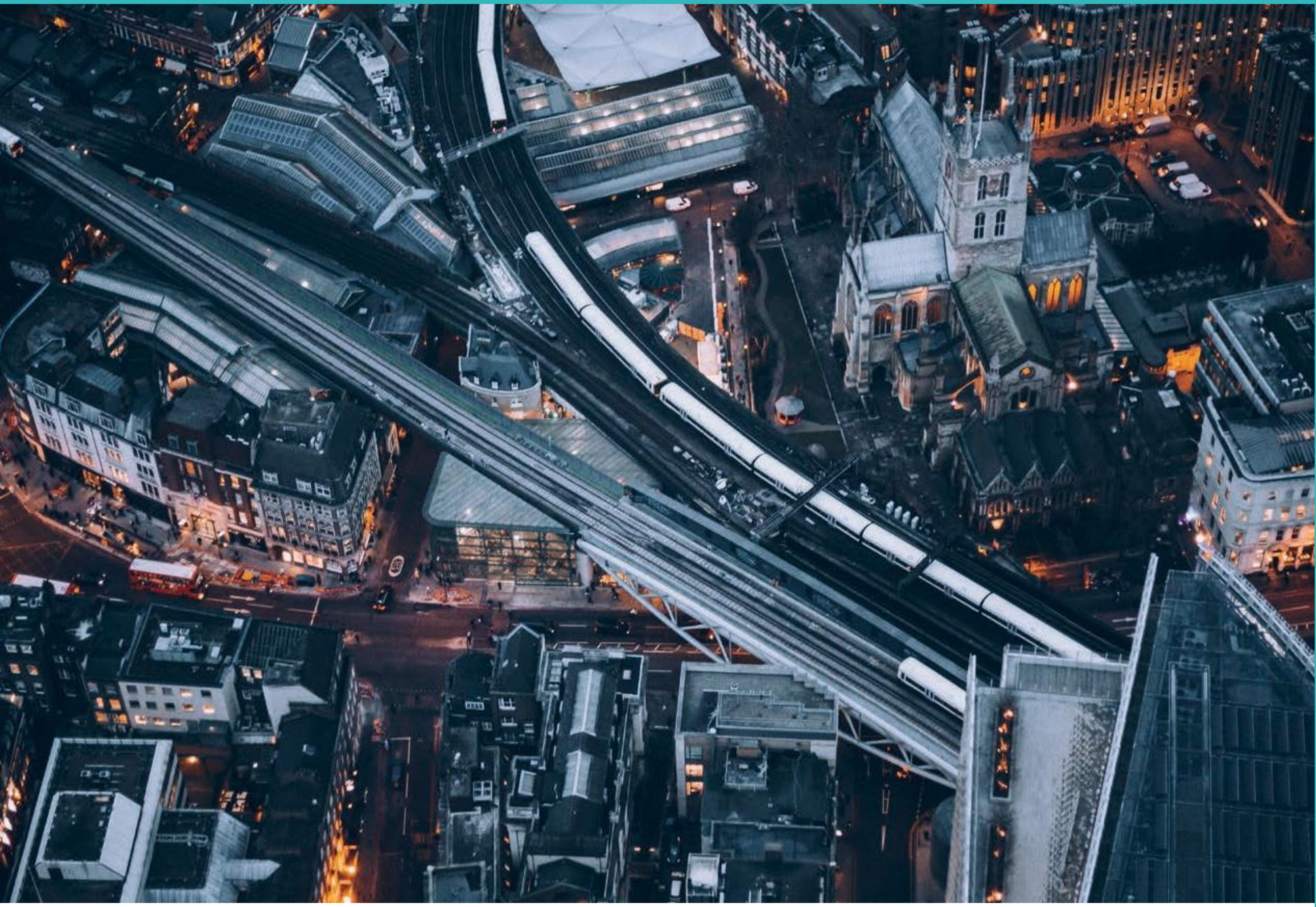

REPORT

EA16141-TR7 Technology Witnessing Report and Final Recommendations

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Executive Summary

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 coming decades. The combined effect will have a profound impact on the electricity network. Large numbers of these technologies will be deployed on the Low Voltage (LV) network, 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 needs to be achieved while minimising costs to consumers resulting from network augmentation but continuing to provide a safe and reliable electricity supply. 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[2] 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 was conducted to identify novel technologies that offer potential value to network operators. The findings are covered in the Literature Review [1]. The aim of this phase of the SILVERSMITH project is to perform a Cost Benefit Analysis (CBA) to determine which of these novel technologies offer value to the network operators and on which feeder types.

