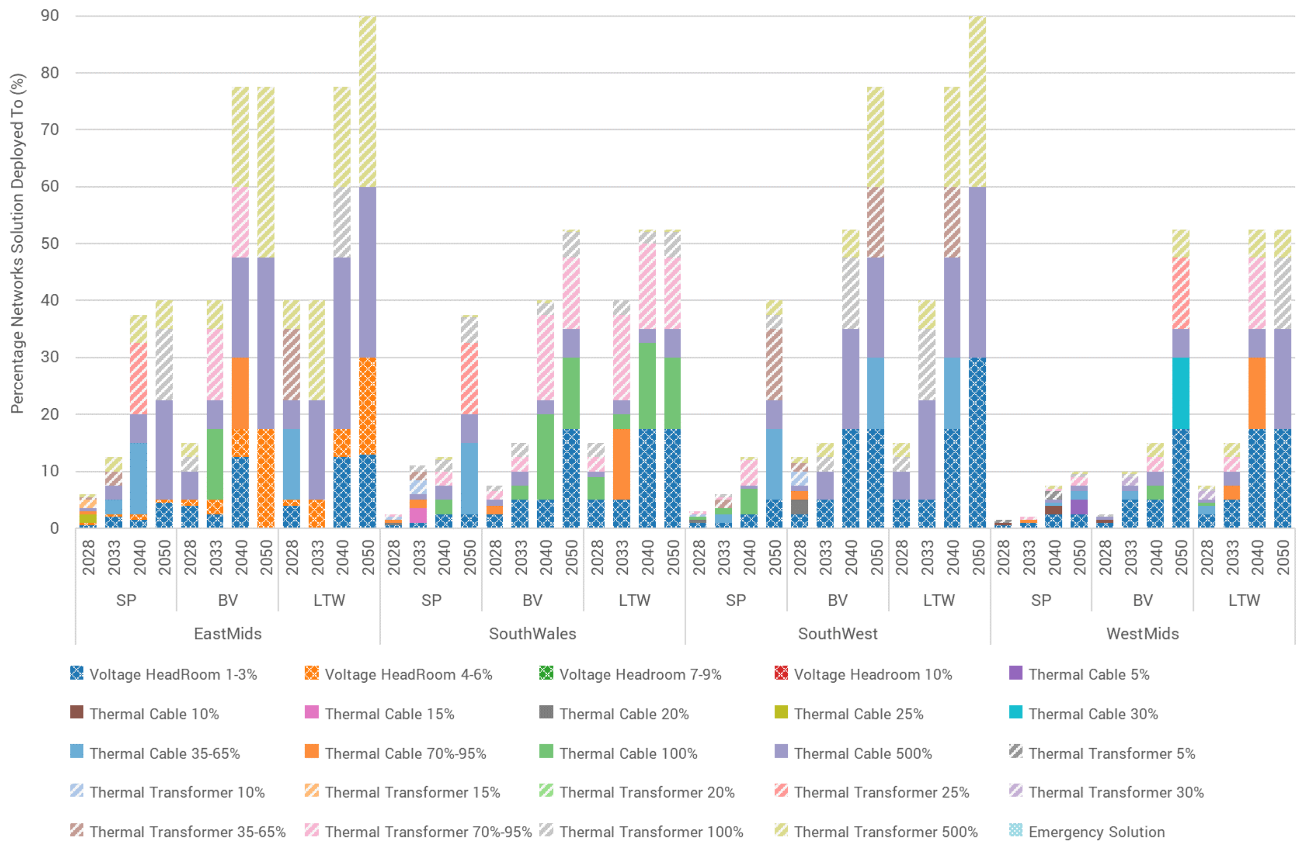

Figure 11: Solutions deployed on LV6

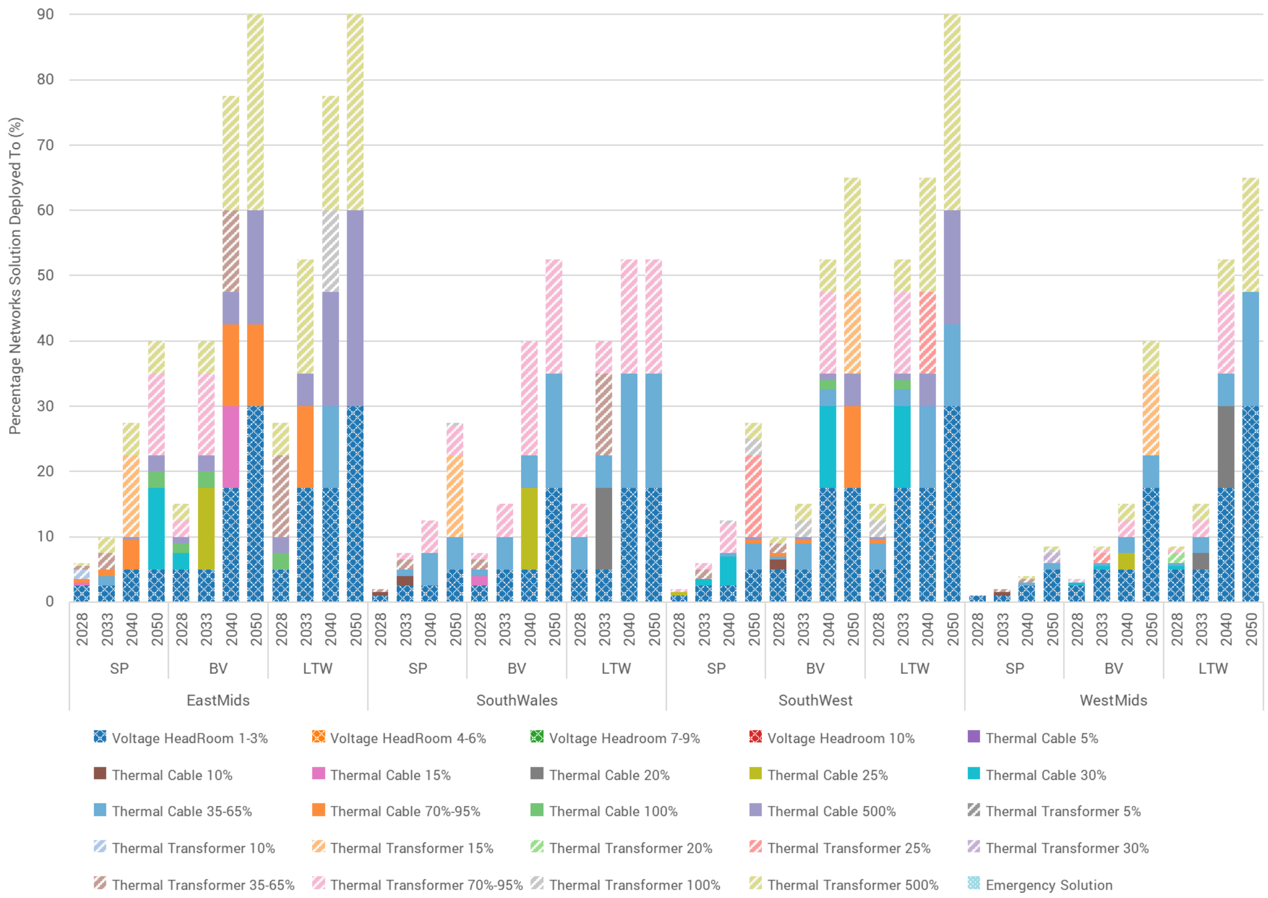

Figure 12: Solutions deployed on LV7

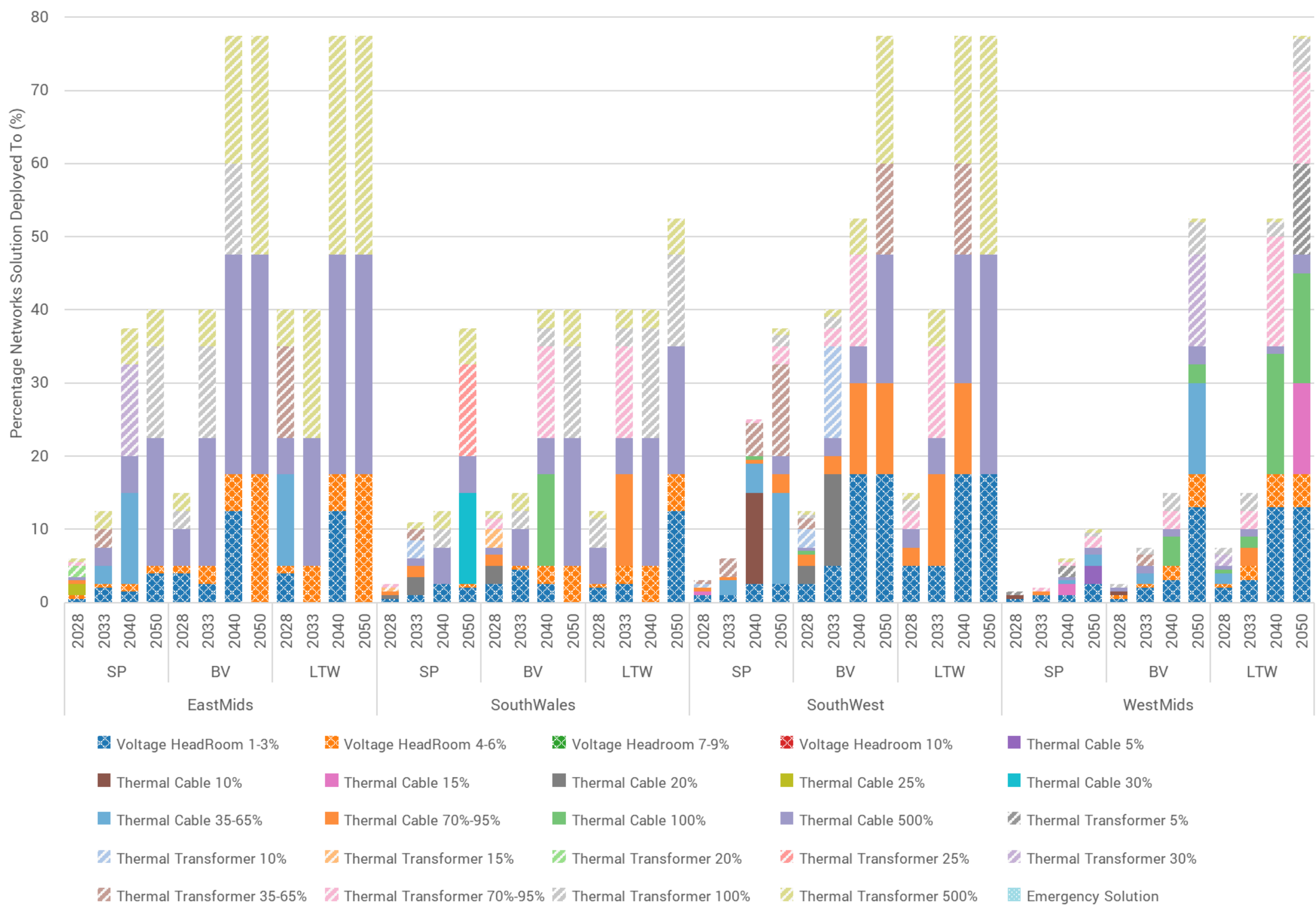

Figure 13: Solutions deployed on LV8

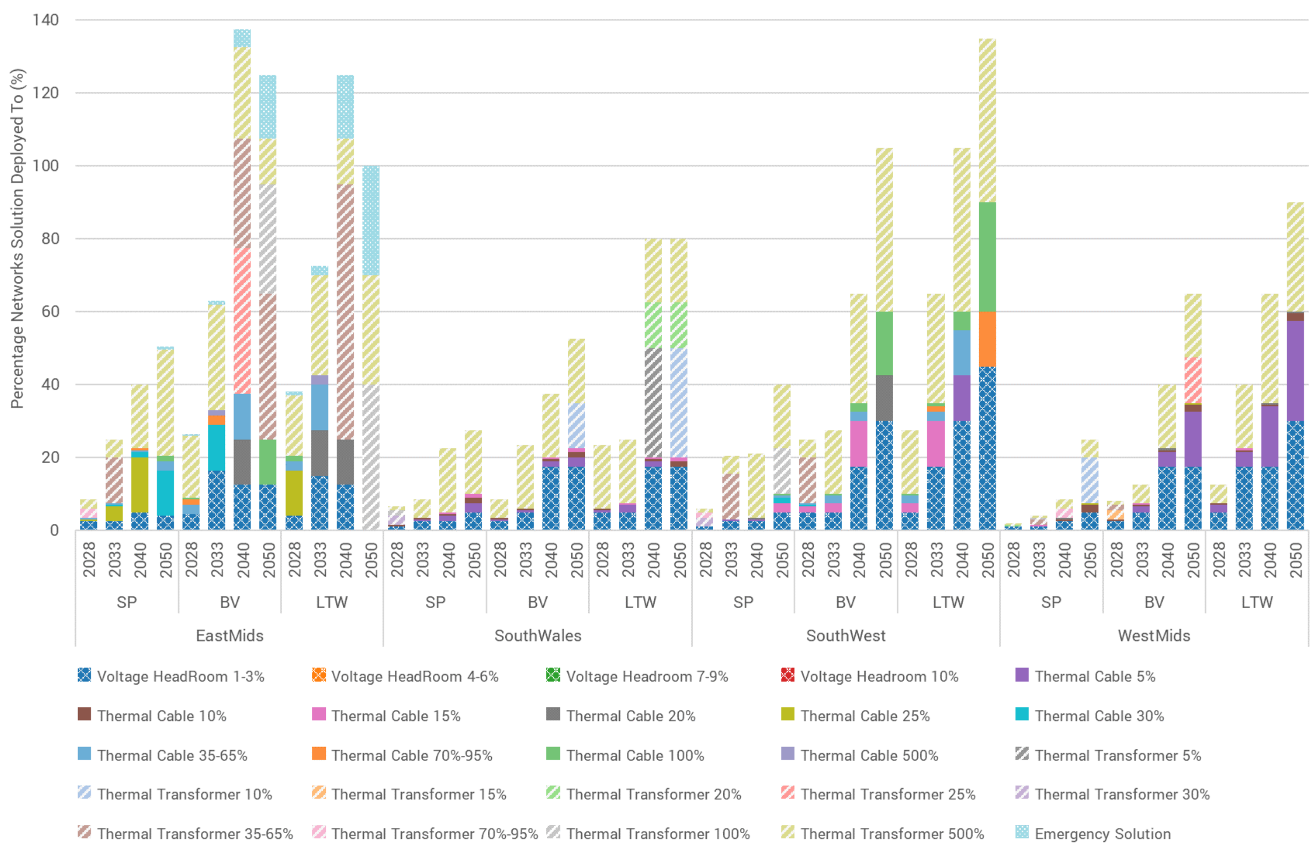

Figure 14: Solutions deployed on LV9

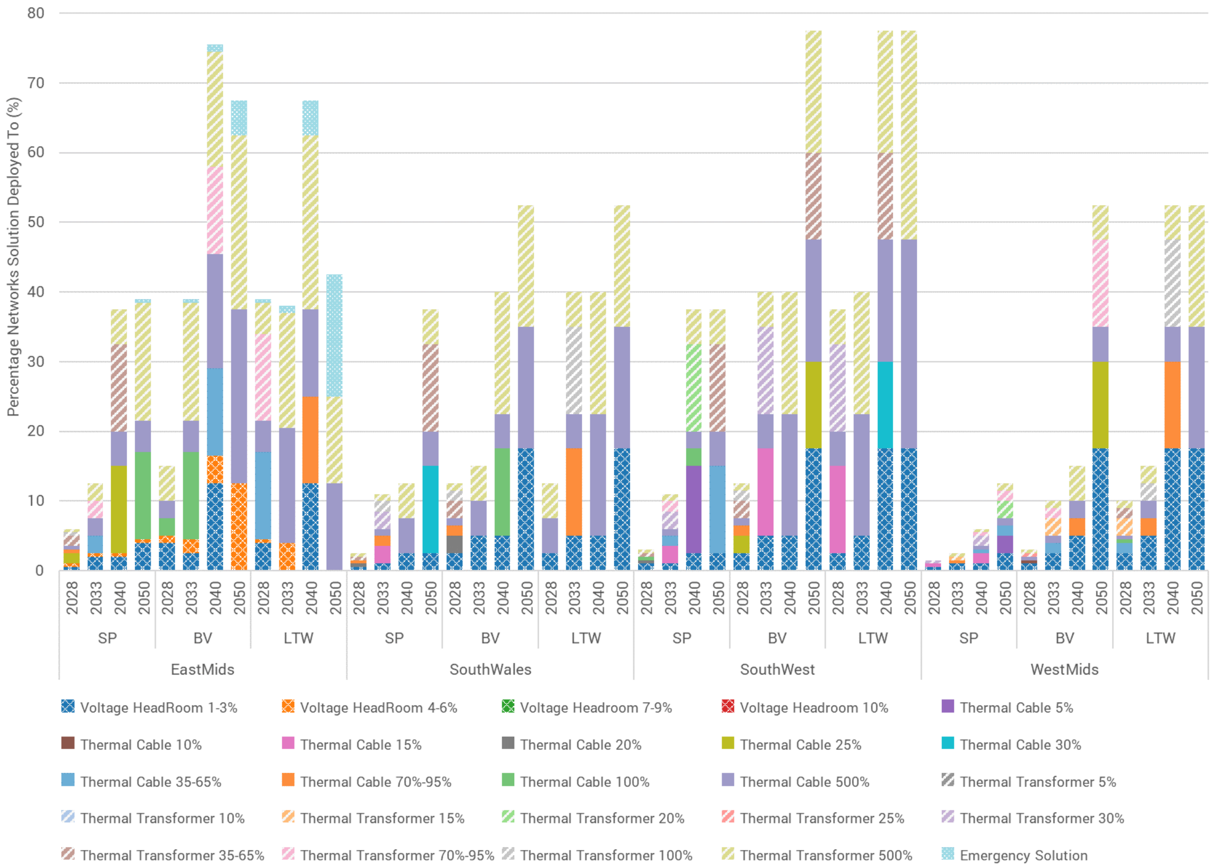

Figure 15: Solutions deployed on LV10

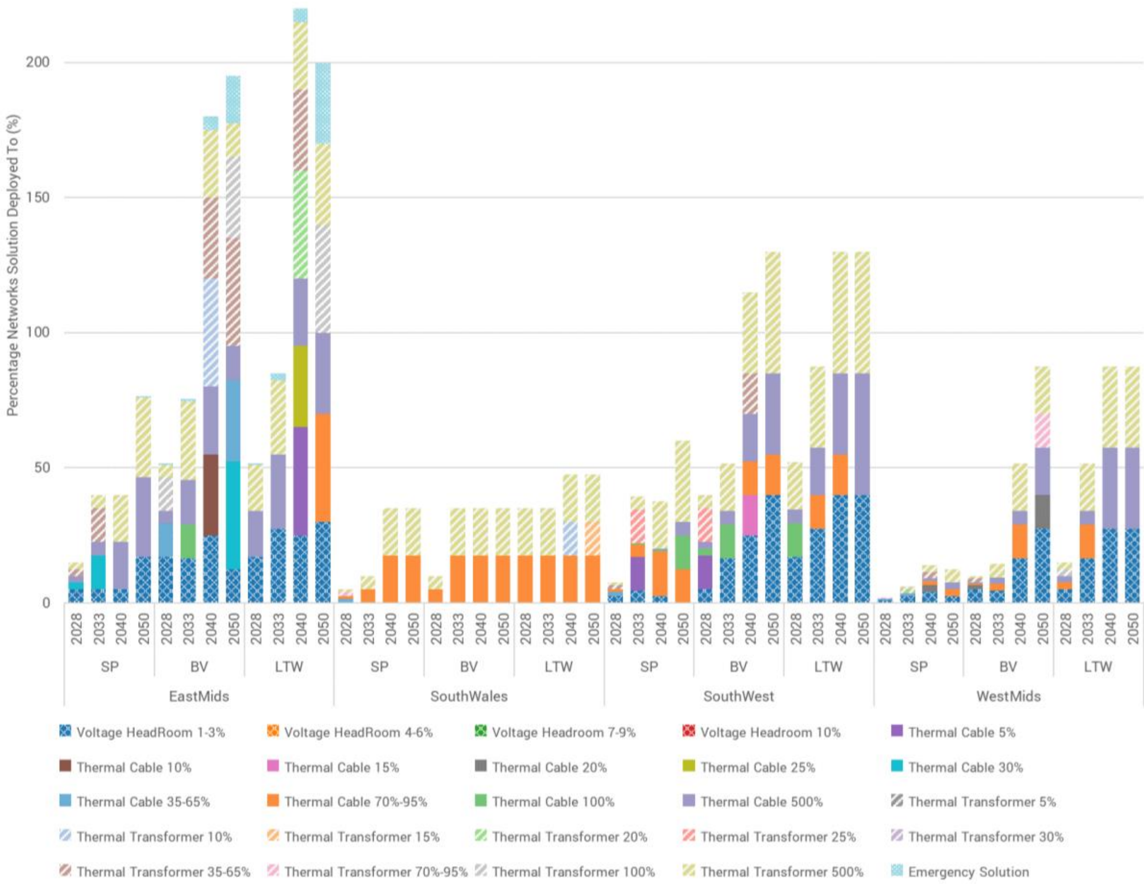

Figure 16: Solutions deployed on LV11

5. Counterfactual Study

The counterfactual study was conducted to act as a baseline against which the value of the novel solutions could be addressed. To perform the counterfactual study, analysis was performed using traditional solution utilised in National Grid's Business as Usual (BaU) operations today. EA Technology and National Grid agreed upon the BaU solution set to use in the counterfactual Transform study, together with each technology's associated parameters (Capex and opex costs and headroom releases). The full list of BaU solutions utilised in the counterfactual Transform study is presented in Appendix II together with assumed Capex and Opex costs and associated headroom releases.