This project utilised EA Technology's Transform Model®, a techno-economic parametric electricity network modelling tool to conduct a CBA and identify the most cost effective solutions to resolve forecast network constraints. The Network Study Results [2] identified the types of constraints experienced across National Grid's four licence areas, and how this varied by area and DFES (Distribution Future Energy Scenarios) scenario at a network and LV network archetype. The Functional Requirements report [3] compared the Business as Usual (BaU) to the novel solutions and determined the value they introduced at the LV network archetypal level.

Complementary PowerFactory analysis was conducted alongside the Transform analysis investigating three case study networks (dense urban, urban and rural) in greater detail. The PowerFactory Network Study Results report [4] investigated the constraints occur across the three case study networks and Load Flow Analysis of Novel Solution report [5] analysed the effect deployment of novel technologies have on the LV network. The effect of novel technology deployment on thermal and voltage headroom was modelled and qualitative assessment of the impact on fault level and harmonic distortion discussed.

The LV Voltage Control Selection Methodology report [6] mapped the types of network constraints encountered to the solutions deployed to resolve them in different scenarios. This allowed the development of flowcharts that can assist network planners in considering appropriate novel technologies when designing the LV network.

This report provides a summary of the results of the analysis conducted throughout the course of the SILVERSMITH project. This includes analysis into which particular technologies were demonstrated to be

[1] National Grid Electricity Distribution, part of the National Grid group, were previously known as Western Power Distribution and renamed in September 2022.
[2] SILVERSMITH: Solving Intelligent LV – Evaluating Responsive Smart Management to Increase Total Headroom

favourable as based on the current forecast requirements they were found to offer value to the network operator. Additionally, this highlights recommendations regarding technologies to trial in deployments across the network and the conditions when those should occur.

Conclusions

The following conclusions can be drawn from the analysis conducted throughout the SILVERSMITH project and summarised in this report.

C1. The novel solutions most commonly deployed across National Grid's LV network and therefore offering value over business as usual solutions are:

- C1.1 Network data monitoring
- C1.2 Active network management (dynamic control of the network by controlling, for example, normally open points)
- C1.3 Active transformer cooling
- C1.4 Real Time Thermal Ratings for HV/LV transformers

C2. Network planners should consider whether flexible solutions can offer a more cost-effective method for resolving network constraints compared to technological solutions. The LV Voltage Control Selection Methodology report [6] quantifies the typical flexibility required per customer to avoid or defer investment by network archetype.

C3. Significant steps in headroom release exist between solutions available to the network operator. If insufficient flexibility services are available to avoid additional investment, the network operator will have no choice but to over procure headroom at a higher cost. Any solution that can cost-effectively provide intermediate steps in headroom release could offer valuable alternative options to the networks.

C4. Major network interventions using business as usual solutions such as new transformers, new feeders and new substations will be required for feeders with very high penetrations of low carbon technology deployment, unless suitable alternative technologies are developed.

C5. Flexible solutions should be considered both as an alternative and complementary solution set to technological solutions.

Recommendations

In delivering this project the following recommendations with regards to technology trials and further work have been highlighted:

R1. Consider the viability of flexible solutions to defer or avoid investment ahead of any decision to invest in the network. Assess likelihood of being able to procure sufficient flexibility to defer investment for each archetype as outlined in LV Voltage Control Selection Methodology [6].

R2. Innovative solutions that could offer thermal capacity release on underground conductors without the associated disruption of BaU conductor replacement would be a valuable alternative option for the network operator.

R3. Innovative technologies that could offer between 15% and 100% thermal cable capacity release for a totex cost below approximately £50,000 would provide significant value to the network operator. Innovation activity could investigate solutions able to fill this gap.

R4. Innovative technologies that could offer between 20% and 80% thermal transformer capacity at less than approximately £16,000 per feeder (for feeders supplied by GMTs) or £7,500 per feeders (for feeders supplied by PMTs) would provide significant value to the network operator. Innovation activity could investigate solutions able to fill this gap.

R5. Verify performance of active transformer cooling technology across a subset of National Grid's heavily loaded distribution Ground Mounted Transformers by the late 2020s.

R6. By the early 2030s trial Real Time Thermal Ratings for HV/LV Transformers across a sample of National Grid's pole mounted transformers forecast to become thermally constrained. Trials should focus on how to install equipment necessary for RTTR on PMTs and on quantifying the benefit of RTTR on thermal PMT capacity.