5.1 Network Wide Solution Analysis

This section of the report analyses the results of the BaU Transform study at the whole network level to give a big picture view of the solutions required by the network in BaU operation. Section 5.2 analyses the results on an LV network archetype basis to show the detail of which BaU solutions get deployed on which networks.

5.1.1 Cumulative Solutions Deployed

Figure 17 to Figure 20 show the cumulative BaU solution deployments until 2028, 2033, 2040 and 2050 respectively across National Grid's four licence areas. Also shown is the weighted average deployment which is calculated as a weighted average taking into accounts the differing number of feeders in each of National Grid's four licence areas. This provides a quick way to visualise the typical deployment of solutions across all of National Grid's electricity distribution licence areas. These figures show that a wide variety of BaU solutions are required to resolve the network constraints forecast to occur. As time progresses, solutions are deployed across a greater proportion of the network corresponding with increasing constraints associated with growing volumes of LCTs connected to the system. The relative proportions of solutions deployed changes over time as different constraint types are encountered across the 11 LV archetypes that make up the modelled network. Figure 17 to Figure 20 show that in many cases solutions deployed across the four licence areas are broadly similar, some variations do exist. This is explored in more detail in section 5.2 of this report.

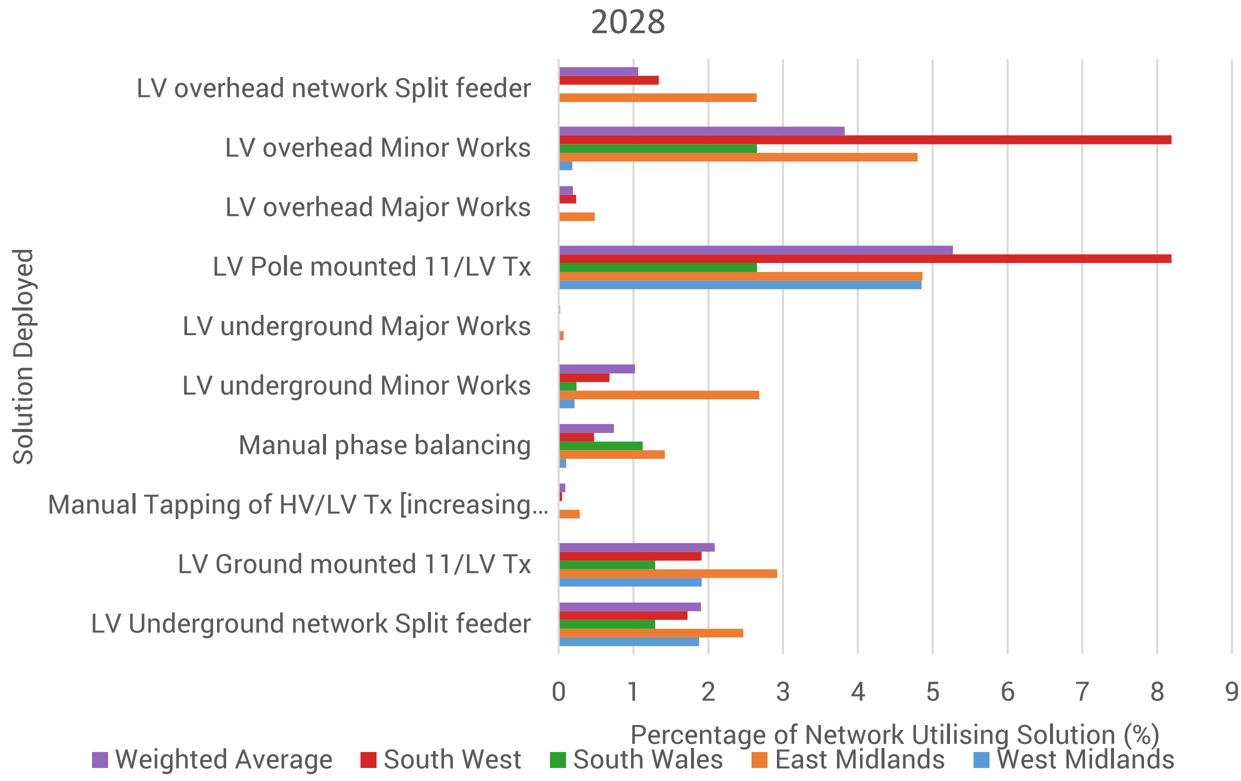

Figure 17: BaU solutions deployed up to 2028.

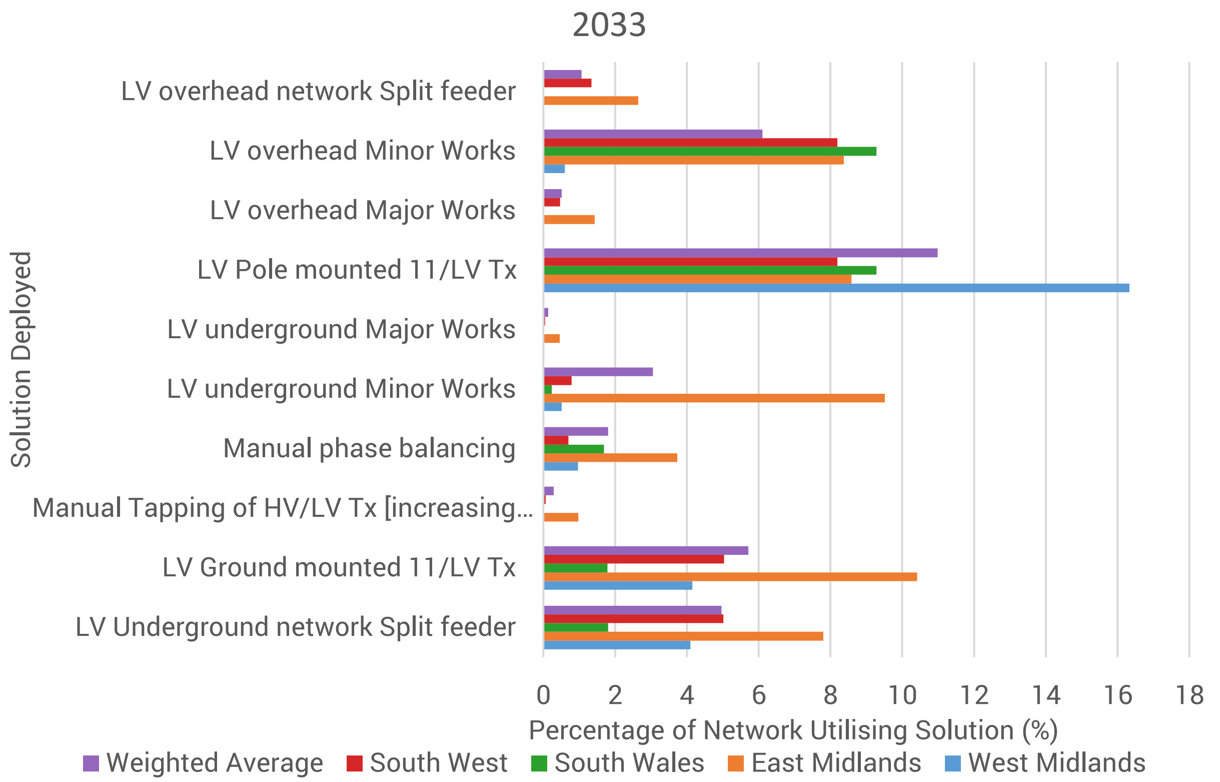

Figure 18: BaU solutions deployed up to 2033.

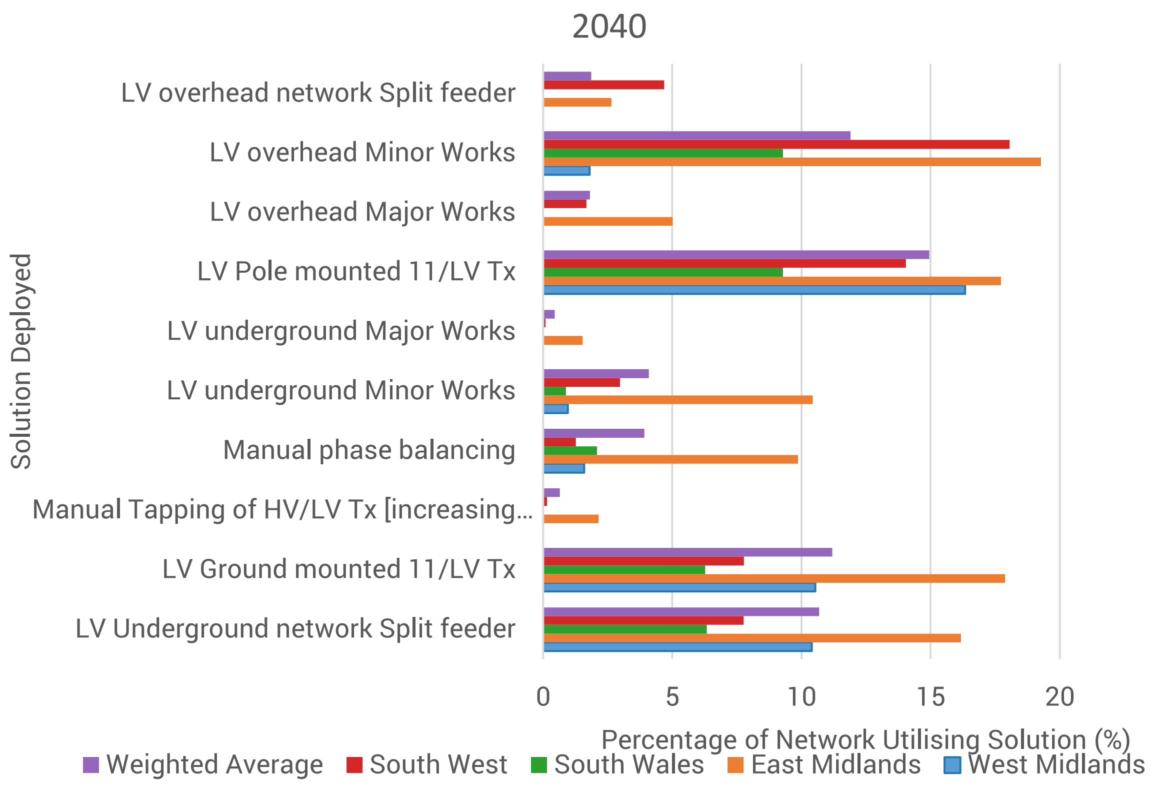

Figure 19: BaU solutions deployed up to 2040.

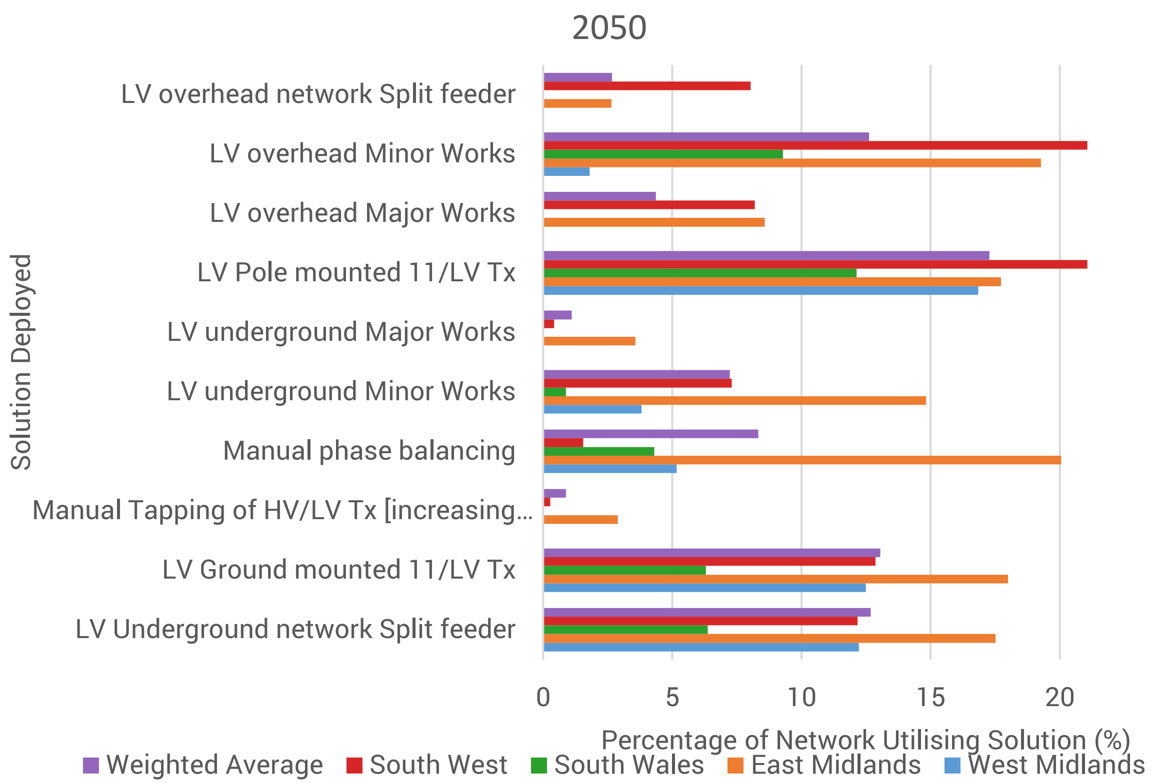

Figure 20: BaU Solutions deployed up to 2050.

5.1.2 Solutions deployed by Period

Figure 21 presents the weighted average deployment of solutions across National Grid's four licence areas in four time periods consistent with those time periods analysed in the Network Study Results report. The weighted average was calculated by normalising the penetration of solution deployment in each licence area by the number of feeders in each licence area. The weighted average therefore represents the average penetration of solution deployment across National Grid's four licence areas. It shows significant solution deployment across all periods considered, with a particular high level of solution deployment required in the 2034-2040 time period. This is consistent with the network constraints analysis presented in the Network Study Results report, which showed that there were high levels of constraints encountered in this time period. The forecast high levels of solution deployment, particularly in the 2034-2040 period will have significant resource (staff, machinery, assets etc.) requirements to ensure that the network reinforcements are completed in a timely manner. Any solutions that can flatten the curve of solution deployment and thus spread workload will assist National Grid and their supply chain to ensure the relevant reinforcements can be made in a timely manner. Similarly, solutions that solve constraints for a short period of time before a more significant, time consuming deployment of another solution may be favoured during times of intense network upgrades to ensure that resource levels are sufficient for the required network upgrades.

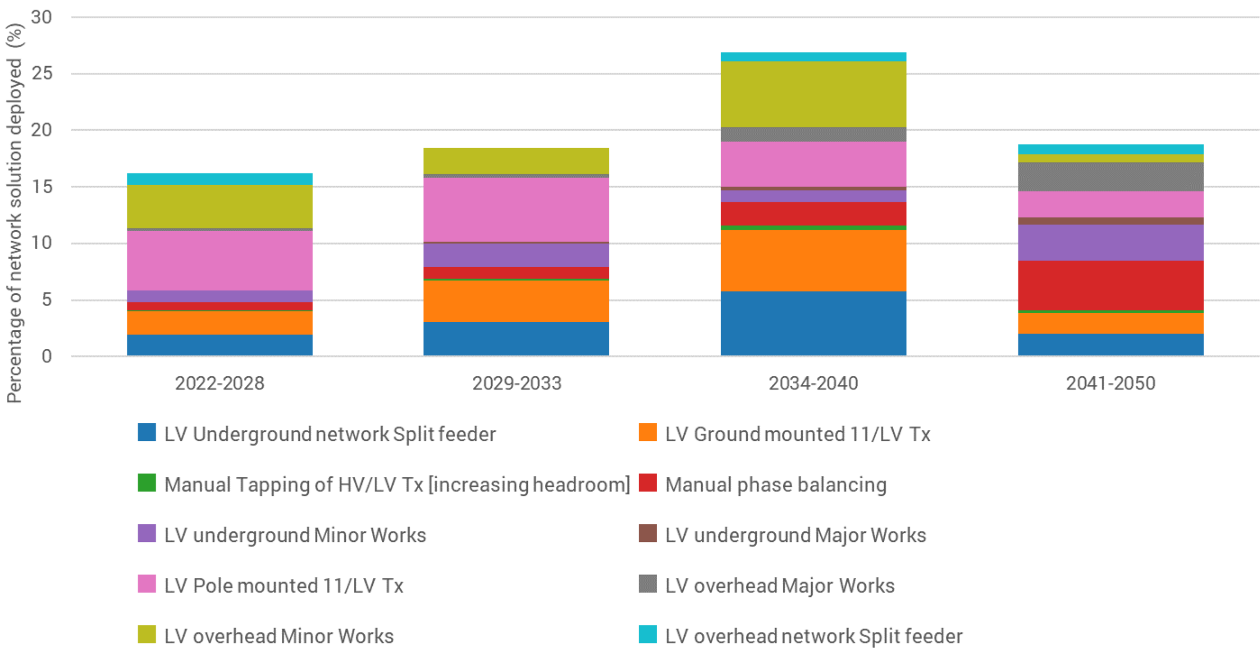

Figure 21: Weighted average of solutions deployed in BaU Transform study by period

5.1.3 Variations in Solution Deployment by Scenario

This project studies three scenarios from DFES 2021, namely Best View, Leading the Way and Steady Progress. LCT uptake rates vary between the scenarios, with the Leading the Way scenario in general having the fastest and highest total uptake of LCTs, Steady Progress having the slowest and lowest total uptake of LCTs and Best View sitting between these two scenarios and considered the most probable scenario.

Figure 22 shows the BaU solutions deployed across the East Midlands, West Midlands, South Wales and South West licence areas as a proportion of the total solutions deployed for each scenario. In general, the overall proportions of solutions deployed for the different scenarios in a given licence area broadly remains fairly similar, indicating technologies are deployed in similar proportions regardless of scenario. Across the three scenarios, the relative prevalence of each solution either:

- Decreases in prevalence as scenarios get more aggressive. Solutions that fall into this category include manual phase balancing and LV overhead major works. These solutions provide a small increase in capacity at a low cost and are thus suitable for less aggressive scenarios.
- Prevalence remains approximately steady across the three scenarios. These solutions can be explained as solutions that get deployed on LV networks linearly with LCT uptake, representing therefore a steady proportion of the total solutions deployed.
- Increases in prevalence as scenarios get more aggressive. These solutions are required due to the more rapid uptake in LCT deployment, necessitating solutions that release either headroom at a quicker rate and/or more total headroom. Examples of this include LV overhead major works in South Wales and South West, and LV underground major works in the East Midlands.

Observations can be made regarding specific solutions deployed at scale according to Figure 22. For example, Manual Phase Balancing is selected by the Transform analysis as a common solution, particularly in the Steady Progress scenario. By shifting customers across phases, the load can be balanced allowing more capacity to be released on the existing LV feeder. However, practically this solution may prove difficult to implement. Firstly, particularly in the case of underground network, it is a time consuming process to rebalance phases by shifting which phase customers are connected to. Secondly, rebalancing phases is likely to prove only a temporary solution as new LCTs are deployed across the feeder. High loads from LCTs such as EVs and heat pumps mean that only a small number of new LCT deployments on one phase may will cause the feeder to become unbalanced once more.

C3.	Practicalities of deploying specific solutions should be considered. For example, Manual Phase Balancing is commonly selected by Transform. Practically this could be difficult to implement particularly in the case of underground networks. It is likely to only prove a temporary solution since a small number of further LCTs deployments is likely to leave the feeder unbalanced once more.