R7. By the mid-2030s trial active network management across a section of National Grid's LV network and quantify the thermal and voltage headroom release achieved.

R8. Continue to deploy targeted LV Network Data Monitoring equipment across National Grid's network. Continue to innovate applications and algorithms deployable to LV monitoring equipment the benefits from the monitoring equipment and to maximise utilisation of existing assets.

R9. Before investing in any technological solution, the network operator should consider whether a flexible solution could be used to more cost-effectively resolve the network constraint.

Contents

Appendices

1. Definitions

Term	Definition
AC	Alternating Current
BaU	Business as Usual
BESS	Battery Energy Storage System
CBA	Cost Benefit Analysis
DC	Direct Current
DFES	Distribution Future Energy Scenarios
DSR	Demand Side Response
EAVC	Enhanced Automatic Voltage Controller
ENW	Electricity North West
EV	Electric Vehicle
GB	Great Britain
GMT	Ground Mounted Transformer
HV	High Voltage
kV	kiloVolt
LCT	Low Carbon Technology
LV	Low Voltage
OLTC	On Load Tap Changer
PMT	Pole Mounted Transformer
PV	Photovoltaics
RfI	Request for Information
RIIO-ED2	Revenue = Innovation + Incentives + Outputs – Electricity Distribution 2 (2023 - 2028)
RTTR	Real time thermal ratings
SILVERSMITH	Solving Intelligent LV – Evaluating Responsive Smart Management to Increase Total Headroom
Totex	Total expenditure (This is made up from up from capex [capital expenditure] costs and ongoing opex [operational expenditure] costs). Totex costs are given on a per feeder basis, and are sourced from either the RfI process (costs marked with an asterisk[*]) or from costs agreed by network operators when the Transform model was developed, adjusted for inflation (costs marked with a dagger[†])
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[3] 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] 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 Transform network study results [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 EA Technology's 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 scenarios in DFES 2021 [7].

The Transform study results 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 archetype.

The PowerFactory network study results [4] presented analysis using DIgSILENT PowerFactory which investigated three case studies of real world networks (dense urban, urban and rural) in National Grid's West Midlands licence area. The constraints posed by the forecast uptake of LCTs according to the DFES scenarios were analysed in the years 2028, 2033, 2040 and 2050.

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

2.3 Functional Requirements Report

The Transform Functional Requirements report [3] identified which solutions are deployed in two instances; the counterfactual instance where only Business as Usual (BaU) solutions were available and with both BaU and novel technologies were available. This showed the variation in technology deployment between the counterfactual and novel studies, and also showed how the solutions deployed varied by network archetype.

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

2.4 LV Voltage Control Selection Methodology

The LV Voltage Control Selection Methodology report [6] looked further into how network constraints were solved by which technologies. This report was aimed at providing network planners a methodology to assist with identifying which novel technologies should be considered when upgrading the network. This was done on an archetypal basis and flowcharts were provided to guide network planners depending on the feeder archetype they are considering.

2.5 This Report

This report acts to summarise which novel technologies meet the functional requirements of National Grid's LV electricity distribution network and thus offer value to the network operator considering the forecast LCT uptake and associated network constraints. This enables National Grid to consider which novel technologies should be progressed to trial and with what priority along with where further innovation should be focussed to work with developers in developing technologies further. This includes in some instances where policy, safety and design implications need to be considered in order for novel technologies to be deployed onto the network.

2.6 Flexibility First

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

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

Flexible solutions were excluded from analysis in this project. This project instead 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 and where they offer a lower cost alternative to managing the LV network to the technological solutions, flexibility should be strongly considered in the first instance. As the flexibility markets develop, a clearer picture will emerge of capacity available from flexibility, the willingness of consumers to engage, and the cost of procuring services.

The LV Voltage Control Selection Methodology report [6] investigated how flexibility could be used to defer or avoid the need for costly network reinforcement. It found that to defer costly network reinforcement for 5 years from the time a constraint first arises, between 0.7 and 2.1kW per customer is required depending on the archetype. For further details regarding the flexibility requirement for each network archetype, the reader is refered to section 4.2 of the LV Voltage Control Selection Methodology report. In line with National Grid's flexibility first principle, it is recommended that consideration is always made about the viability of flexible solutions ahead of any decision to invest in the network.

R1. Consider the viability of flexible solutions to defer or avoid investment ahead of any decision to invest in the network. Assess likelihood of being able to procure sufficient flexibility to defer investment for each archetype as outlined in LV Voltage Control Selection Methodology [6].

3. Constraints and Novel Technologies Deployed

3.1 Constraint Types

The Transform analysis conducted throughout this project considered six common, distinct constraint types.

1. Voltage drop constraints: Occur when the voltage drop along a feeder exceeds the maximum designed level to ensure it remains within statutory limits.
2. Voltage rise constraints: Occur when the voltage rise along a feeder exceeds the maximum designed level to ensure it remains within statutory limits.
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.

The Cost Benefit Analysis performed by Transform ensures that the most cost effective solution is deployed to resolve the constraint (or constraints) when they are encountered, and any further constraints that arise within the next 5-year period.

Figure 1 breaks down the types of constraints averaged across National Grid's four licence areas. The primary challenge the facing the network is thermal constraints caused by the adoption of LCTs such as heat pumps and EVs. Feeders with high levels of solar PV adoption are forecast to witness voltage rise constraints. Further discussic und the types of constraints forecast across National Grid's network and the implications for the network or can be found in the Network Study report [2],

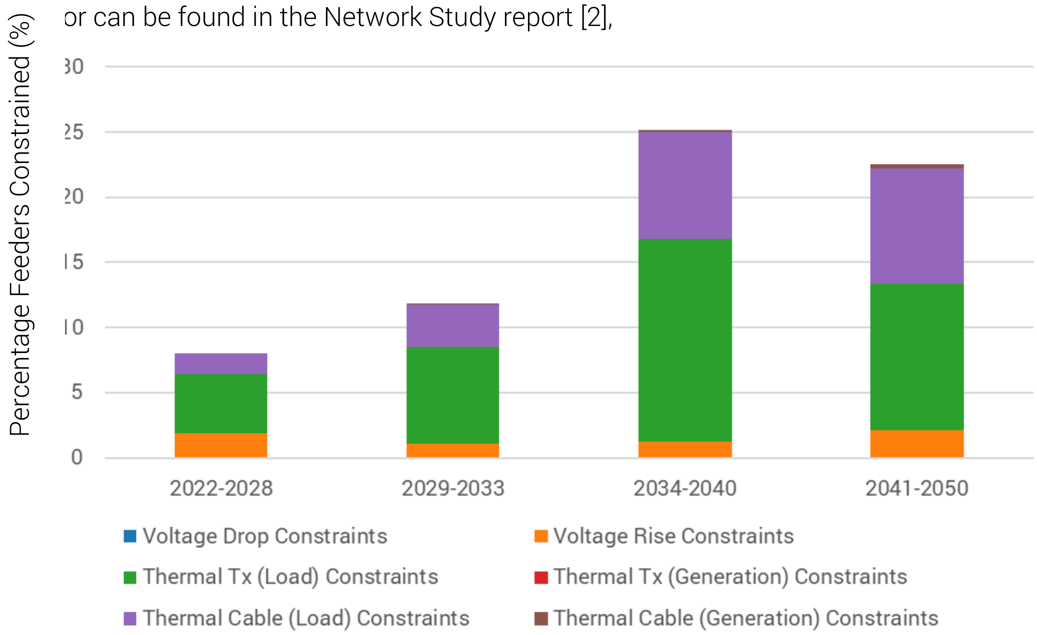

Figure 1: Weighted average of network constraints encountered across National Grid's four licence areas under the Best View scenario.

The Transform model does not consider the impact of technology deployment on other technical parameters, such as harmonics or fault level. Detailed consideration of these parameters when reinforcing the network could lead to alternative solution deployments. Separate analysis using PowerFactory are detailed in the Functional Requirements report [5] which discussed the effect of novel solutions on these parameters, in addition to investigating the impact on voltage and thermal capacity for specific feeders.

3.2 Novel Technologies Deployed

Figure 2 shows the percentage of feeders BaU (represented by solid bars) and novel (represented by diamond patterned bars) solutions get deployed to, across National Grid's four licence areas. The Transform model selects the most cost effective solution (or solution set) to resolve the constraint, and any further constraint in the following 5-year period. After this time period is elapsed, if LCT deployment continues to grow and further constraints are enountered, additional solutions are deployed to resolve the new constraints. Due to the combined effect of multiple solutions being required to solve constraints on some feeders, together with repeated intervention due to further constraints that occur at a later time, it is possibble that solution deployment can effectively exceed 100%. This does not mean that all feeders require intervention, rather some feeders require multiple interventions. Some feeders do not encounter constraints, and therefore no solutions are required for these feeders.