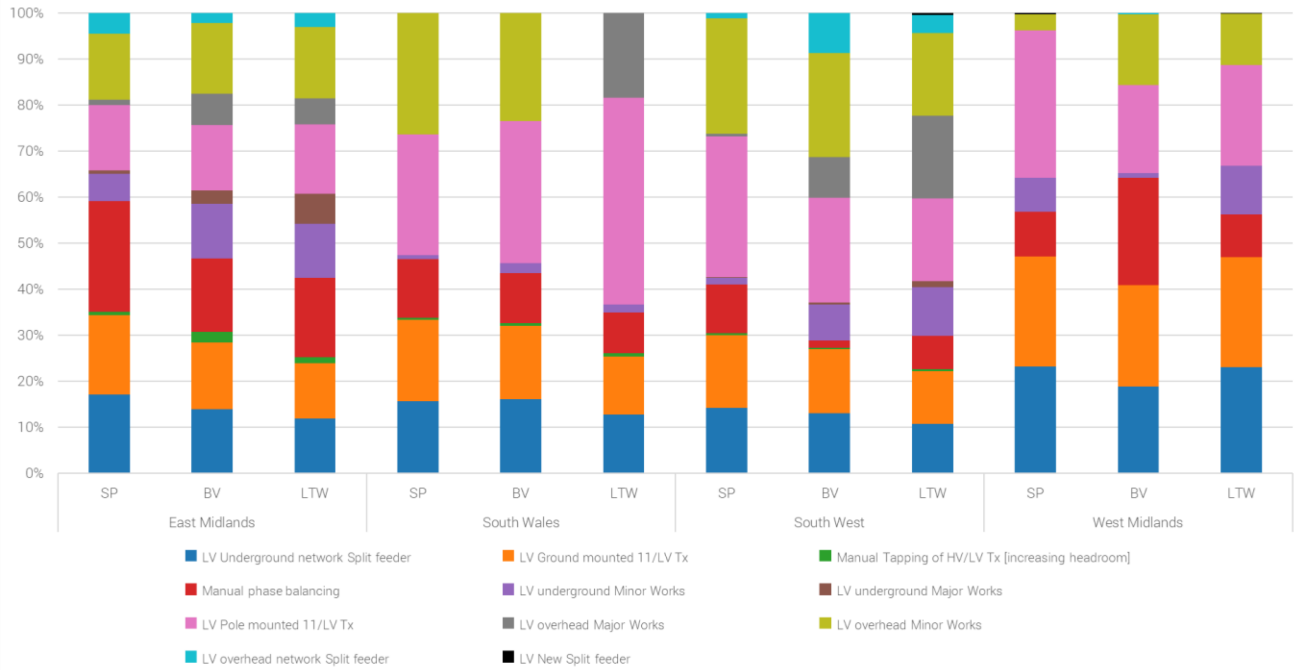

Figure 22: Proportions of each solution deployed in the East Midlands, South Wales, South West and West Midlands licence areas by scenario.

5.2 Solution Analysis by Archetype

Analysis conducted in section 5.1 considered the network as a whole. This section analyses how the solutions deployed vary by LV network archetype. The LV network archetypes utilised in the Transform study were introduced in the Network Study Results report and are summarised in Appendix I. Details for each LV archetype are summarised in Appendix II. This section therefore adds detail aiming to show which solutions get deployed where on the network, and additionally reveals detail that may be washed out in the above section due to the low prevalence of particular network archetypes.

Figure 23 to Figure *26* show the BaU solutions deployed in the Best View scenario across each LV network archetype as a proportion of the solutions deployed for each LV network archetype for the East Midlands, West Midlands, South Wales and South West licence areas respectively. These figures show how the solutions deployed to resolve constraints vary both by archetype and licence area.

The figures show that:

- For network archetypes LV1 (Central Business District), LV3 (Town Centre), LV4 (Business Park) and LV5 (Retail Park), the solutions LV Underground Network Split Feeder, Manual Tapping of HV/LV Transformer (Increasing Headroom) and Manual Phase Balancing are commonly deployed solutions across the East Midlands, South Wales and South West licence areas. In the Network Study Results report, it was shown that the LV1, LV3, LV4 and LV5 feeders experience voltage rise constraints. Manual tapping of the HV/LV transformer is a commonly deployed solution as it releases voltage headroom allowing more PV to connect to the system. Manual phase balancing and LV underground split feeders releases moderate amounts of thermal headroom allowing more EVs and heat pumps to connect to the system. In the West Midlands, LV Underground Network Split Feeder and Manual Phase Balancing remain common solutions, however, LV Ground Mounted 11kV/LV Transformers are also a common solution in place of Manual Tapping of HV /LV Transformer.
- Solutions deployed for network archetype LV2 (Dense Urban (apartments etc)) vary by licence area. In East Midlands and South West solutions most commonly deployed are LV Underground Network Split Feeder, LV Ground Mounted 11kV/LV Transformer and LV Underground Minor Works. Solutions less

commonly deployed on these networks are Manual Tapping of HV/LV Transformer and Manual Phase Balancing. In South Wales, LV Underground Network Split feeder and Manual Phase Balancing are deployed. In the West Midlands, the solutions deployed are LV Underground Network Split Feeder, LV Ground Mounted 11kV/LV Transformer and Manual Phase Balancing are deployed.

- For network archetypes LV6 (Suburban street (3 or 4 Bed Semi Detached or Detached Houses)), LV7 (New Build Housing Estate) and LV8 (Terraced Street), the solutions LV Underground Network Split Feeder, LV Ground Mounted 11kV/LV Transformer and Manual Phase balancing are deployed to resolve constraints across all four licence areas. In the East Midlands licence area, the solution LV Underground Minor Works is also commonly deployed to resolve network constraints. In the Network Study Results report, thermal constraints were shown to be the dominant constraint type of these LV networks. Splitting feeders and manual phase balancing releases modest amounts of thermal headroom, whereas new GMTs and minor works release lots of thermal headroom. Differing headroom releases are required on feeders with different levels of LCT clustering.
- The most common solutions across all licence areas for LV9 (Rural Village (Overhead Construction)) and LV11 (Rural Farmstead Small Holdings) are LV Pole Mounted 11kV/LV Transformer and LV Overhead Minor Works. A range of other solutions are used less frequently. Significant additional load from high uptakes of LCTs was shown to cause significant voltage and thermal constraints in the Network Study Results report. The high uptake of LCTs combined with small initial thermal capacities of the existing rural assets, result in the most feasible solutions to release sufficient headroom is installing new transformers and new circuits.
- For all licence areas, solutions deployed on LV10 (Rural Village (Underground Construction) are LV Underground Network Split Feeder, LV Ground Mounted 11kV/LV Transformer and LV Underground Minor Works. High uptake rates of LCTs were shown to cause significant voltage and thermal constraints in the Network Study Results report. This high uptake combined with relatively small initial headroom of rural assets necessitate new assets to release sufficient headroom to support the LCT uptake.

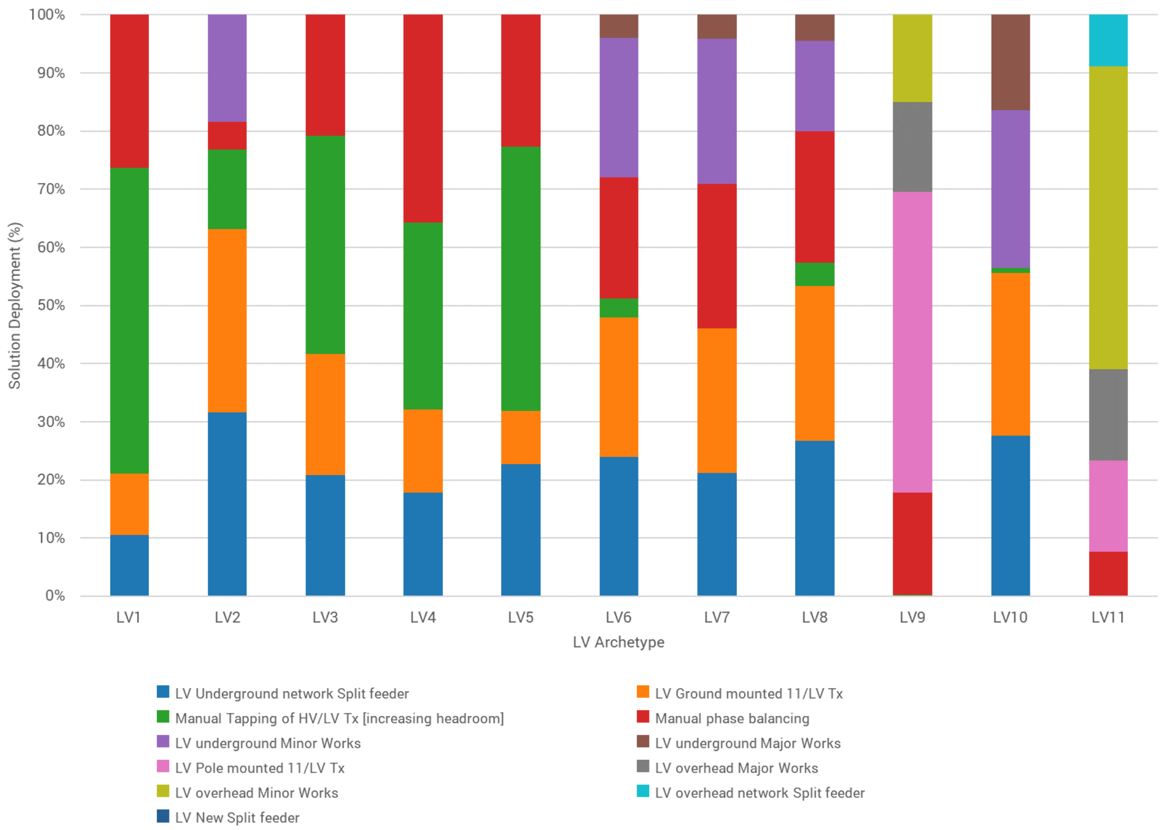

Figure 23: BaU solutions deployed across the LV network archetypes in the Best View scenario in the East Midlands.

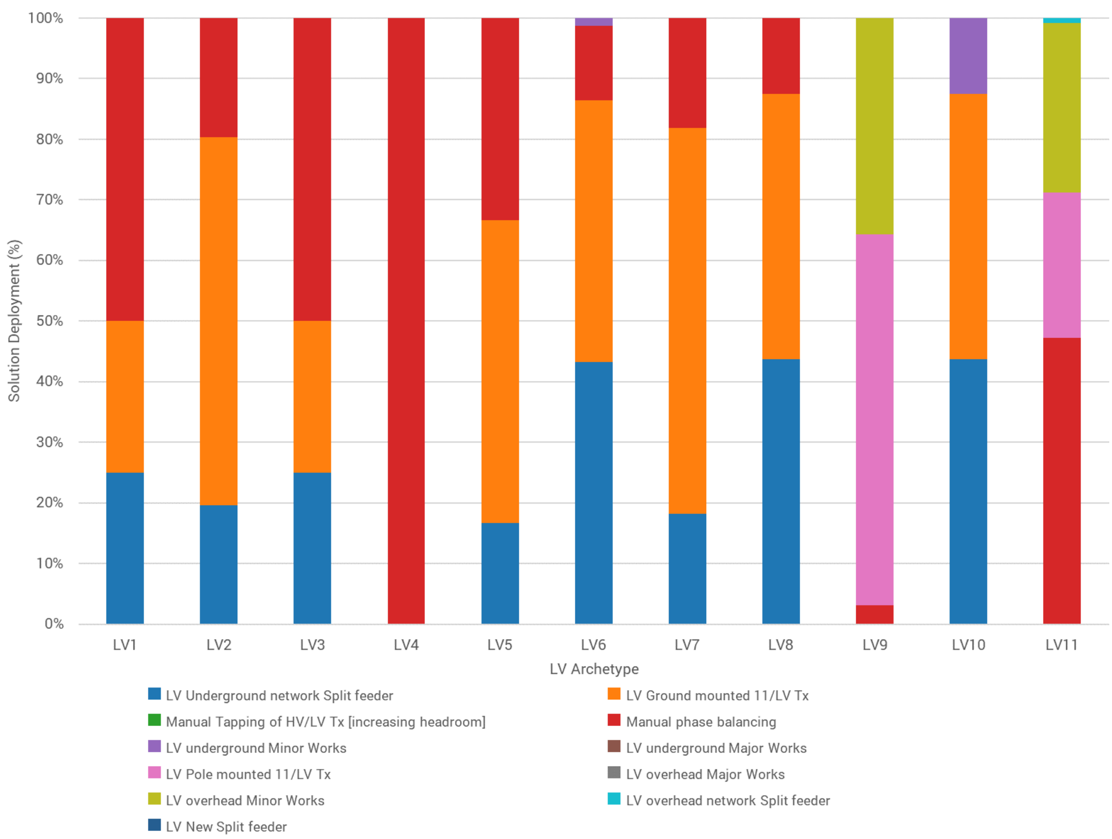

Figure 24: BaU solutions deployed across the LV network archetypes in the Best View scenario in the West Midlands.

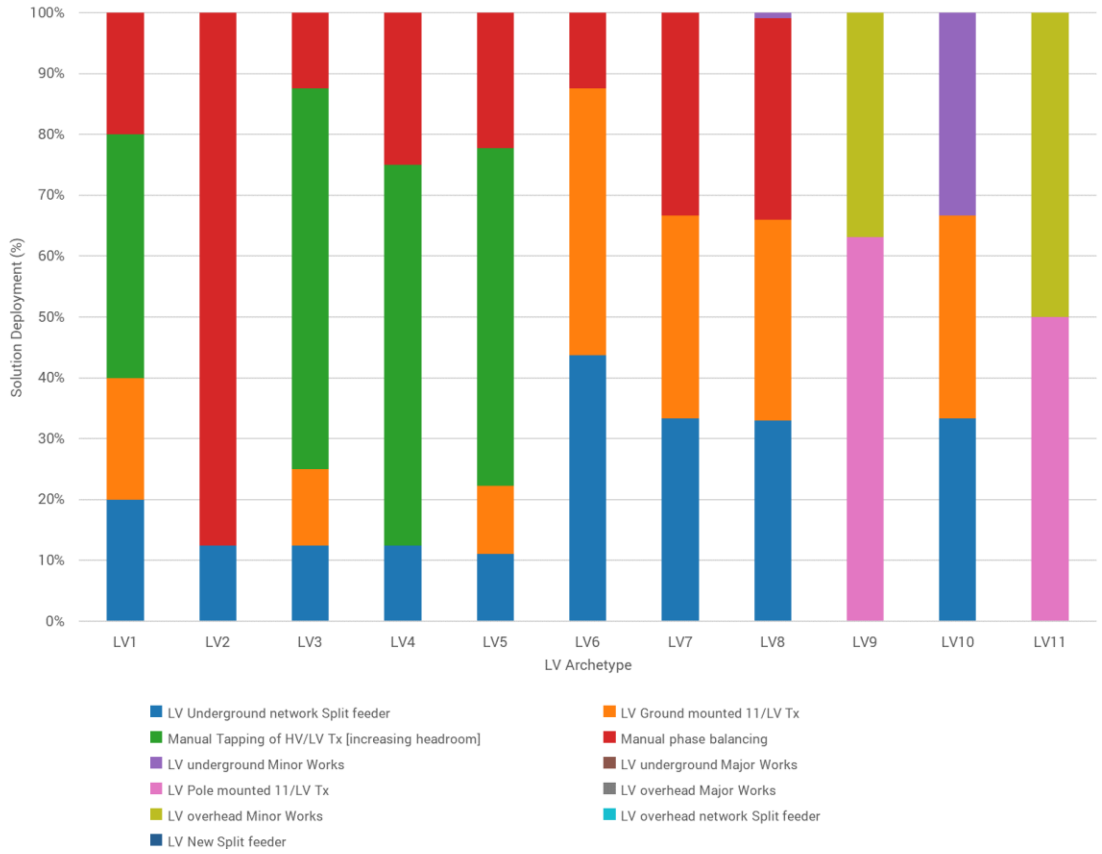

Figure 25: BaU solutions deployed across the LV network archetypes in the Best View scenario in South Wales.

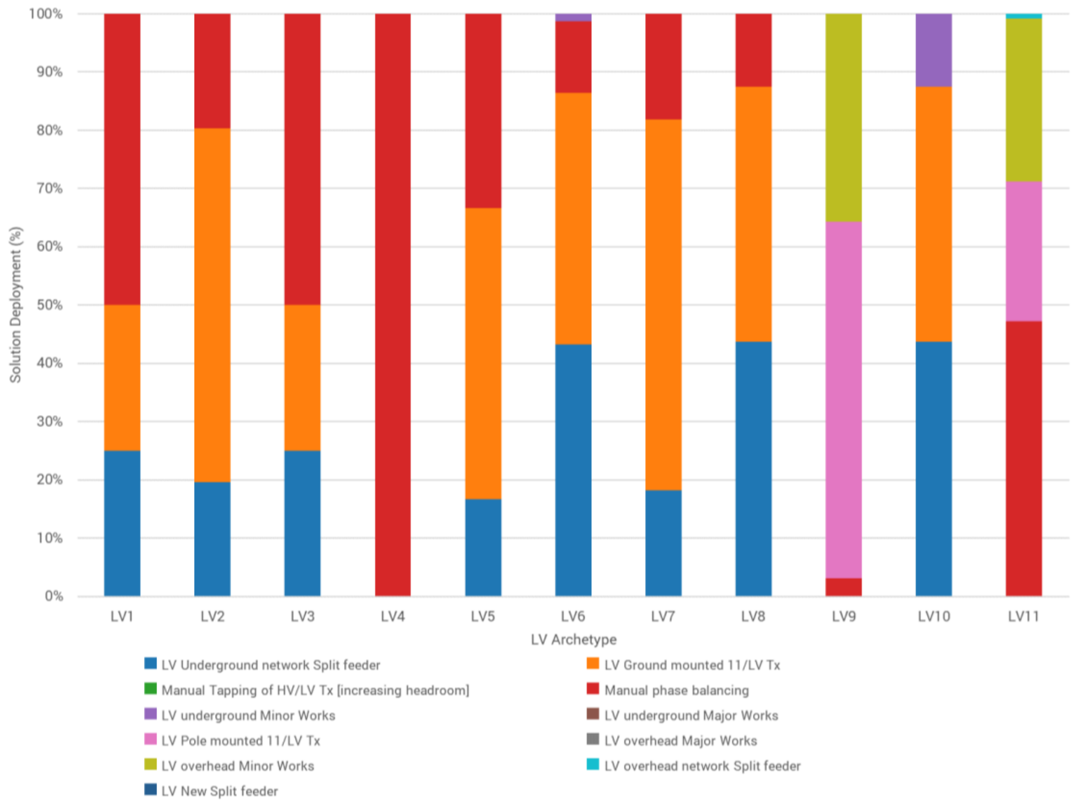

Figure 26: BaU solutions deployed across the LV network archetypes in the Best View scenario in the South West.

6. Novel Solutions Study

The aim of this project is to increase utilisation of existing LV assets to extract most possible value at the minimum cost to the consumer. The Literature Review [1] and RfI process was conducted to identify novel solutions that may offer value to the network operator by allowing the network operator to extract more value out of the existing LV network.

To assess which novel solutions are cost effective technologies for extracting more value from the existing LV network, a study was conducted with a solution set containing the BaU solutions (see Table AIII.1) used in the counterfactual case (see section 3), together with the novel solutions. Further discussions were held with providers who engaged in the RfI process to gather a thorough understanding of how to model each technology in the analysis. The full set of novel technologies modelled, together with their associated parameters (Capex, Opex and headroom release) were agreed and can be found in Table AV.1 with their assumed costs and headroom releases. This section of the report presents analysis of the results from this study.

Flexible Solutions

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
- Behind-the-meter 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. Should flexibility solutions offer an alternative method of managing the LV network at a lower cost than the technological solutions covered in this report, then flexibility should be strongly considered as an alternative to a technological solution. 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 flexibility services.

R2. Managing the LV network utilising flexible solutions should be revisited once understanding of flexible solutions including customer engagement and price point has been developed further.

6.1 Network Wide Solution Analysis

6.1.1 BaU and Novel Deployment

Figure 27 shows the proportion of the LV network that BaU and Novel technologies are deployed to, by licence area and scenario. It shows that novel technologies get deployed in conjunction with BaU technologies showing that although novel technologies offer value to the network operator there will remain a need for BaU technologies. While novel technologies will help extract greater value from existing assets, there will be many cases where new BaU assets will need to be installed in order to support the forecast deployment of LCTs. Section 6.1.3 gives more detail on the relative proportions of BaU and novel technologies deployed.

Figure 28 shows the BaU and novel proportions of total technologies deployed across National Grid's four licence area and the three scenarios. BaU and novel technologies are deployed in roughly equal ratios. There is some variation between licence areas and scenarios, although the variation is small. In South Wales, the proportion of novel technologies increases in the Best View scenario compared to the Steady Progress scenario, whereas in the other licence areas this proportion decreases as more aggressive uptake rates of LCTs drive the need for increasing traditional BaU interventions ahead of novel interventions. In South Wales, the uptake rates are such that in particular clustering bins novel technologies are required with the higher uptake rate associated with Best View compared to Leading the Way where no solutions are required. This increases the proportion of novel technologies in the Best View scenario relative to the proportion of BaU technologies in the Steady Progress scenario.

C4. Novel technologies offer alternative solutions and get widely deployed in parallel with BaU technologies across all licence areas and scenarios

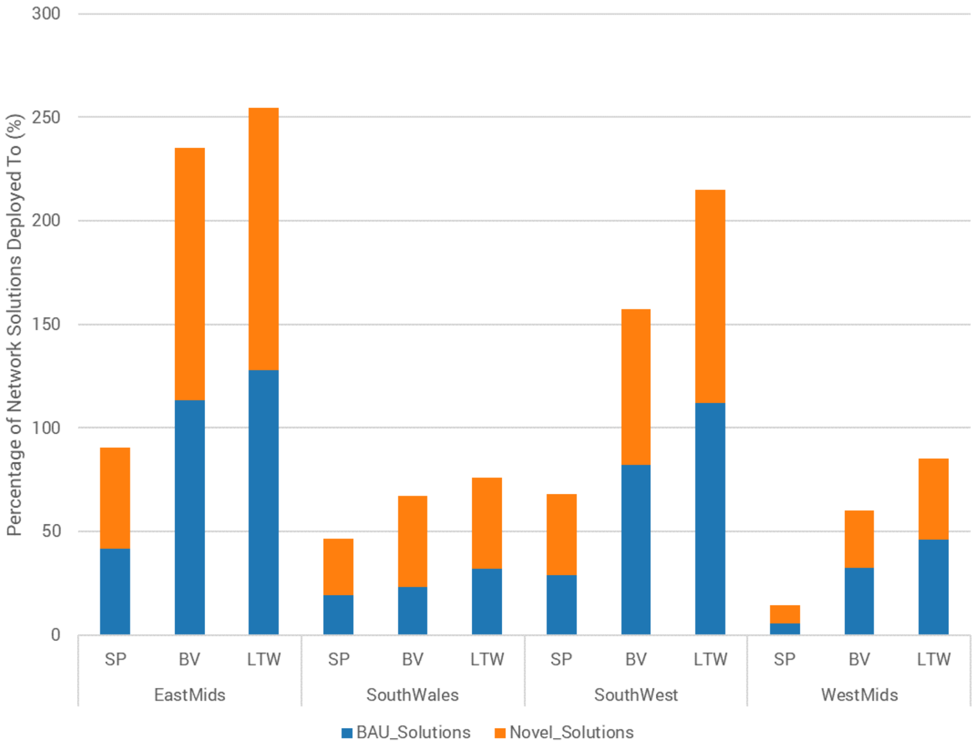

Figure 27: Proportion of novel and BaU technologies deployed to the LV network

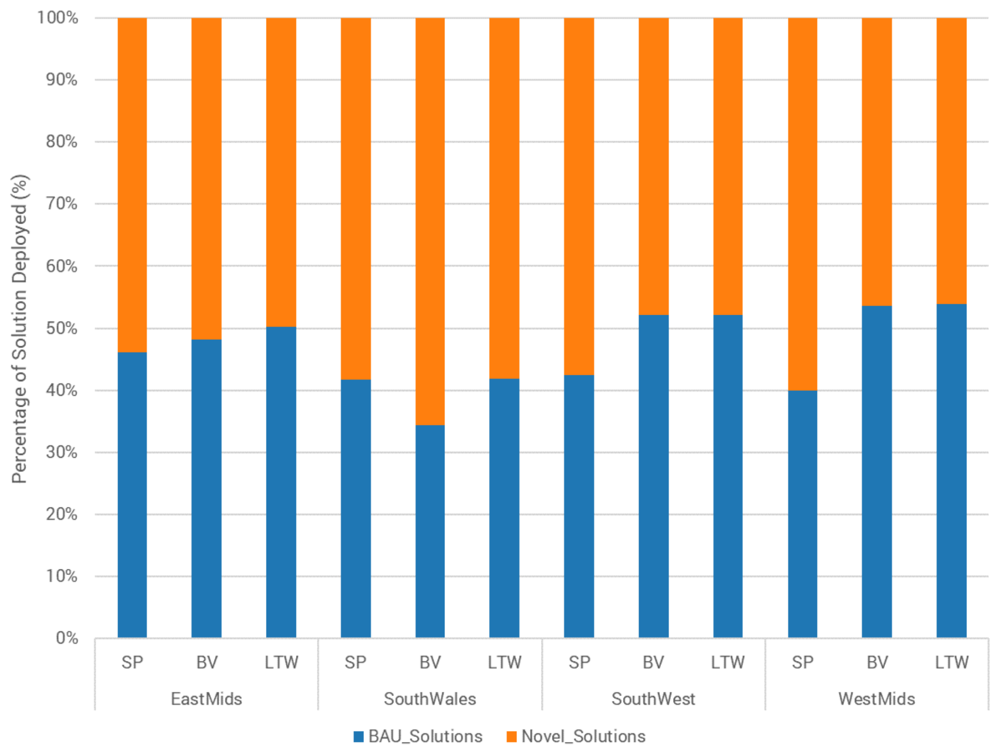

Figure 28: Proportion of technologies deployed that are BaU solutions and Novel solutions

6.1.2 Cumulative Solution Deployment

Figure 29 to Figure 32 show the cumulative deployment of BaU and Novel technologies in the Best View scenario for the years 2028, 2033, 2040 and 2050 respectively. A large variety of both BaU and novel solutions get deployed in varying quantities. Solution deployment increases as years progress, due to further constraints that occur on the LV network. There is a distinct increase in the ratio of novel technologies deployed compared to BaU technologies as years progress, which is analysed further in section 6.1.3. The most commonly deployed novel technologies across National Grid's four licence areas by 2050 are:

1. Network Data Monitoring
2. Active Network Management
3. Active Transformer Cooling
4. Permanent Meshing of Network (both LV Urban and LV Sub-Urban)

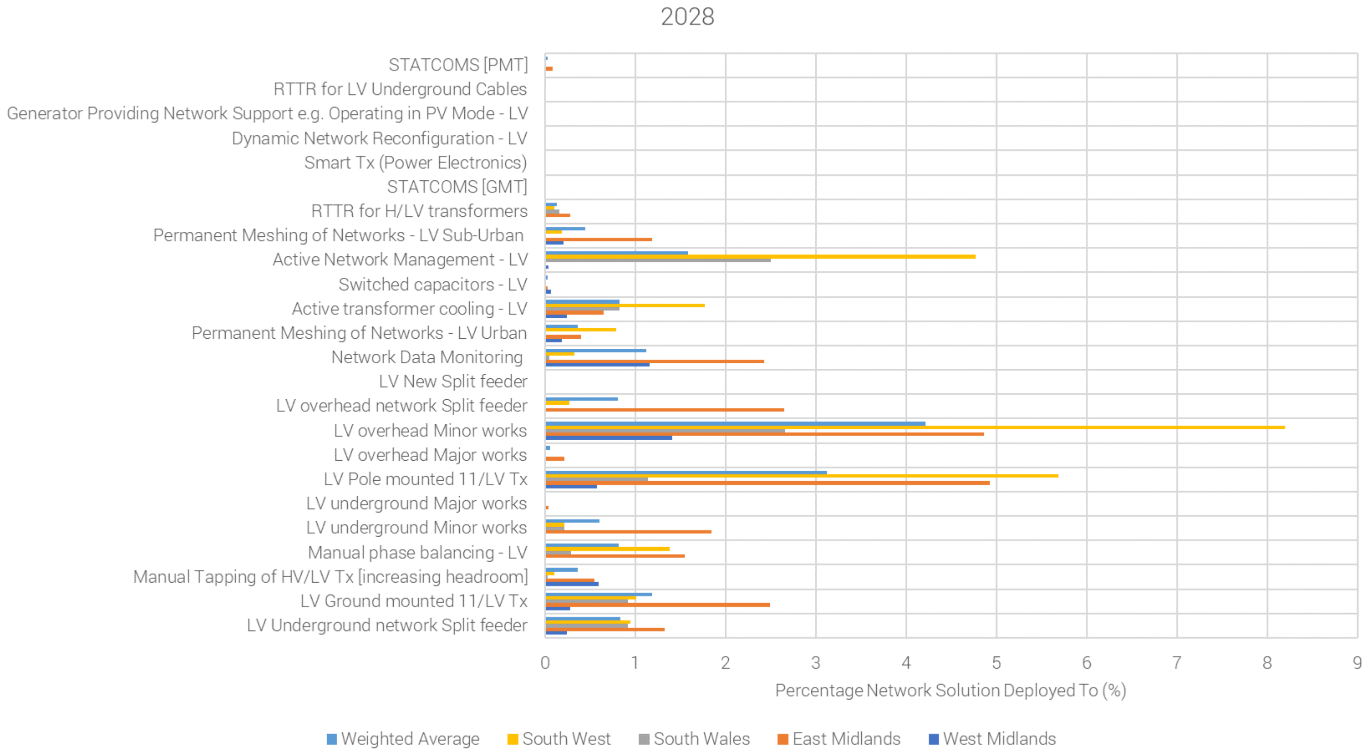

Figure 29: BaU and Novel solutions deployed up to 2028

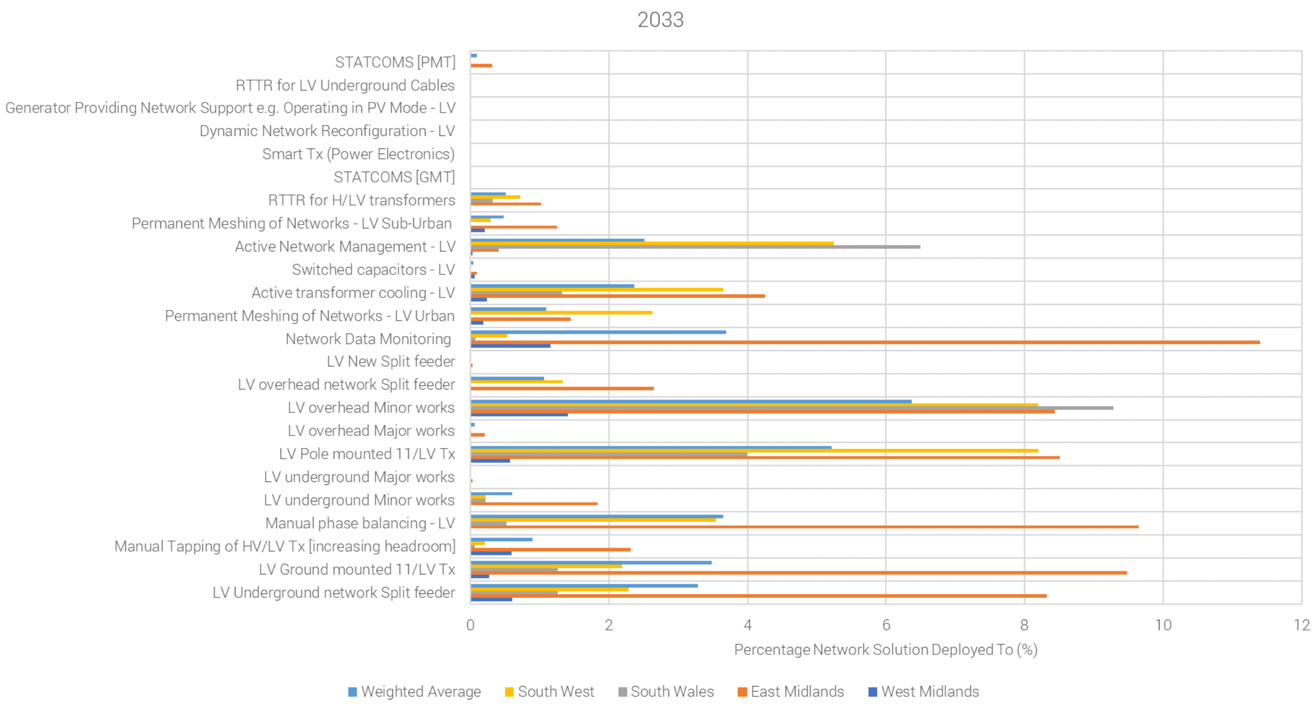

Figure 30: BaU and Novel solutions deployed up to 2033

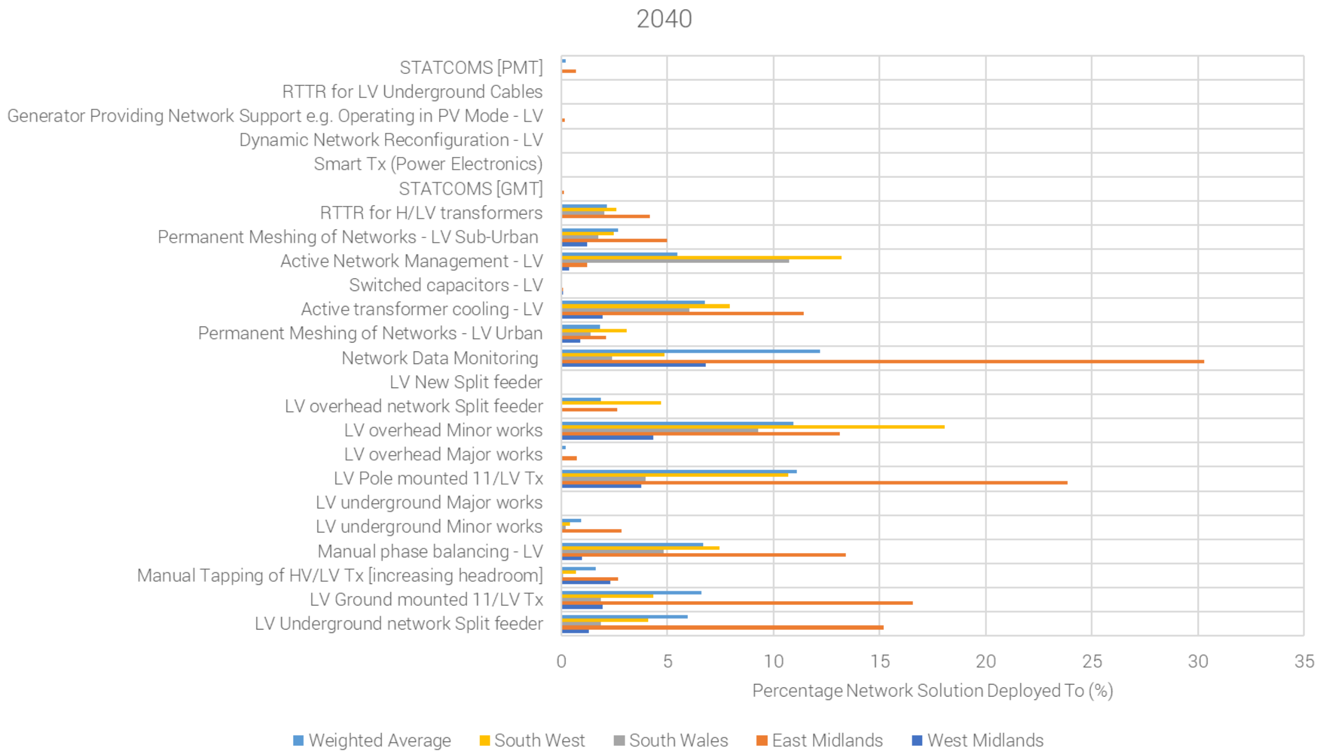

Figure 31: BaU and Novel solutions deployed up to 2040

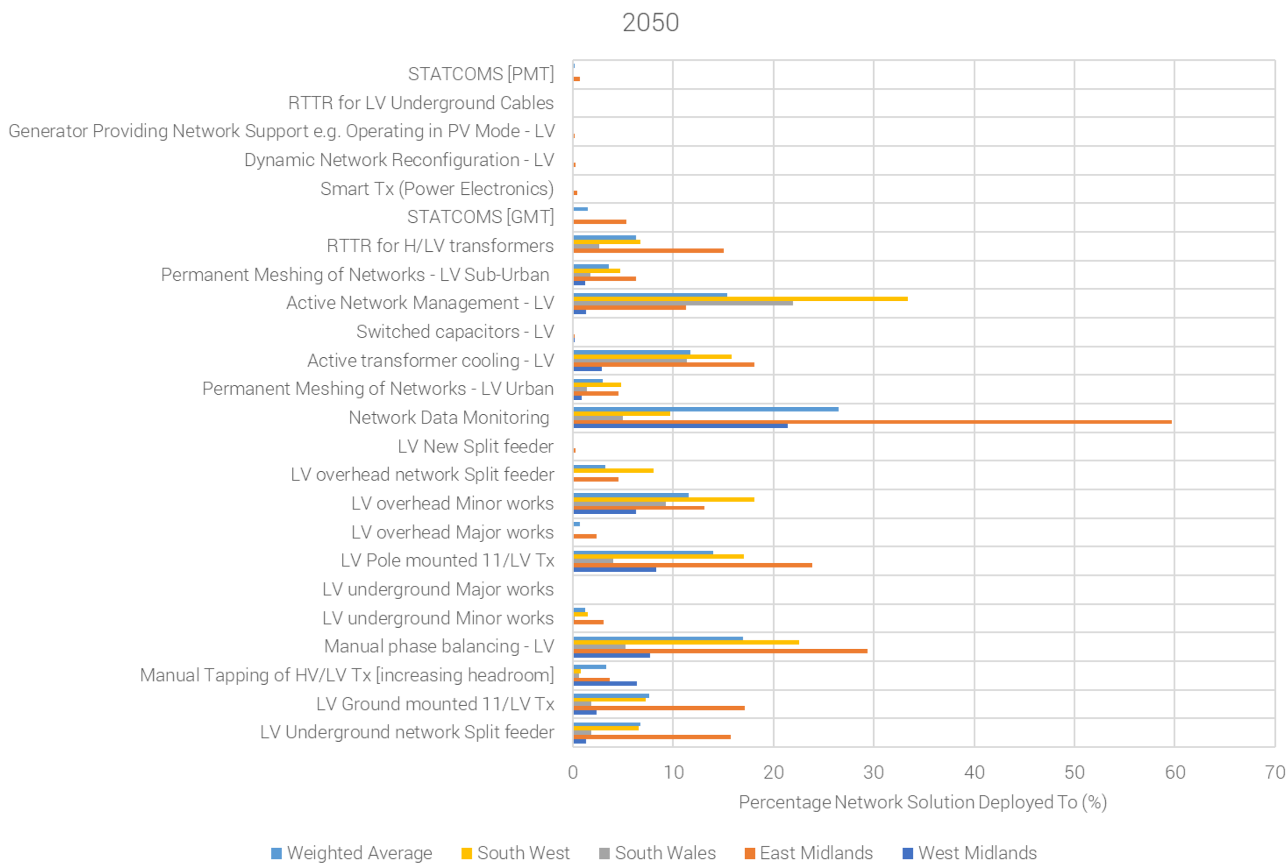

Figure 32: BaU and Novel solutions deployed up to 2050

6.1.3 Solutions by Period

Figure 33 shows the (weighted average across all National Grid licence areas) BaU (solid colours) and novel (hatched colours) solutions deployed grouped into the time periods 2022-2028, 2029-2033, 2034-2040 and 2041-2050. A comparison can be made with Figure 21, which shows the solutions deployed when only BaU solutions were available to the model. Figure 34 compares the solutions deployed in when in the counterfactual (BaU only) study compared to the study with BaU and Novel technologies available. This plot shows that:

- The total volume of interventions required in the counterfactual and novel studies are similar in the first two time periods 2022-2028 and 2029-2033. The number of BaU solutions deployed in the novel study is less than in the counterfactual study, with novel technologies deployed to fill the gap.
- The total volume of interventions required in the novel study is significantly higher than in the counterfactual study for the time periods 2034-2040 and 2041-2050. Again the number of BaU technologies deployed is reduced in the novel study, but the number of novel interventions required exceeded the BaU interventions avoided, leading to the greater total number of interventions. The impact of this on resourcing levels will need to be carefully considered. For example, this could increase total staff workload but delay some of the more time consuming heavy network interventions until later. Additionally, novel solutions will increase diversity in solution requiring potentially decreasing pressure on procurement from the supply chain.
- In the novel study, the interventions required in the 2041-2050 time period was higher than the 2034-2040 time period, whereas in the counterfactual study a drop in numbers of interventions required between the two time periods is observed.

Assessing the technologies deployed, it can be observed that:

- BaU technologies such as LV overhead minor works, LV Ground Mounted 11kV/LV Tx, LV underground network split feeder and LV underground minor works are deployed in reduced numbers in the BaU & Novel study compared to the counterfactual study. Alternative novel solutions are selected by Transform as a more cost-effective means of resolving LV network constraints.
- LV Pole Mounted 11kV/LV Tx also see reduced deployment in the time periods 2022-2028, with alternative novel technologies being selected by Transform as a more cost effective means to resolve network constraints. However, in the time periods 2034-2040 and 2041-2050 the number of PMTs deployed actually increases, suggesting that on particular feeders novel technologies act as temporary solutions in earlier time periods, delaying the need the higher cost new PMT.
- Noticeably Manual Phase Balancing is deployed in greater numbers in the 2041-2050 time period in the novel study than the counterfactual study. A large number of novel technologies are also deployed in this time period but a small number of many BaU solutions discussed in the above two bullet points. This suggest that a number combining novel and BaU technologies that release moderate headroom (such as manual phase balancing) can combine to release sufficient headroom and act as a more cost effective means of resolving network constraints than traditional BaU technologies.
- Novel technologies that see high levels of deployment include (in decreasing order of prevalence): Network Data Monitoring, Active Network Management, Active Transformer Cooling, RTTR for H/LV transformers, STATCOMs (ground mounted).