The assumed technical details utilised in the Transform modelling such as totex cost, voltage and thermal headroom release for BaU and Novel solutions are shown in Appendix II and Appendix III respectively. Section 4 of this report discusses why these novel technologies are deployed and what constraint types they are deployed to resolve.

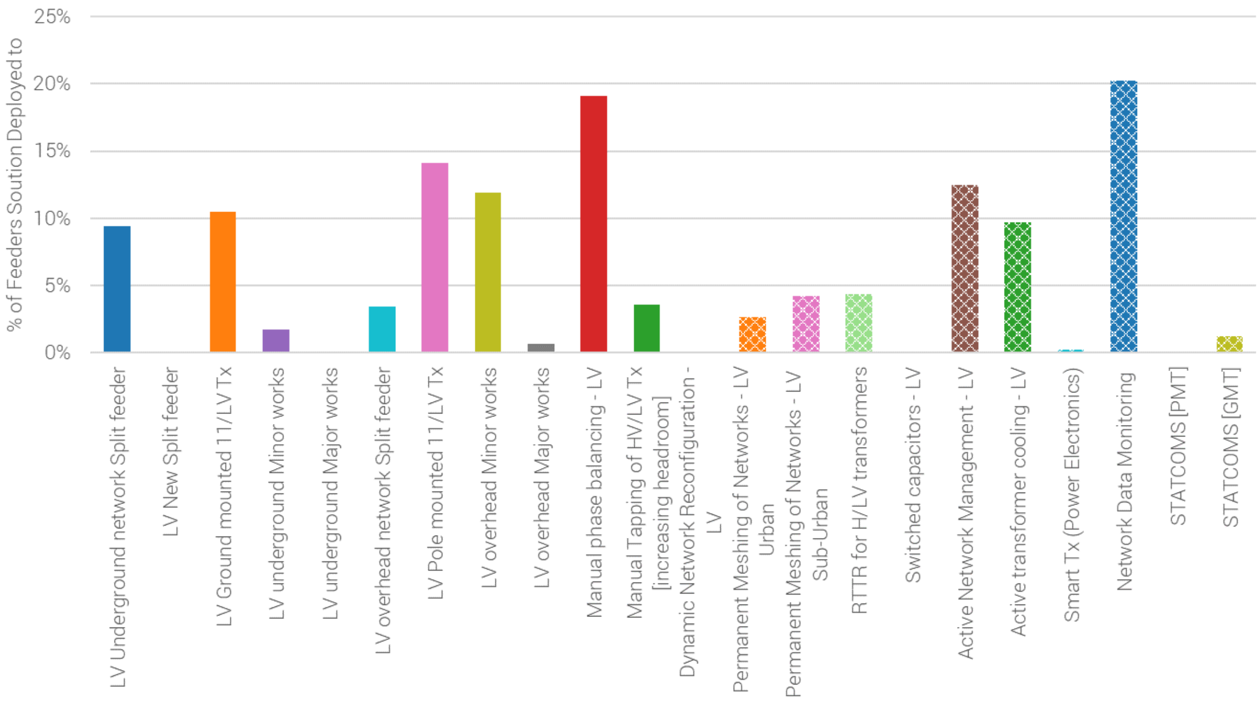

Figure 2: Plot showing the percentage of feeders supplied by both BaU and novel solutions

Many technologies do not get deployed at all so are omitted from the graph above. Novel Technologies with zero deployements include:

- DFACTS-LV
- Embedded DC Network
- EAVC HV/LV Transfromer Voltage Control
- EAVC LV Circuit voltage regulators
- EAVC LV PoC votlage regulators
- Generator Constraint Management
- RTTR for LV Overhead Lines
- RTTR for LV Underground Cables
- Widening of the Design Votlage Tolerance
- Magnetic Power Flow Controller Tx
- Smart Tx (OLTCs)

Section 5 of this report discusses the reasons why these technologies are not deployed.

4. Novel Technologies that Offer Value to National Grid

The study has shown that particular novel technologies are favoured depending on the type and extent of network constraints. Table 1 provides a summary of the novel technologies that are selected by the Transform model as they offer value to the network operator over the existing BaU solutions (further details on each solution is included in Appendix III). These technologies in Table 1 are the technologies that demonstrate the greatest value of being rolled out across the network in addition to BaU solutions. This section then outlines the situations in which each novel technology type is deployed to the network.