A key conclusion from this section is:

C5. In total, more solutions are deployed in the BaU plus Novel solution study than in the BaU solution study only. More solution deployments leads to a lower overall totex spend and wider supply chain diversity but may require additional staffing so careful management of resource will be required when deciding which technologies to deploy.

C6. The most commonly deployed novel solutions are (in descending order of prevalence): Network Data Monitoring, Active Network Management, Active Transformer Cooling, Real Time Thermal Ratings (RTTR) for H/LV transformers

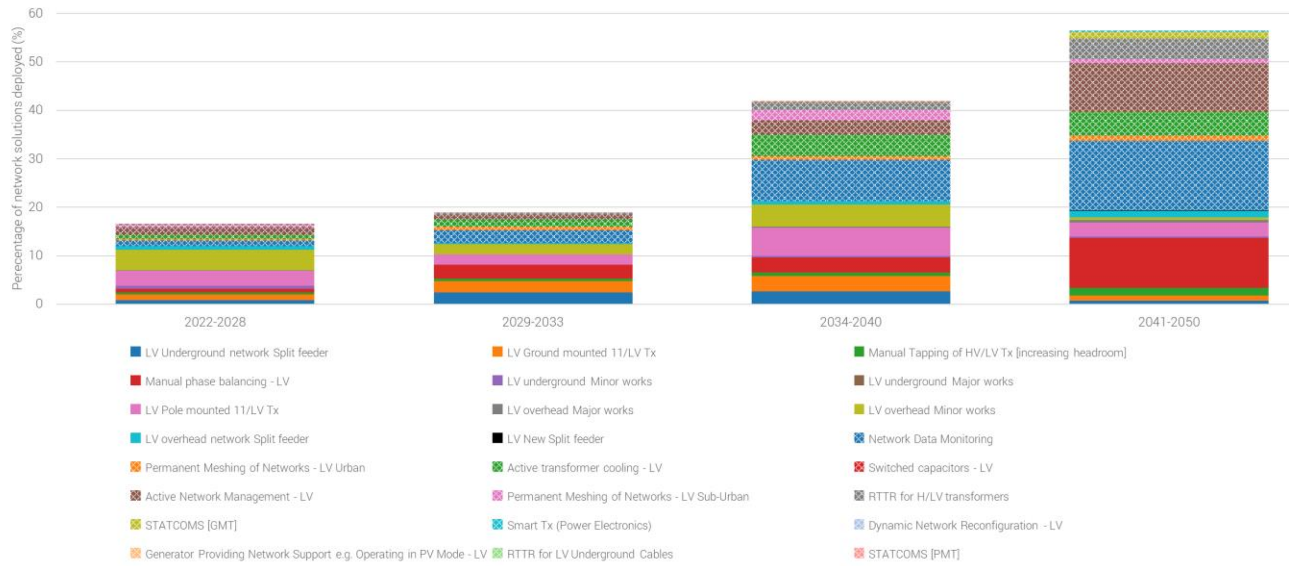

Figure 33: Deployment of Solution in time periods 2022-2028, 2029-2033, 2034-2040 and 2041-2050. BaU solutions are solid colours, whereas Novel solutions are hatched (patterned) colours.

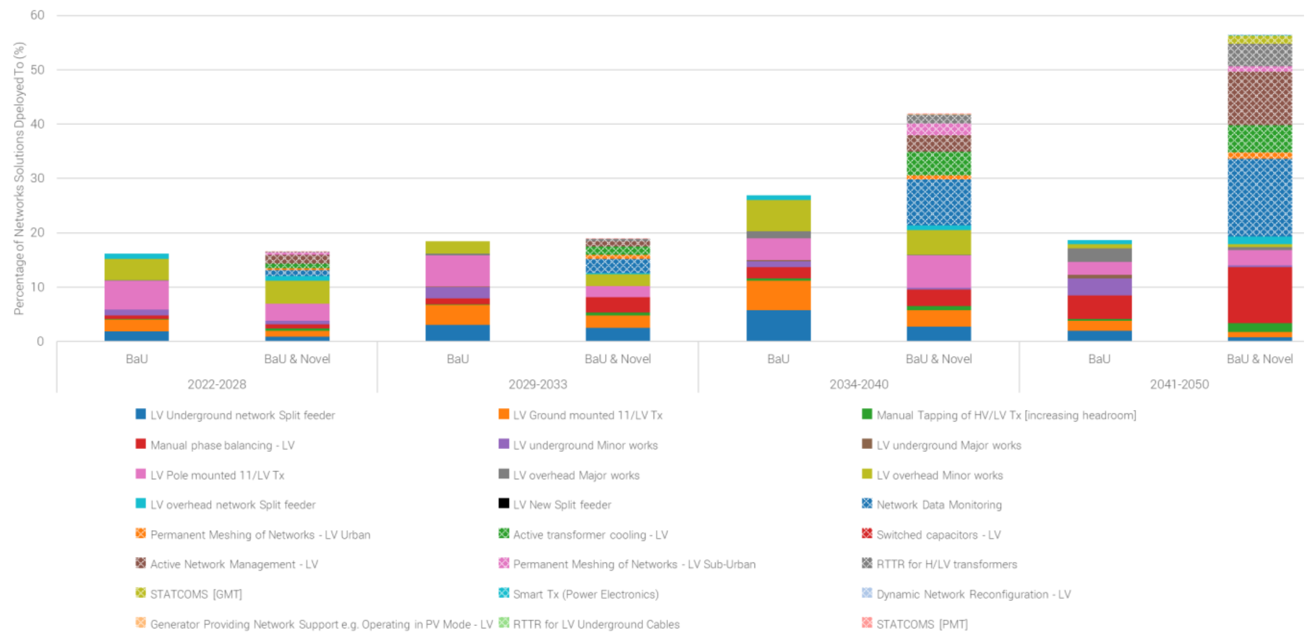

Figure 34: Side by side comparison of solutions deployed in counterfactual (BaU) study compared to BaU & Novel study.

6.1.4 Variation in Solution Deployment by Scenario

Figure 35 shows the proportion of BaU and Novel solutions deployed across National Grid's four licence areas under the three DFES scenarios. Comparison can be made with Figure 22 which plots the proportions of BaU solutions deployed across National Grid's four licence areas under the three DFES scenarios where only the BaU solutions were available. This leads to the following observations:

- In the BaU and Novel study, typically approximately 50%-60% of the solutions deployed are novel technologies, with the remainder of the solutions being BaU solutions.
- Solutions deployed across all four licence areas are broadly similar, but there is significant variation in ratios of solution deployment between licence areas.
- BaU solutions selected are similar in both studies, showing all BaU solutions are still required to resolve constraints on the LV network. However, the relative prevalence of BaU solution decreases as Novel technologies displace the need for as many interventions on the network. Note also the effect shown in section 6.1.3 where it is shown more solutions are deployed in total in the BaU plus novel study than in the BaU only study.
- Novel solution deployment in East Midlands and West Midlands is broadly similar, dominated by Network Data Monitoring. Other novel technologies are deployed in these licence areas in much small quantities.
- Novel solution deployment in South Wales and South West is broadly similar, dominated by Active Network Management and Active Transformer Cooling. Other novel technologies such as Network Data Monitoring, Permanent Meshing of Networks and RTTR for H/LV Transformers are deployed in much small quantities.

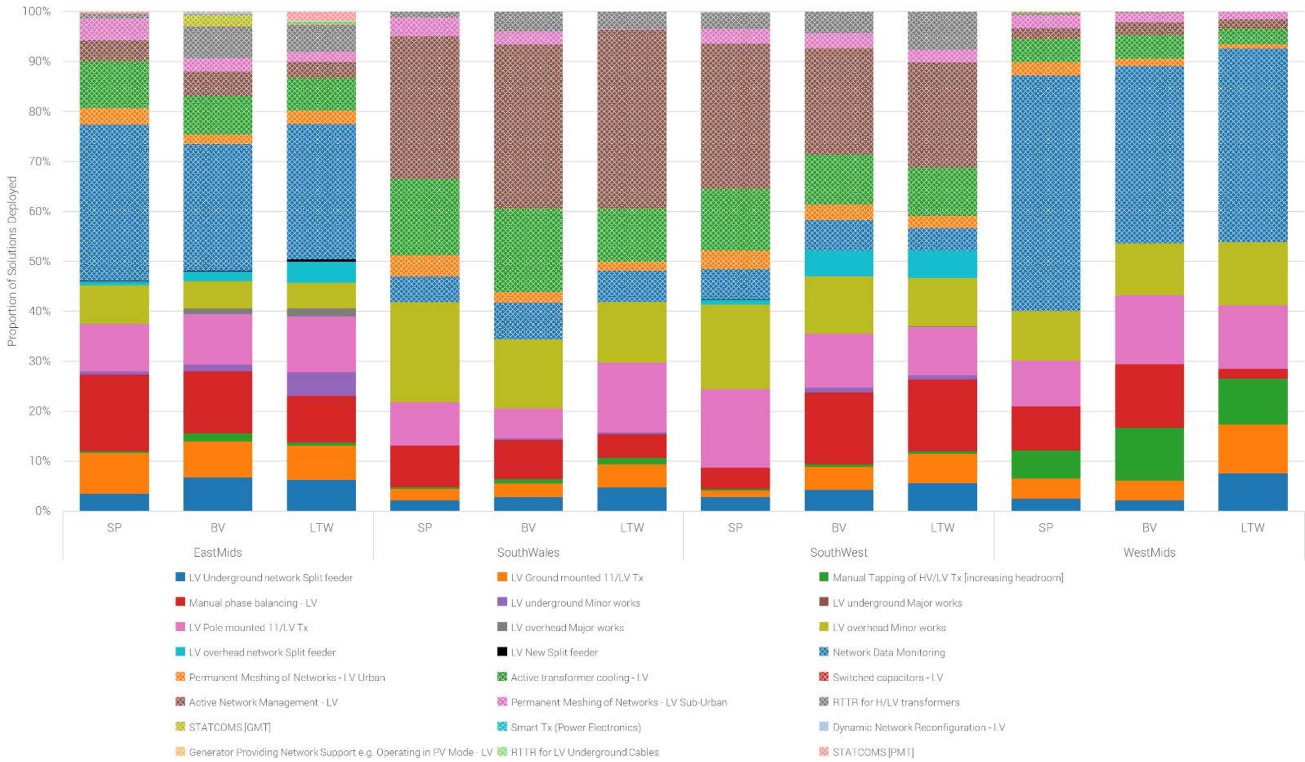

Figure 35: BaU and Novel Solution Deployments as proportion of total interventions for National Grid's four licence areas and three DFES scenarios

In conclusion:

C7. Solutions deployed across each licence area are broadly similar regardless of the DFES scenario. Therefore, the network operator can have confidence that regardless of the uptake rate of LCTs, similar types of solutions will be required. (The quantity of solution deployment will depend on the LCT uptake rates).

C8. Variation in technology uptake prevalence deployed in different licence areas shows that the technology deployment is highly sensitive to LCT uptake rate.

6.1.5 System Cost Analysis

Cumulative costs for reinforcing National Grid's electricity distribution licence area to support the growth of LCTs using BaU solutions only and combination of BaU and novel solutions have been plotted in Figure 36 to Figure 39. These figures display the discounted totex expenditure, with an assumed discount rate of 3.5%.

Figure 36 to Figure 39 show that the total expenditure is reduced when novel technologies are introduced for all licence areas. They also show that the reduced total expenditure when novel technologies are introduced occurs across all three scenarios[4]. 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 in the real world, 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.

[4] The benefit for South Wales in the Steady Progress scenario is marginal

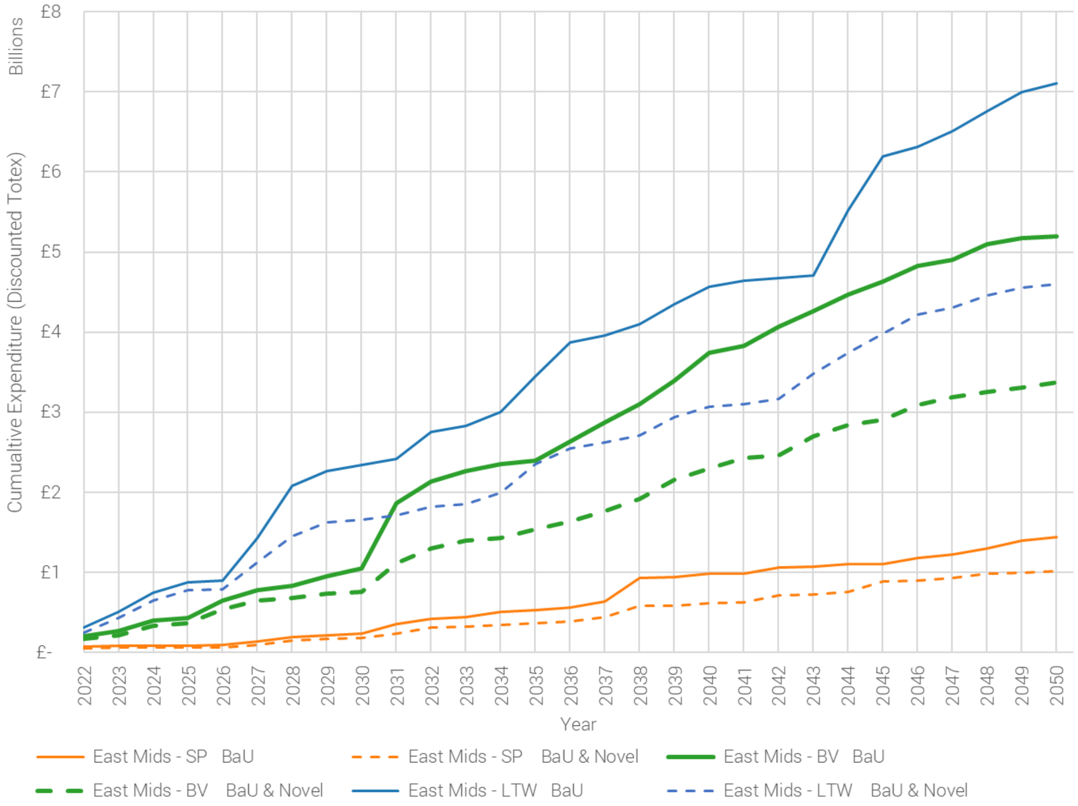

Figure 36: Cumulative discounted totex expenditure across the East Midlands licence area by scenario.

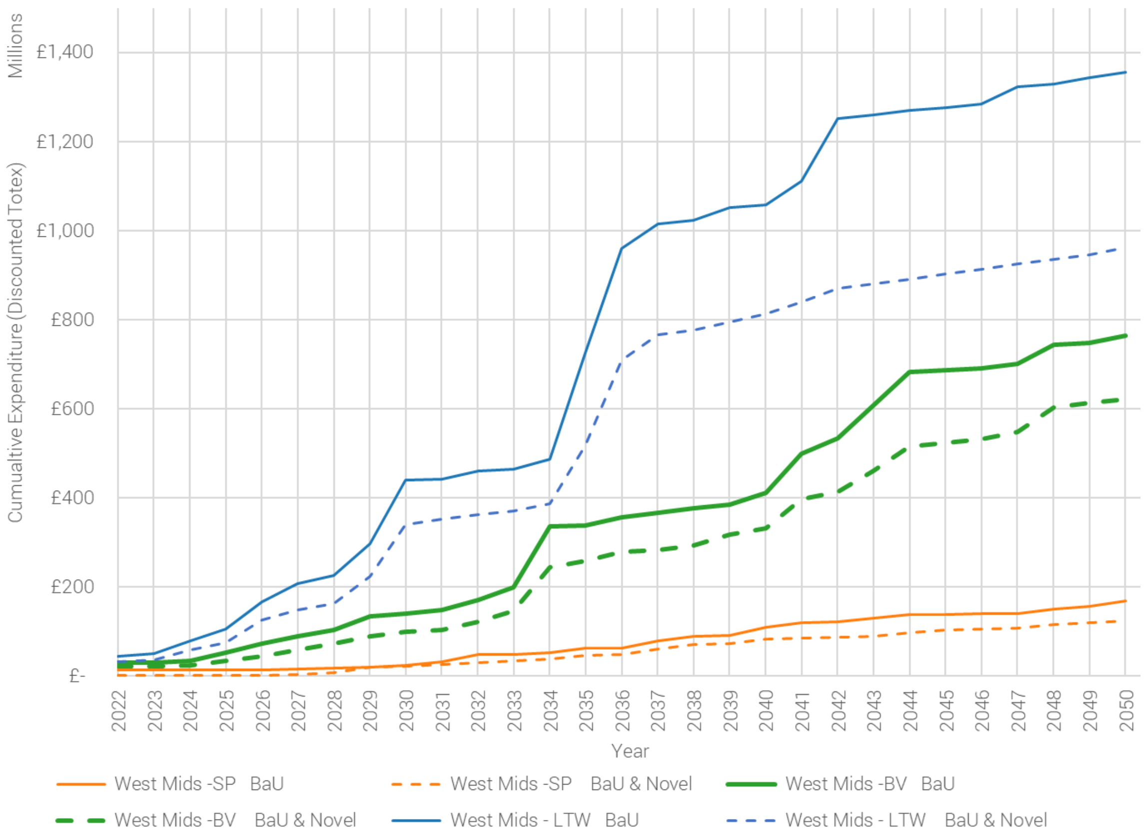

Figure 37: Cumulative discounted totex expenditure across the West Midlands licence by scenario.

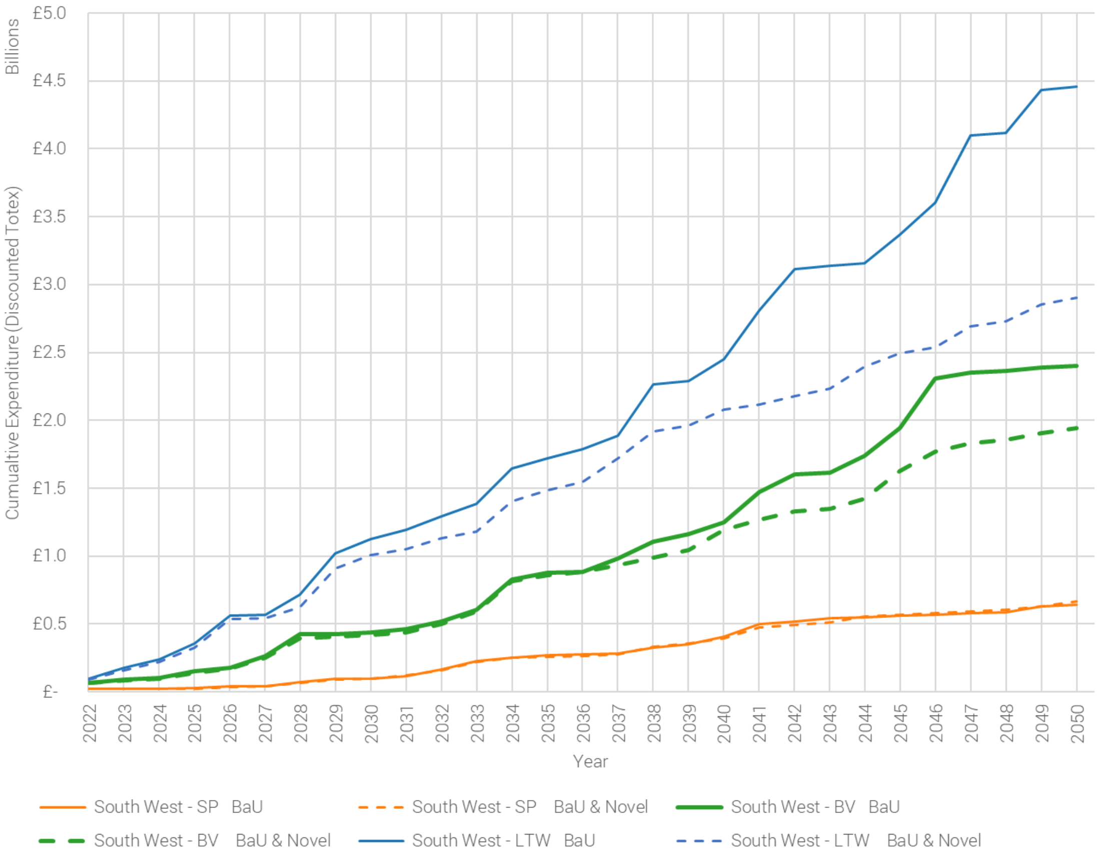

Figure 38: Cumulative discounted totex expenditure across the South West licence area by scenario.

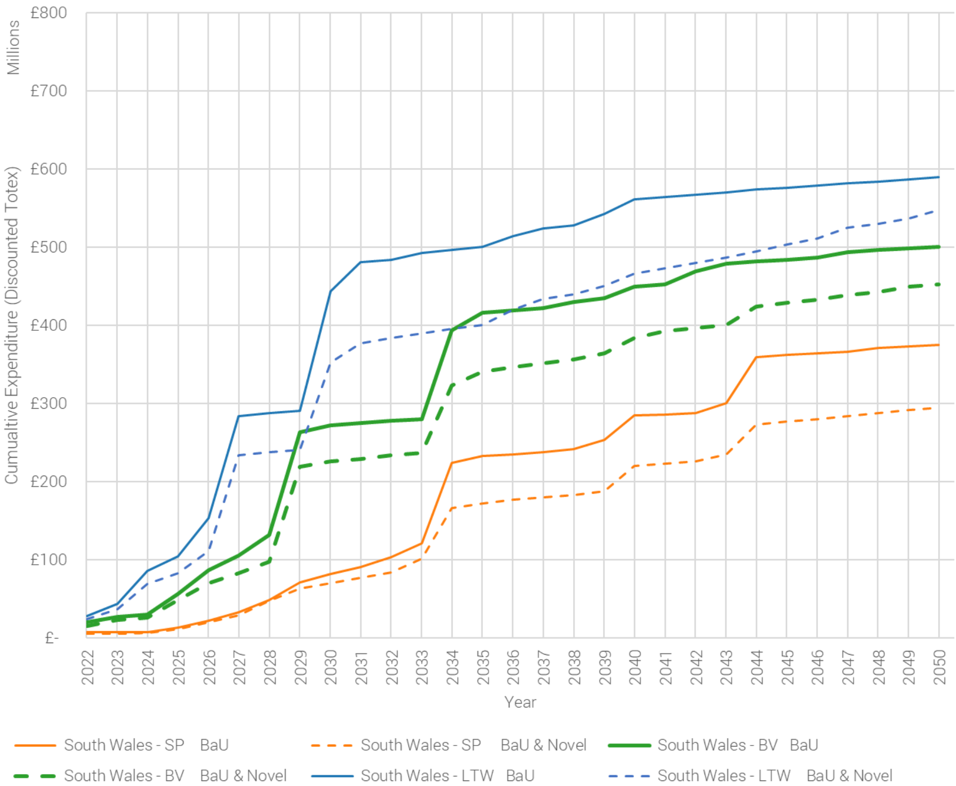

Figure 39: Cumulative discounted totex expenditure across the South Wales licence area by scenario.

C9. Novel solutions provide a saving of BaU costs through the deferral of investment. Sensitivity studies show that these savings are robust across differing LCT uptake rates and network topologies.

6.1.6 Solution Cost Sensitivity Study

The costs associated with BaU solutions in the Transform Model can vary from real world costs due to the wide variety of factors that impact the implementation of BaU solutions in the real world.. To reflect the uncertainty in BaU costs, two sensitivity studies have been performed, one where the BaU solution costs have been increased by 20% and the other where the BaU solution costs have been decreased by 20%. Figure 40 compares the solutions deployed in the Best View scenario for the West Midlands licence area with the costs varied as described. It shows little variation in the quantity and type of solutions that are deployed. This shows that the solutions deployed are not highly sensitive to the costs associated with them. This gives confidence that the results presented in this report are valid even accounting the real-world uncertainty and variation in technology prices,

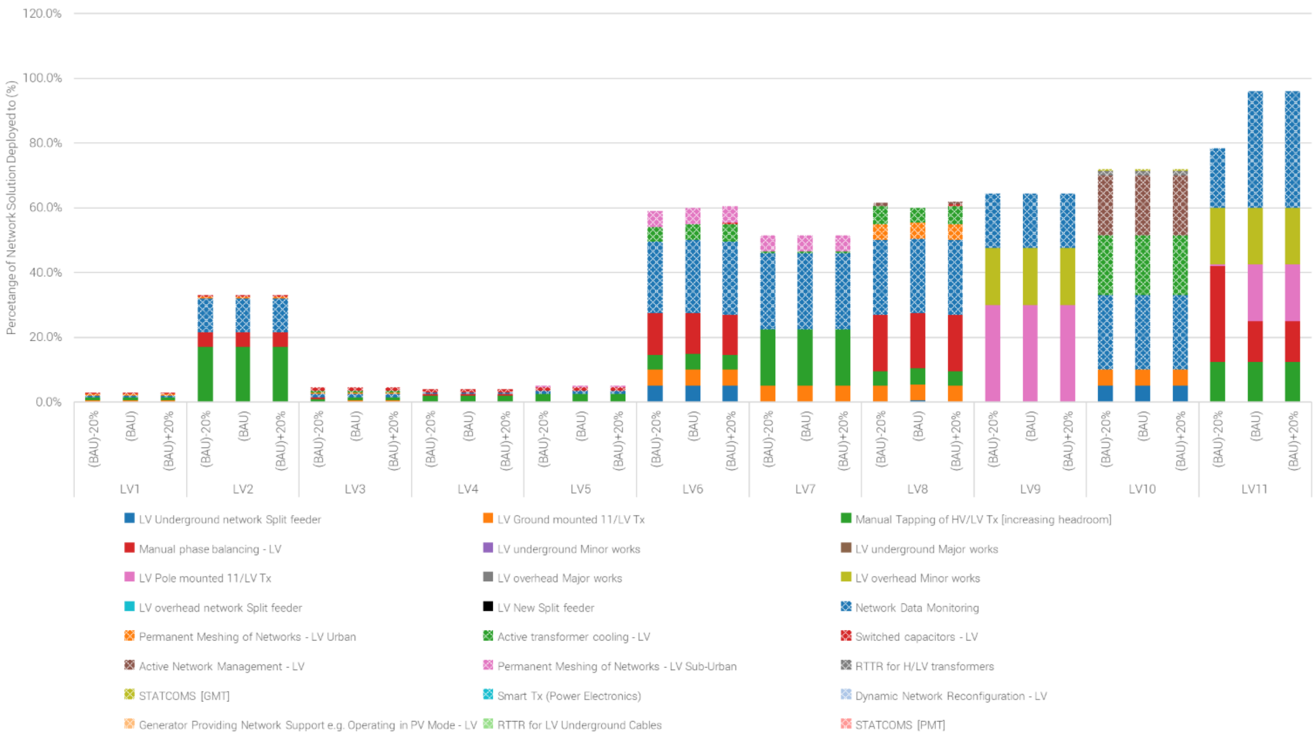

Figure 40: Sensitivity study showing solution deployed across all LV network archetypes in Best View scenario for West Midlands

6.2 Solution Analysis by Archetype

This section of the report presents analysis of the BaU and Novel technologies Transform study, breaking down which solutions are deployed to which LV network archetypes. Figure 41 to Figure 44 show the solution deployed across the 11 LV network archetypes in the Steady Progress scenario, Figure 45 to Figure 48 show the solutions deployed across the 11 LV network archetypes in the Best View scenario and Figure 49 to Figure 52 show the solutions deployed across the 11 LV network archetypes in the Leading the Way scenario. This analysis shows that:

- Most LV network archetypes under most scenarios have a range of both BaU and novel technologies deployed to resolve constraints.
- In Steady Progress, urban predominantly commercial LV archetypes LV1 (Central Business Districts), LV3 (Town Centres), LV4 (Business Parks) and LV5 (Retail Parks) witness only BaU technology deployments.
- Urban and sub-urban predominantly domestic LV archetypes LV6 (Suburban Streets), LV7 (New Build Housing Estates) and LV8 (Terraced Streets) often witness high levels of novel technology deployment, frequently in excess of 50% and sometimes approaching 80% novel technology deployment.
- Overhead rural LV archetypes LV9 (Rural Village Overhead Construction) and LV11 (Rural Farmsteads) often see high levels of BaU solution deployment, particularly in the more aggressive LCT uptake scenarios associated with Best View and Steady Progress.

Explanation for those LV network archetypes that see limited or no deployment of novel technologies is given in section 7 of this report.

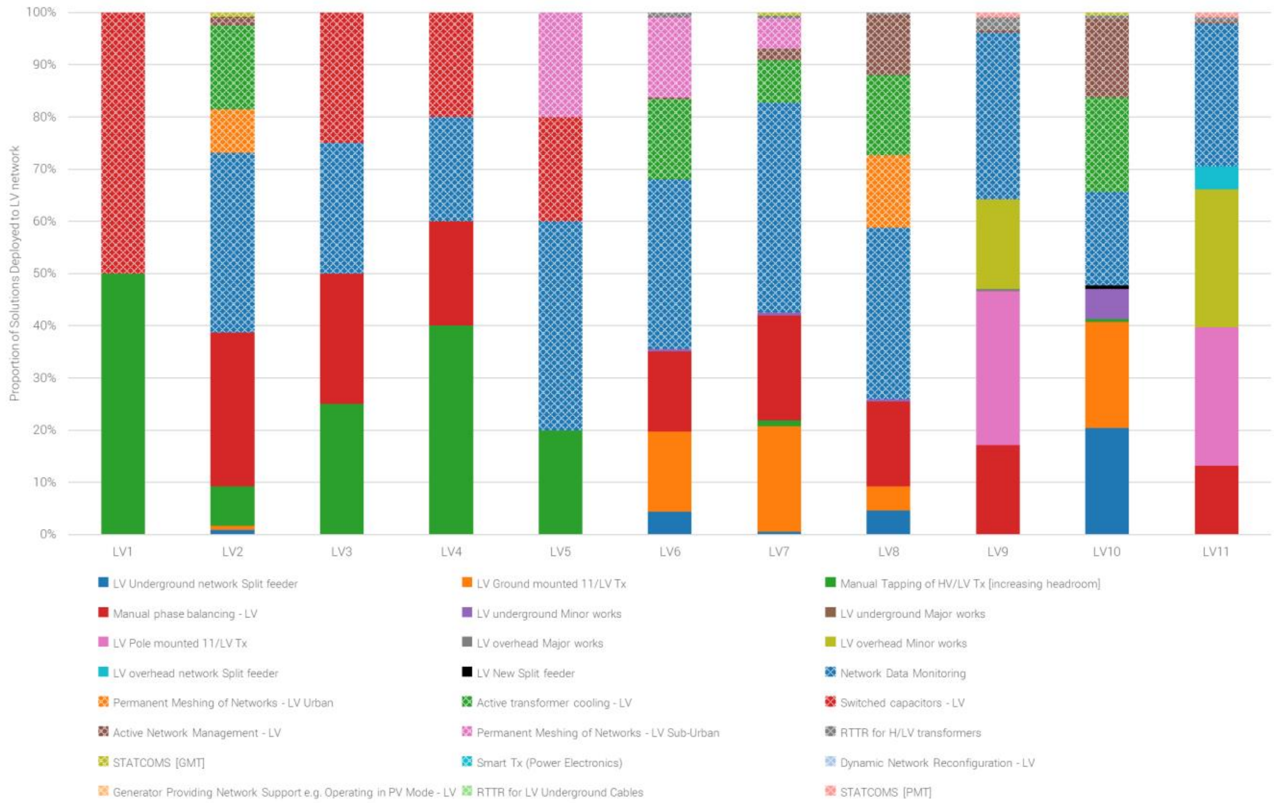

Figure 41: Proportion of BaU and Novel Solutions deployed by LV Network Archetype in East Midlands, Steady Progress scenario

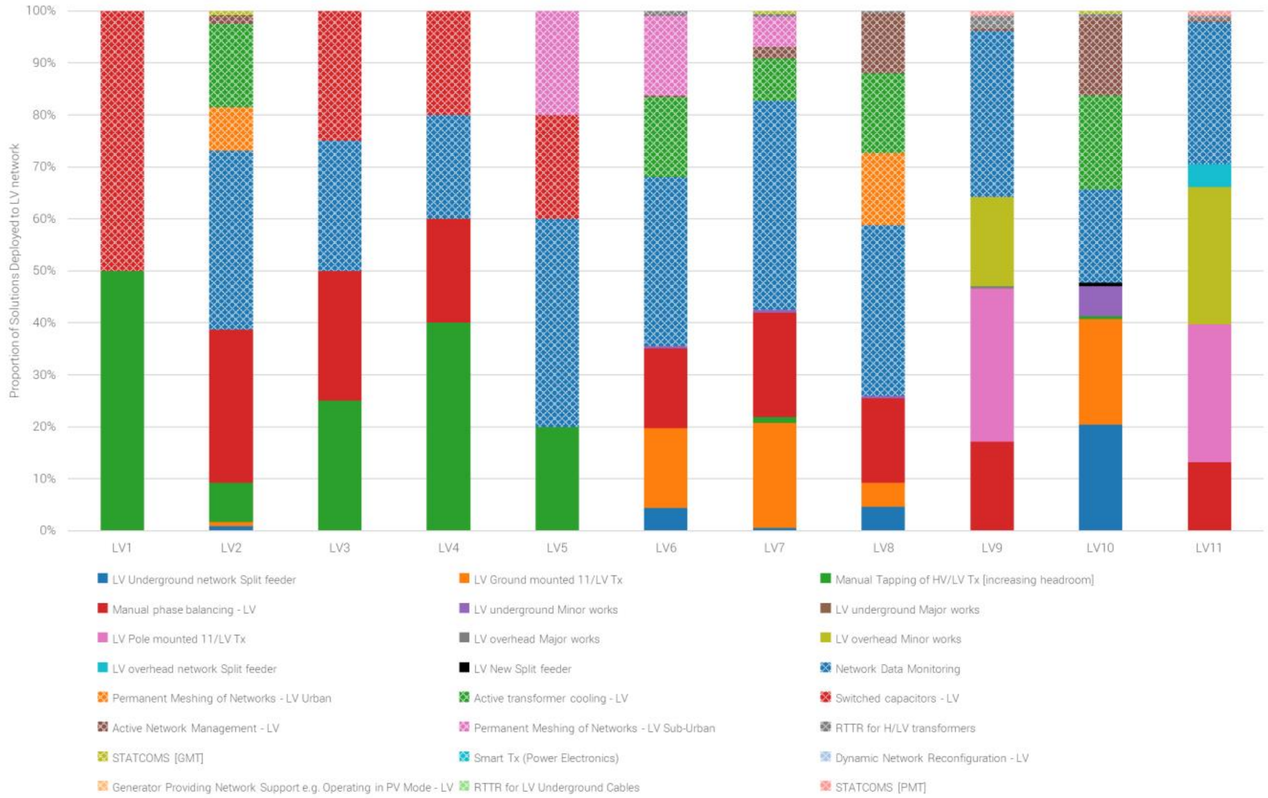

Figure 42: Proportion of BaU and Novel Solutions deployed by LV network archetype in West Midlands, Steady Progress scenario

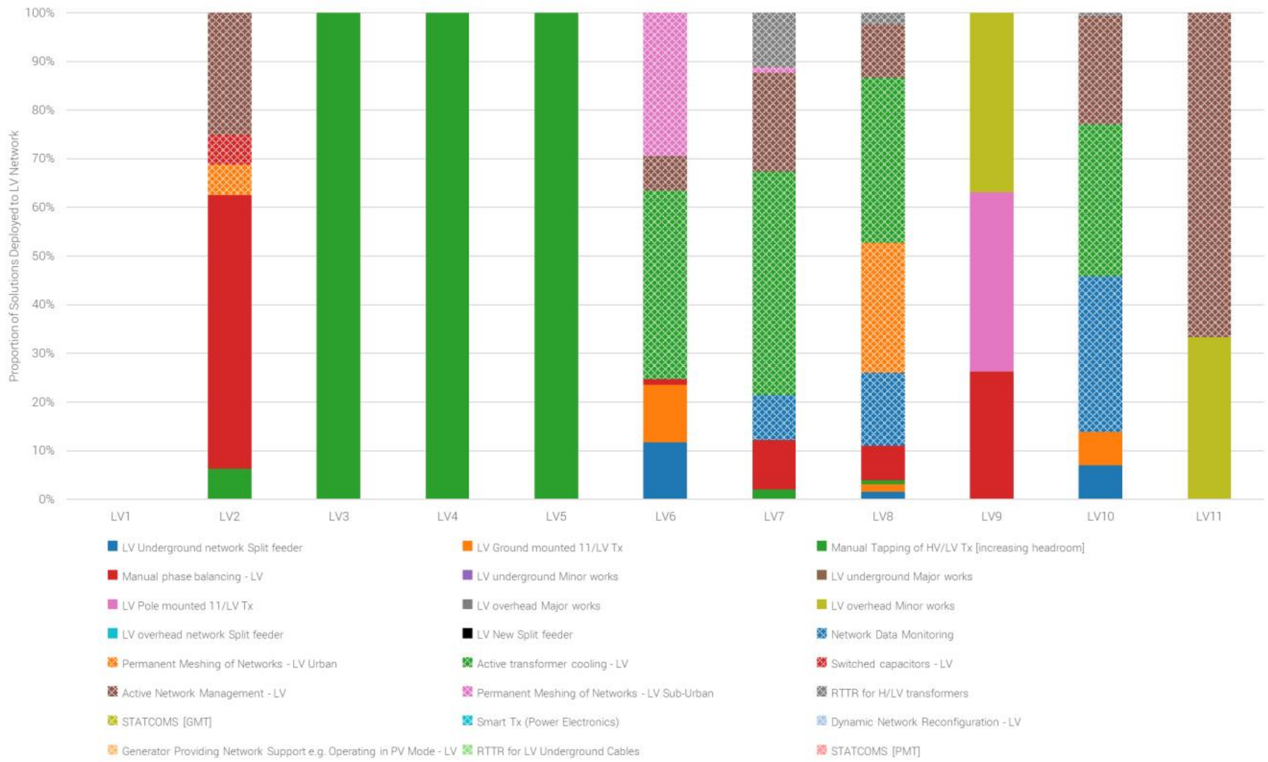

Figure 43: Proportion of BaU and Novel Solutions deployed by LV network archetype in South Wales, Steady Progress scenario

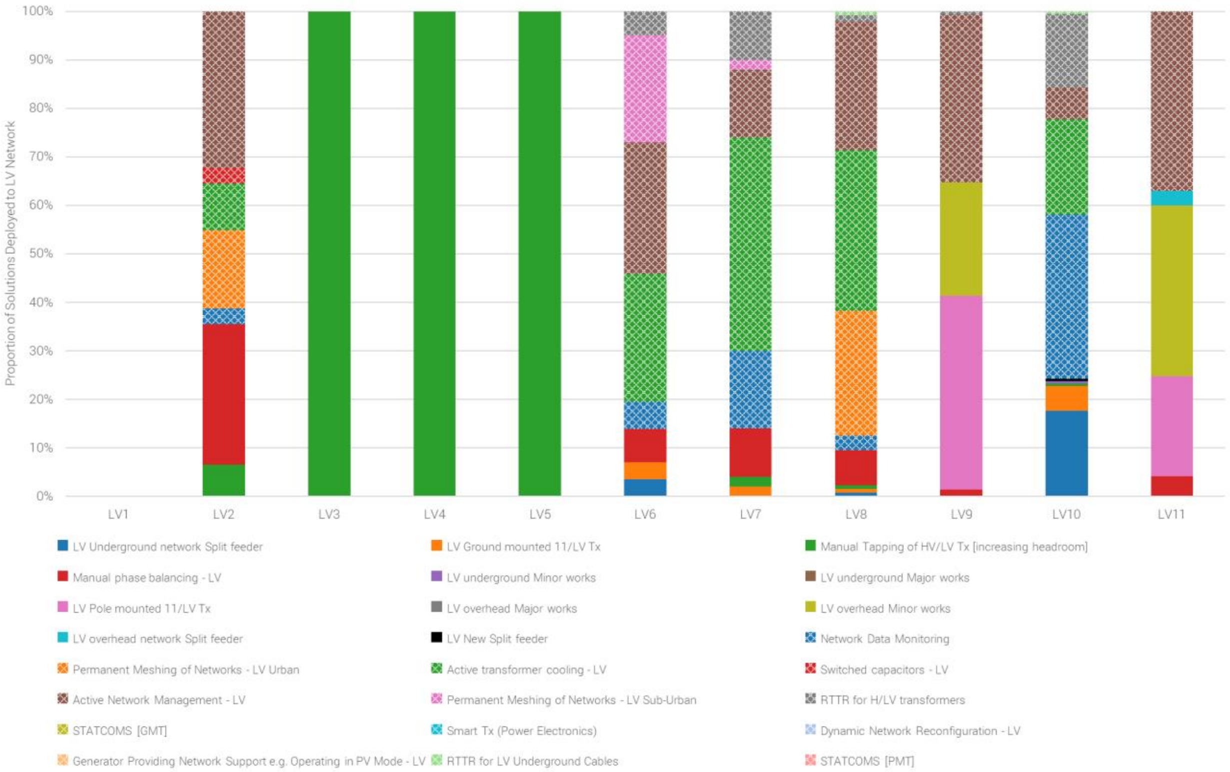

Figure 44: Proportion of BaU and Novel Solutions deployed by LV network archetype in South West, Steady Progress scenario

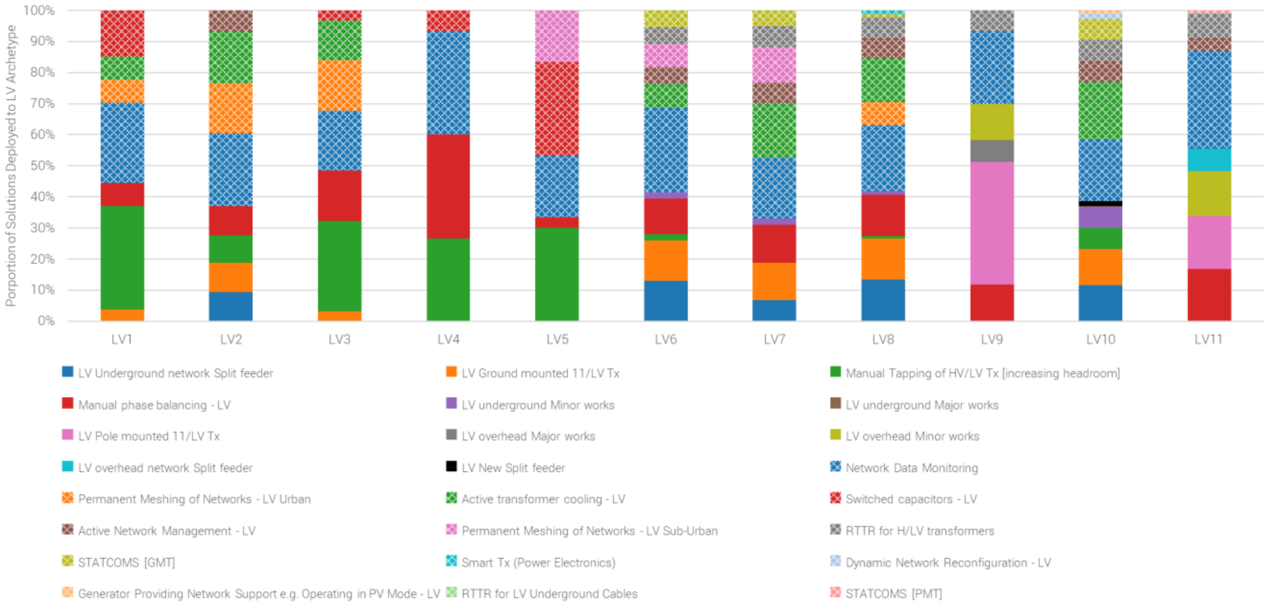

Figure 45: Proportion of BaU and Novel Solutions deployed by LV Network Archetype in East Midlands, Best View scenario

Figure 46: Proportion of BaU and Novel Solutions deployed by LV network archetype in West Midlands, Best View scenario

Figure 47: Proportion of BaU and Novel Solutions deployed by LV network archetype in South Wales, Best View scenario

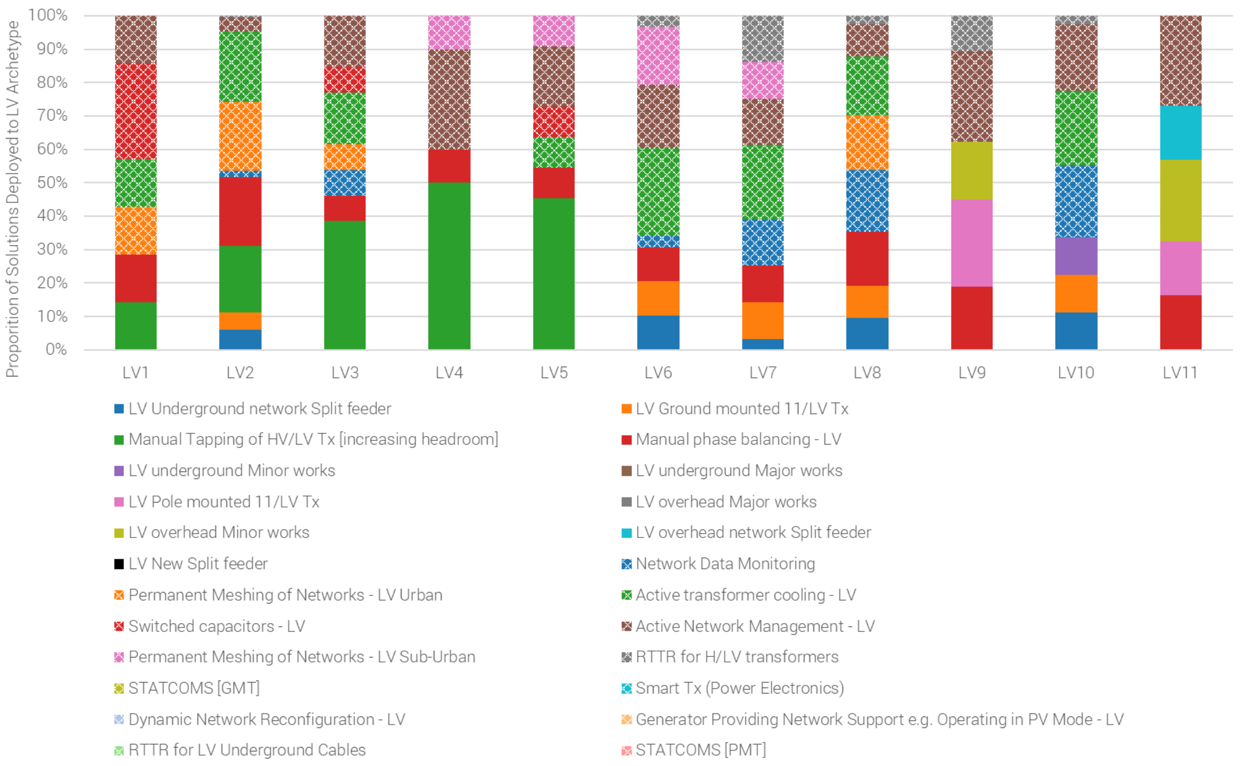

Figure 48: Proportion of BaU and Novel Solutions deployed by LV network archetype in South West, Best View scenario

Figure 49: Proportion of BaU and Novel Solutions deployed by LV Network Archetype in East Midlands, Leading the Way scenario

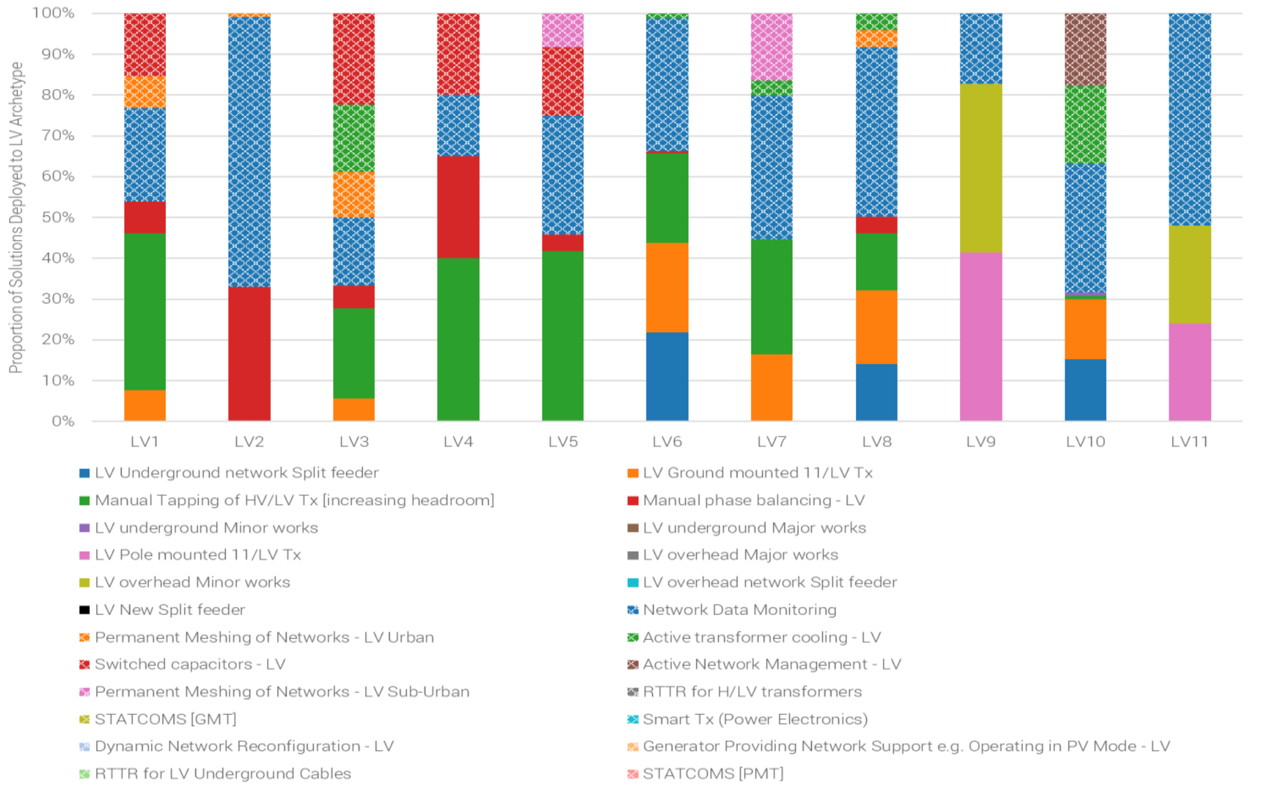

Figure 50: Proportion of BaU and Novel Solutions deployed by LV Network Archetype in West Midlands, Leading the Way scenario

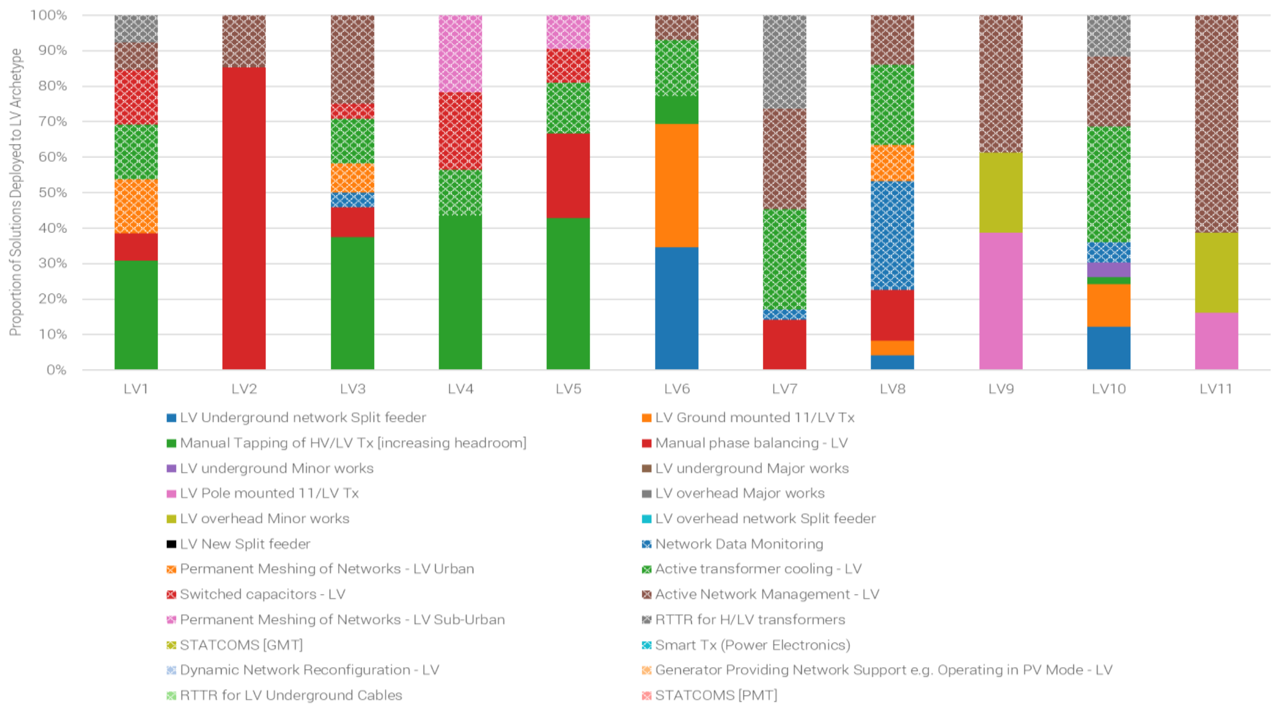

Figure 51: Proportion of BaU and Novel Solutions deployed by LV Network Archetype in South Wales, Leading the Way scenario

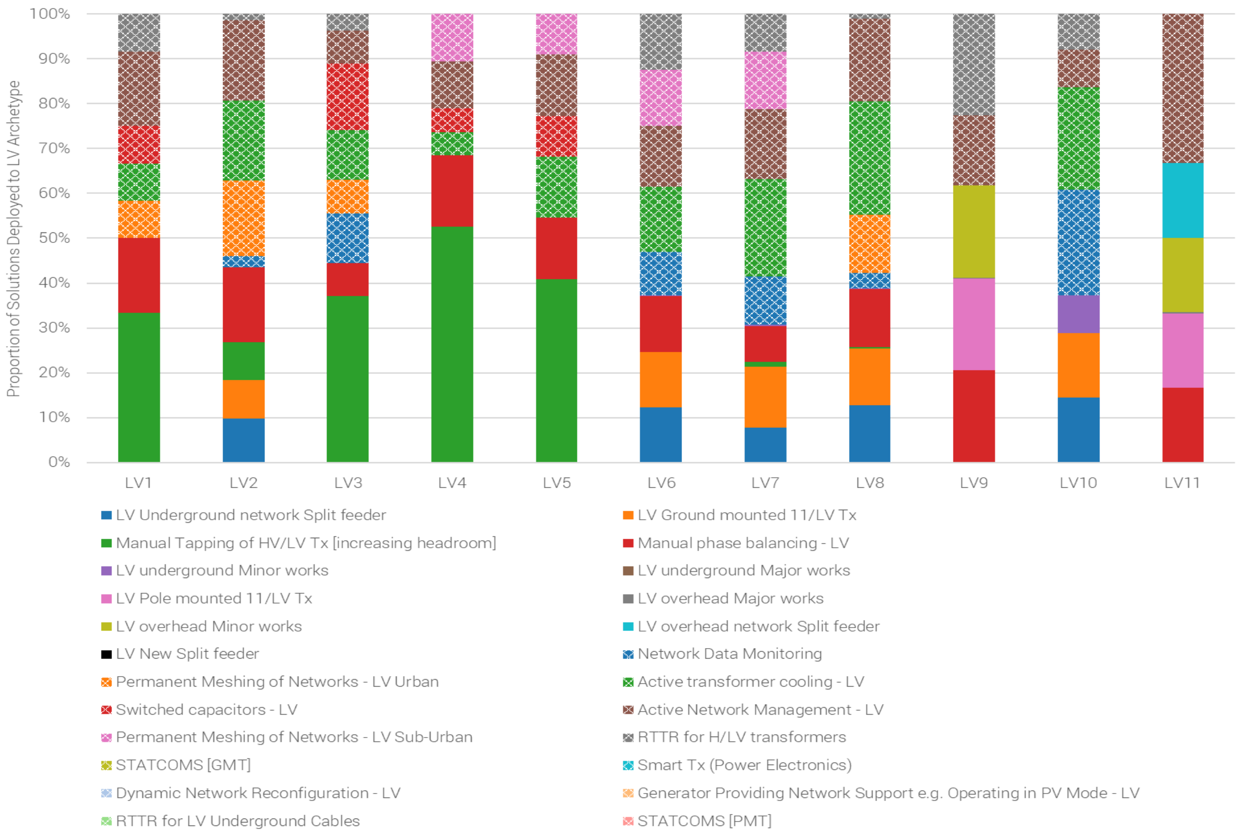

Figure 52: Proportion of BaU and Novel Solutions deployed by LV Network Archetype in South West, Leading the Way scenario

7. Analysis of Value Provided by Novel Solutions

This section of the report analyses those LV archetypes shown to be dominated by BaU deployment in section 6.2. The aim of this section is to explain why BaU solutions are selected preferentially to novel technologies for those LV network archetypes. It also explains how headroom release from other novel technologies could be provided and at what price point or other characteristic it may become valuable to distribution networks. The deployment of technologies was shown in section 6.2[5] to be dependent upon the scenario; significant variation in solution deployments exist between the different scenarios. As such, this section of the report is broken down by scenario. Table 1 summarises the functional requirements needed from novel solutions in order for them to outperform BaU solutions for selected LV network archetypes and scenarios.

Table 1: Summary of requirements from novel solutions to outperform BaU solutions

LV Archetype(s)	Scenario	Functional Requirement	Maximal Totex Cost (per feeder)	Minimal Solution Lifetime [Years]
LV1, LV3, LV4 & LV5	Steady Progress	1.5% Voltage Headroom	£2,495	40
LV9 & LV11	Steady Progress	200% Thermal Headroom	£43,390	45
		80% Thermal Headroom	£7,470	45
		100% Thermal Headroom	£35,920	45
LV3, LV4 & LV5	Best View	2.5% Voltage Headroom	£2,495	40
LV9	Best View	200% Thermal Headroom	£43,390	45
		80% Thermal Headroom	£7,470	45

[5] This section refers to voltage and thermal limits assumed for the LV feeder archetypes studied, summarised in Appendix II.

		100% Thermal Headroom	£35,920	45
LV6	Leading the Way	100% Thermal Cable	£53,880	45
		80% Thermal Transformer	£15,987	45
		100% Thermal Cable and 80% Thermal Transformer	£69,867	45
LV9	Leading the Way	80% Thermal Headroom	£7,470	45
		100% Thermal Headroom	£35,920	45
		90% Thermal Headroom	£14,504	45

7.1 Steady Progress

7.1.1 Urban Predominantly Commercial Environments (LV1, LV3, LV4 & LV5)

Figure 41 to Figure 44 show that across all National Grid's licence areas there is significant deployment of the BaU solution manual tapping of HV/LV transformer (increasing voltage headroom) for LV1, LV3, LV4 and LV5. For LV3, LV4 and LV5 in the West Midlands, South Wales and South West this is the only solution deployed by the Transform model. As an aside, no solutions are deployed to LV1 feeders in the Steady Progress scenario for South Wales and South West because uptake of LCTs in this scenario is insufficient to drive any network constraints (for example, examining the Transform output results maximum net export for South Wales Steady Progress is 18kW for LV1 which is below the feeders' voltage rise limit of 40kW net export).

Examining the Transform results, it is observed that the highest net export that occurs in South Wales occur on LV4, where the next export reaches 83kW. This requires a voltage headroom release of 1.075%. Manual tapping increases voltage headroom by 2.5% by manually changing the tap position on the distribution transformer. Thus the manual tapping solution releases sufficient voltage headroom to resolve the constraint. The cost associated with this solution is £2,495 totex over a 40-year time period. The Transform results also show that there are no thermal issues or issues with voltage drop (even after the tap position change). Therefore, for a novel technology to be deployed on these networks, it would need to release a voltage headroom of approximately 1.5% at a totex cost of less than £2,495 over a 40-year time period.

As noted in the Network Study Results report, no commercial heat pumps were considered in this analysis. If the study was to be repeated with updated assumptions regarding commercial heat pump uptake, the findings would likely show some differences due to the additional thermal loading. However, the voltage issues with PV would likely remain, since heat pumps would be expected to have minimal load during the time of peak PV generation in summer. Additional solutions may be required to resolve thermal or voltage drop issues in the winter caused by the additional load.

7.1.2 Rural Overhead Environments (LV9 & LV11)

Figure 41 to Figure 44 show that there is significant deployment of the BaU solutions LV Pole Mounted Transformers and LV overhead minor works on both LV network archetypes LV9 and LV11.

- LV Pole Mounted Transformers are replacement upgraded transformers with higher capacities than the existing PMTs. LV pole mounted transformers release a highly significant 80% thermal transformer capacity and small voltage headroom benefit of 1%.
- LV overhead minor works represent a new transformer together with associated new conductor releasing therefore 100% thermal capacity. LV overhead minor works releases 100% thermal transformer and thermal cable capacity, also with a small voltage headroom benefit of 1%.
- When these solutions are deployed together the existing transformer is replaced with a higher capacity transformer, and an additional new transformer with associated conductor

Examining the Transform results for the South Wales case, in the cluster bins with highest penetration levels of LCTs, thermal load per feeder along the circuit rises quickly to a maximum of up to 146kW, which is 3.07 times the thermal rating of the transformer. The thermal cable rating of 130kW is also exceeded but by a much more modest factor of 1.12 times the initial thermal cable rating. They key constraint on this feeder type is thus thermal transformer capacity. In order to release over 200% capacity, the most cost effective solution available to Transform is combining the Pole Mounted Transformer (PMT) and overhead minor works solutions. This pattern is common across all licence areas for the cluster bins with the highest penetrations of LCTs.

For cluster bins with lower penetrations of LCTs, the growth of demand on the network is more gradual. Since Transform selects the solution or combination of solutions that most cost effectively resolve the network constraints encountered over the following 5-year periods, the slower growth of loading on the network results in a combination of the Pole Mounted transformer with another solution that releases a smaller quantity of thermal headroom as it is the most effective means of achieving the total thermal headroom release required to relieve the thermal constraint. For example, in South Wales, manual phase balancing coupled with a PMT is selected as the most cost effective solution. Continued growth of demand on the feeder later results in overhead major works being deployed. The combination of PMT with overhead minor works would be sufficient to solve for all network constraints encountered out until 2050, but the additional solution is deployed as a consequence of Transform solving for constraints in 5-year time periods.

The additional solution deployed coupled with PMTs is highly sensitive to the uptake rate of the LCTs, as Transform selects the least costly option that release sufficient thermal headroom over a 5 year time horizon. For other licence areas this solution is commonly Network Data Monitoring (West Midlands / East Midlands) or Active Network Management (South West). Similar reasoning is also applicable to LV11.

For a novel technology to be deployed on these networks:

- It would need to be capable of tripling the capacity of an existing transformer (200% thermal headroom release) at a cost less than the combined £43,390 totex cost of PMT and overhead minor works over their 45-year lifetime.

- Alternatively, it would need to outperform either the PMT (e.g. release 80% thermal headroom at less than the £7,470 totex cost of a PMT over its 45-year lifetime) or overhead major works (release 100% thermal headroom at less than the £35,920 totex cost of overhead major works over its 45-year lifetime) and such that it would be selected in combination with the other solution(either PMT or overhead minor works) to resolve the network constraint.

It seems unlikely that any novel solution will achieve these headrooms at or below the totex costs of the traditional solutions. Another option for novel technology deployment could be solutions that provide 10-20% thermal headroom at low totex cost as a temporary solution to postpone more costly network interventions via traditional solution. This may be viable particularly if the solution could be redeployed elsewhere on the network at a later stage. One potential option for this which is beyond the scope of this project is BESS which could be used to provide flexibility services to postpone costly traditional network interventions. Temporary flexible solutions could be particularly beneficial in the Steady Progress scenario due to the slower uptake rates of LCTs resulting in these solutions potentially being viable for longer time periods than with more aggressive scenarios.

7.2 Best View

7.2.1 Urban Predominantly Commercial Environments (LV3, LV4 & LV5)

In many cases in the Best View scenario, as with the Steady Progress scenario, the manual tapping solution is commonly deployed across the LV network archetypes LV3, LV4 and LV5, particularly in South Wales and South West where penetration of this solution is typically between 35% and 55%. The manual tapping solution is deployed to resolve moderate voltage rise constraints due to the deployment on PV across these LV network archetypes. Manual tapping release 2.5% voltage headroom at a modest totex cost of £2,495 over a 40-year lifetime. In order for a novel technology to be deployed it would need to release a similar voltage headroom release at lower totex cost than manual tapping.

7.2.2 Rural Villaged Overhead Construction (LV9)

BaU solutions PMT and LV overhead minor works are commonly deployed solutions on LV9 network archetype. LV pole mounted transformers release a highly significant 80% thermal transformer capacity and small voltage headroom benefit of 1%. LV overhead minor works releases 100% thermal transformer and thermal cable capacity, also with a small voltage headroom benefit of 1%.

In the West Midlands (see Figure 46) PMTs are the most commonly deployed solutions, followed by LV overhead minor works and network data monitoring. The explanation behind this is similar to the explanation for LV9 in the Steady Progress scenario. In the West Midlands case, in the clustering bin with the highest deployment rates of LCTs requires PMTs and overhead minor works solutions to resolve the first network constraint encountered (this is a thermal transformer constraint). In most other cluster bins, thermal transformer constraints are encountered from the mid 2020s. The uptake rate of LCTs (EV and heat pumps) drives a thermal headroom constraint. When the constraint is first encountered, Transform solves for the five following years. The constraint in five years requires marginally greater than 100% capacity release. Therefore, to most cost effectively solve the network constraint, Transform selects the combination of solutions that resolves the constraint. The combination involves the LV overhead minor works, and another (often novel) solution to ensure that sufficient transformer headroom release such that the constraint is resolved. In the West Midlands case, the most cost effective combination is LV overhead works and network data monitoring (which release 15% thermal headroom).

The solution combined with LV overhead minor works is highly dependent on the uptake rates of LCTs, Slight lower penetrations in South Wales ensure the Active Network Management releasing 10% thermal headroom. Later, as LCTs deployment continues to grow thermal constraints are encountered again, requiring pole mounted transformers to be deployed in order to resolve this subsequent thermal constraint. In scenarios with lower penetrations of LCTs, only the PMT is required as this resolve all the network constraint.

As such, the conclusions are similar to in Steady Progress. For a novel technology to be deployed on these networks:

- It would need to be capable of releasing approximately 200% thermal headroom release at a cost less than the combined totex cost of PMT and overhead minor works (£43.390 over their 45-year lifetime).
- Alternatively, it would need to outperform either the PMT (e.g. release 80% thermal headroom at less than the £7,470 totex cost of a PMT over its 45-year lifetime) or overhead major works (release 100% thermal headroom at less than the £35,920 totex cost of overhead major works over its 45-year lifetime) and such that it would be selected in combination with the other solutions to resolve the network constraint.
- Alternatively, as with Steady Progress there is potential for a novel solution releasing 10-20% thermal headroom that could be flexibly deployed and redeployed to provide value to the network as a short term solution by enabling the network operator to postpone costly traditional network interventions. Even though the uptake of LCTs is faster in Best View, this is likely to still be a viable option on feeders where the clustering of LCTs is such that their growth rate is sufficiently low to enable this. .

7.3 Leading the Way

7.3.1 Suburban Streets (LV6)

In Leading the Way, West Midlands, solutions deployed to LV6 are dominated by LV Ground Mounted 11kV/LV transformers, LV underground network split feeders, manual tapping and network data monitoring. Due to fast uptake rates and highly clustered LCT deployment, when Transform first encounters constraints on a feeder, it deploys LV underground split feeder and a GMT to resolve the constraint, together with network data monitoring which provides additional thermal capacity release[6] to ensure that the constraints are most cost effectively resolved for the 5-year period.

Manual tapping is typically deployed later to release additional voltage rise capacity to ensure that rising levels of PV deployment can be facilitated on the network. In order for novel technologies to be deployed:

- ahead of LV underground split feeders a solution would need to release 100% thermal cable capacity at less than the £53,880 totex cost of the underground split feeder over its 45-year lifetime.
- Ahead of GMT it would need to release 80% thermal transformer capacity at less than the (normalised, per feeder) £15,987 totex cost of a GMT over its 45-year lifetime. Here, the normalised totex cost per feeder is the totex cost of the feeder divided by the assumed number of feeders (three). This implicitly assumes all feeders from a transformer need upgrading at the same time.

Alternatively, if a novel technology could offer 80% thermal transformer and 100% thermal cable capacity at less than the combined totex cost per feeder (£69,867) of the GMT and underground split feeder, then it would be selected ahead of this combination of solutions.

Short term use of flexible, redeployable, novel solutions (such a potentially BESS, DSR or DSM, all beyond the scope of this project) releasing 10-20% thermal headroom at relatively low cost could potentially be used to delay costly traditional network interventions by a small number of years.

7.3.2 Rural Villages Overhead Construction (LV9)

In the West Midlands, LV9 solutions are dominated by PMTs and LV overhead minor works. Network data monitoring is deployed on a relatively small proportion of LV9 feeders where clustering levels of LCTs are lower, such that there is a slower uptake rate of LCTs. As such, network data monitoring can be combined with LV

[6] Network data monitoring alone doesn't release thermal capacity but it does improve knowledge of the network loading conditions allowing margins to be reduced and greater utilization of an assets rating.

overhead minor works when the thermal constraint first occurs. This delays the deployment of the PMTs until later years. The combination of network data monitoring and LV overhead minor works releases sufficient capacity to resolve the thermal constraint over a five year time period at lowest total overall totex cost (totalling £42,954, £35,920 of which is for LV overhead minor works and £7,034 for network data monitoring). The selection of the solution deployed in combination with LV overhead minor works is sensitive to the uptake rates of the LCTs (EVs and heat pumps). If the uptake rates were slightly higher or slightly lower, then it to release sufficient thermal headroom a different novel technology releasing either higher or lower capacity may be selected to be deployed instead.

In South Wales for example, there is a slightly slower uptake rate of LCTs, such that the most cost effective combination of resolving network constraints when they first occur is to combine PMTs with active network management (which releases less thermal capacity than network data monitoring). In order for novel technologies to be more widely deployed:

- It either needs to release more thermal capacity than PMT (totex cost £7,470 over 45-year lifetime) or LV overhead minor works (totex cost £35,920 over 45-year lifetime) at a lower totex cost,.
- Alternatively it needs to release more thermal capacity than PMTs and network data monitoring combined at a totex cost lower than the combined totex cost (£14,504) of PMT and network data monitoring.
- Once again, short term use of flexible, redeployable, novel solutions releasing 10-20% thermal headroom at relatively low cost could potentially be used to delay costly traditional network interventions by a small number of years.

R3. Solutions that release 10-20% thermal headroom at relatively low totex cost may prove highly valuable by allowing the network operator to postpone costlier network interventions. These solutions may be particularly valuable if they can later be redeployed elsewhere on the network. National Grid should continue to monitor novel technologies for any that fulfil these requirements as these could provide significant value to the network operator.

8. Conclusions, Recommendations and Next Steps

Forming a section of the SILVERSMITH project, the purpose of this report is to identify the requirements of the network from solutions for use across National Grid's licence areas. This study used the Transform models setup for the Network Study Results report to conduct BaU only and BaU plus novel solutions studies to identify which novel technologies offered value to the network operator [2]. Novel solutions were identified from the Literature Review and RfI processes and incorporated as the solution set available to the Transform model [1].

This report presents analysis to show which novel technologies offer value to the network operator across National Grid's four licence areas. In addition to analysis showing which technologies offer value across each licence areas, analysis has been conducted to break this down to show where novel technologies off value on a LV network archetype basis. Analysis has also been performed to show what would be required from novel technologies for deployment of novel technologies to be selected on

8.1 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. Solutions that release voltage rise headroom, and solutions that release thermal (transformer and thermal cable) headroom are required in order to resolve the forecast network constraints across the LV network.

C2. Increasing volumes of solutions are required in later years as more LCTs are connected to the network. Increasingly, solutions that deliver significant headroom release are necessary to keep pace with high levels of LCT installation.

C3. Practicalities of deploying specific solutions should be considered. For example, Manual Phase Balancing is commonly selected by Transform. Practically this could be difficult to implement particularly in the case of underground networks. It is likely to only prove a temporary solution since a small number of further LCTs deployments is likely to leave the feeder unbalanced once more.

C4. Novel technologies offer alternative solutions and get widely deployed in parallel with BaU technologies across all licence areas and scenarios

C5. In total, more solutions are deployed in the BaU plus Novel solution study than in the BaU solution study only. More solution deployments leads to a lower overall totex spend and wider supply chain diversity but may require additional staffing so careful management of resource will be required when deciding which technologies to deploy.

C6. The most commonly deployed novel solutions are (in descending order of prevalence): Network Data Monitoring, Active Network Management, Active Transformer Cooling, Real Time Thermal Ratings (RTTR) for H/LV transformers

C7. Solutions deployed across each licence area are broadly similar regardless of the DFES scenario. Therefore, the network operator can have confidence that regardless of the uptake rate of LCTs, similar types of solutions will be required. (The quantity of solution deployment will depend on the LCT uptake rates).

C8. Variation in technology uptake prevalence deployed in different licence areas shows that the technology deployment is highly sensitive to LCT uptake rate.

C9. Novel solutions provide a saving of BaU costs through the deferral of investment. Sensitivity studies show that these savings are robust across differing LCT uptake rates and network topologies.

8.2 Recommendations

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

R1. National Grid should consider whether to perform a similar study considering constraints on and solutions for the HV network in addition to the LV network.

R2. Managing the LV network utilising flexible solutions should be revisited once understanding of flexible solutions including customer engagement and price point has been developed further.

R3. Solutions that release 10-20% thermal headroom at relatively low totex cost may prove highly valuable by allowing the network operator to postpone costlier network interventions. These solutions may be particularly valuable if they can later be redeployed elsewhere on the network. National Grid should continue to monitor novel technologies for any that fulfil these requirements as these could provide significant value to the network operator.

8.3 Next Steps

Detailed analysis and case studies showing how novel technologies offer value to specific LV network archetypes will be presented in a subsequent report for Deliverable 2.2. of this project (LV Voltage Control Selection Methodology). This report will consider how specific novel technologies offer value to specific LV network archetypes, to allow network planners to easily identify the technologies most likely to provide value for specific LV network archetypes when resolving network constraints.

9. References

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

[2] T. Stone, “EA16141-TR2 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].

Appendix I LV Feeder Archetypes

The Transform model for National Grid's licence areas makes use of 11 LV network archetypes representing different types of representative LV feeder. Table AI.1 gives a brief description of each of these and the same are used across all 4 licence areas.

Table AI.1 Description of LV Network Archetypes used in National Grid's Transform Models

Number	Network Archetype Name	Description
LV1	Central Business District	Radial underground central business district feeders supplying only commercial customers. Typically found in town and city centres.
LV2	Dense Urban (Apartments etc.)	Radial underground feeder typical of those found in areas on dense population in cities (such as where there are many apartments in close proximity). Feeder supply a range of residential property types.
LV3	Town Centres	Radial underground feeder typical of those found in town centres. These feeders supply primarily commercial customers but also have a small number of domestic customers.
LV4	Business Park	Radial underground feeder with only commercial customers representative of a typical business park.
LV5	Retail Park	Radial underground feeder with only commercial customers representative of a typical retail park.
LV6	Suburban Street (3 4 Bed Semi-detached or Detached Houses)	Radial underground feeder representative of a typical suburban area. This feeder supplies detached and semi-detached residential properties.
LV7	New Build Housing Estate	Radial underground feeder representative of a typical new build housing estate.
LV8	Terraced Street	Radial underground feeder representative of a typical feeder supplying a row of terraced houses.
LV9	Rural Village (Overhead Construction)	Radial overhead feeder supplying mostly domestic customers, typical of that found in rural villages.
LV10	Rural Village (Underground Construction)	Radial underground feeder supplying mostly domestic customers, typical of that found in rural villages.
LV11	Rural Farmsteads Small Holdings	Radial overhead feeder typically used to supply small groups of houses or small farms.

Appendix II Network Details

Table AII.1 Network details used in Transform for the LV network archetypes.

LV Network	Substation Capacity (kW)	Thermal Conductor (kW)	Planning Voltage Upper Headroom Limit (%)	Planning Voltage Lower Limit (%)	kW/%	Number of Networks (East Mids | West Mids | South Wales | South West)
LV1 Central Business District	238	231	1%	15%	40	1,275 | 1305 | 484 | 869
LV2 Dense urban (apartments etc)	190	164	1%	15%	40	4,288 | 4389 | 1630 | 2922
LV3 Town centre	190	179	1%	15%	40	2,876 | 3093 | 1124 | 1949
LV4 Business park	238	184	1%	15%	40	4,999 | 5920 | 2235 | 2975
LV5 Retail park	238	184	1%	15%	40	2,517 | 2248 | 1056 | 1369
LV6 Suburban street (3 4 bed semi detached or detached houses)	119	111	1%	15%	40	18,590 | 17547 | 7937 | 9990
LV7 New build housing estate	119	164	1%	15%	40	9,506 | 7060 | 3752 | 4631
LV8 Terraced street	119	111	1%	15%	40	17,033 | 17209 | 6488 | 11227
LV9 Rural village (overhead construction)	48	131	1%	15%	40	12,339 | 16317 |13346 | 16146
LV10 Rural village (underground construction)	100	113	1%	15%	40	6,413 | 7142 | 2773 | 6883
LV11 Rural farmsteads small holdings	48	56	1%	15%	40	14,716 | 20860 | 17693 | 21544

Appendix III Business as Usual Solutions

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%
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	£133,288	£1,333	£179,599	45	100%	100%	1%	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 (%)
	new LV cable to supply two new circuits at an average length of 300m each.								
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 connecting the new split feeder into the existing network	£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 (%)
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 compoased 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%
Manual phase	Rebalancing phases by changing which phases customers are connected to	£22,440	£224	£41,232	45	20%	20%	20%	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 (%)
balancing - LV									
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 Artificial Solutions

Table AIV.1 Table 2: Artificial solutions used in artificial solution Transform study.

Solution	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
Thermal Transformer 1	5%	0%	0%	0%
Thermal Transformer 2	10%	0%	0%	0%
Thermal Transformer 3	15%	0%	0%	0%
Thermal Transformer 4	20%	0%	0%	0%
Thermal Transformer 5	25%	0%	0%	0%
Thermal Transformer 6	30%	0%	0%	0%
Thermal Transformer 7	35%	0%	0%	0%
Thermal Transformer 8	40%	0%	0%	0%
Thermal Transformer 9	45%	0%	0%	0%
Thermal Transformer 10	50%	0%	0%	0%
Thermal Transformer 11	55%	0%	0%	0%
Thermal Transformer 12	60%	0%	0%	0%

Solution	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
Thermal Transformer 13	65%	0%	0%	0%
Thermal Transformer 14	70%	0%	0%	0%
Thermal Transformer 15	75%	0%	0%	0%
Thermal Transformer 16	80%	0%	0%	0%
Thermal Transformer 17	85%	0%	0%	0%
Thermal Transformer 18	0%	0%	0%	0%
Thermal Transformer 19	100%	0%	0%	0%
Thermal Transformer 20	500%	0%	0%	0%
Thermal Cable 1	0%	5%	0%	0%
Thermal Cable 2	0%	10%	0%	0%
Thermal Cable 3	0%	15%	0%	0%
Thermal Cable 4	0%	20%	0%	0%
Thermal Cable 5	0%	25%	0%	0%
Thermal Cable 6	0%	30%	0%	0%

Solution	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
Thermal Cable 7	0%	35%	0%	0%
Thermal Cable 8	0%	40%	0%	0%
Thermal Cable 9	0%	45%	0%	0%
Thermal Cable 10	0%	50%	0%	0%
Thermal Cable 11	0%	55%	0%	0%
Thermal Cable 12	0%	60%	0%	0%
Thermal Cable 13	0%	65%	0%	0%
Thermal Cable 14	0%	70%	0%	0%
Thermal Cable 15	0%	75%	0%	0%
Thermal Cable 16	0%	80%	0%	0%
Thermal Cable 17	0%	85%	0%	0%
Thermal Cable 18	0%	0%	0%	0%
Thermal Cable 19	0%	100%	0%	0%
Thermal Cable 20	0%	500%	0%	0%

Solution	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
Voltage Headroom 1	0%	0%	1%	0%
Voltage Headroom 2	0%	0%	2%	0%
Voltage Headroom 3	0%	0%	3%	0%
Voltage Headroom 4	0%	0%	4%	0%
Voltage Headroom 5	0%	0%	5%	0%
Voltage Headroom 6	0%	0%	6%	0%
Voltage Headroom 7	0%	0%	7%	0%
Voltage Headroom 8	0%	0%	8%	0%
Voltage Headroom 9	0%	0%	9%	0%
Voltage Headroom 10	0%	0%	10%	0%
Voltage Legroom 1	0%	0%	0%	1%
Voltage Legroom 2	0%	0%	0%	2%
Voltage Legroom 3	0%	0%	0%	3%
Voltage Legroom 4	0%	0%	0%	4%

Solution	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
Voltage Legroom 5	0%	0%	0%	5%
Voltage Legroom 6	0%	0%	0%	6%
Voltage Legroom 7	0%	0%	0%	7%
Voltage Legroom 8	0%	0%	0%	8%
Voltage Headroom 1	5%	0%	0%	0%
Voltage Headroom 2	10%	0%	0%	0%
Voltage Headroom 3	15%	0%	0%	0%
Voltage Headroom 4	20%	0%	0%	0%
Voltage Headroom 5	25%	0%	0%	0%
Voltage Legroom 6	30%	0%	0%	0%
Voltage Legroom 7	35%	0%	0%	0%
Voltage Legroom 8	40%	0%	0%	0%
Emergency Solution	5000000%	5000000%	5000000%	5000000%

Appendix V Novel Solutions

Table AV.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 distribution voltages). A retrofit solution to existing circuits.	£144,878	£5,795	£377,194	30	0%	20%	10%	10%
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	£42,057	£0	£54,674	40	0%	0%	9%	7%

Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
	grid and primary transformers. Together these new and existing voltage control devices will constitute an EAVC system.								
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 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.	£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 (%)
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 ensure that the voltage on the network is not excessively raised at the point of connection.	£17,391	£1,739	£30,292	5	10%	10%	3%	3%
Permanent Meshing of	Converting the operation of the LV network from a radial feeder (with	£23,181	£927	£48,443	45	10%	50%	0%	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 (%)
Networks - LV Urban	split points) to a solid mesh configuration.								
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%
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	£29,172	£0	£37,924	15	0%	5%	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 (%)
	mode. This variant considers RTTR for LV underground cable circuits								
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%
Magnetic Power Flow Controller (Tx)	Smart Tx technology controlling magnetic flux through transformer	£40,000	£800	£54,135	15	20%	0%	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 (%)
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%

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Safer, Stronger, Smarter Networks

EA Technology Limited
Capenhurst Technology Park
Capenhurst, Chester CH1 6ES

t +44 (0) 151 339 4181
e sales@eatechnology.com
www.eatechnology.com