It is recognised that future innovation will lead to new novel technologies that offer value to the network operator and similarly continued innvoation in novel technologies identified in this project could lead to cost reduction or greater capacity releases, increasing its potential value to the network operator. Future novel technologies are therefore expected to compete against both BaU solutions along with the novel solutions in Table 1 below. Future technologies that can offer more headroom at similar costs to the technologies below, or similar headroom at lower costs will be a favourable option to most effectively manage the LV network.

Solution Costs

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

The literature review [1] identified additional novel solutions that the network operator might consider deploying to increase LV network capacity. Headroom releases and costs associated with these technologies were agreed by GB network operators during development of the Transform model. The same methodology was applied to cost the BaU solutions. These costs have been adjusted for inflation and were agreed by National Grid and EA Technology during the analysis for the Functional Requirements [3]. These costs are marked throughout this report with a dagger (†).

To allow Transform to perform a totex cost comparison between different solutions, totex costs are given on a per feeder basis. Solutions such as new Ground Mounted Transformers cannot be applied to a single feeder, but to allow a comparison the totex cost of implementing the solution is given on a per feeder basis. For example, if a solution such as a new GMT had a totex cost of £30,000[4], and was assumed to supply three feeders, the totex cost modelled in Transform would be £10,000.

[4] This is not the assumed cost of a GMT in the model. £30,000 has been used as a round number to keep the maths in the illustrative example simple.

Table 1: Novel technologies suitable for different constraint types and extents.

Solution ID	Technology	Constraint Type	Constraint Extent	Notes
NT21	Network Data Monitoring	Thermal constraints in cables and/or transformers.	Up to 15% thermal cable headroom release *or* Up to 15% thermal cable and Transformer headroom release	Network Data Monitoring does not directly release capacity on the network. Instead, it increases visibility of assets, reducing uncertainty in investment decisions. It also acts as an enabler / improver for other solutions such as RTTR for HV/LV transformers.
NT15	Active Network Management	Simultaneous voltage and thermal constraints	Up to 10% thermal headroom release and between 2.5%-3% voltage headroom release *Or* Up to 10% thermal headroom release and up to 3% voltage headroom release with less than 2.5% voltage legroom capacity available	Active Network Management is the dynamic management of the LV network by controlling, for example, normally open points.
NT16	Active Transformer Cooling	Thermal constraints in transformers	Up to 22% thermal transformer headroom release	Suitable for GMTs only
NT11	RTTR for HV/LV transformers	Thermal constraints in transformers	Up to 15% thermal transformer headroom release	Most commonly deployed where Active Transformer Cooling is not an option (for example, feeders supplied from PMTs) Occasionaly deployed if further transformer headroom release required after Active Transformer Cooling deployed,
NT9 / NT10	Permanent Meshing of Network (LV Urban / Sub-Urban)[5]	Thermal constraints in cables or both cables and transformers	Up to 50% thermal cable release and up to 10% thermal transformer headroom release	Available in urban and sub-urban networks

[5] While permanent meshing may be suitable in some specific areas, it is not recommended as a widescale retrofit solution due to implication for substation protection and network operating practices.

4.1 Network Data Monitoring

Network data monitoring is a solution that typically gets deployed to resolve thermal constraints, by providing visibility of the LV network thermal capacity. Network data monitoring is being widely deployed by GB DNOs so can be thought of as currently undergoing the transition from novel to BaU technology. Network data monitoring is modelled as releasing 15% thermal headroom for a totex cost of £7,034* over its 10-year lifetime. This cost is composed of the capital cost of the monitoring unit and the annual operating cost of deploying applications to the units in addition to the costs of data transmission. Research conducted for the OpenLV [8] project suggested Network Data Monitoring could release up to 30% thermal capacity, by more effectively utilising the capacity of the existing assets.

For feeders encountering thermal constraints, network data monitoring is an effective option for managing the constraint due to its significant thermal cable headroom release at moderate cost; network data monitoring is the most cost effective option in the solution set available to Transform for feeders requiring thermal cable capacity release of up to 15%. Since network data monitoring also releases thermal transformer headroom, this option is also favoured for feeders that encountered transformer and cable constraints requiring up to 15% capacity release simultaneously.

Monitoring can also be conducted via use of smart meter data. The ongoing project Smart Meter Innovations and Test Network (SMITN) [9] is assessing how smart meter data can be utilised to provide similar insights to that from direct LV feeder monitoring, which may provide a cheaper or more timely method for monitoring the network.

4.2 Active Network Management

Active network management involves dynamic management of the LV network by controlling, for example, normally open points. This allows the network operators to temporarily reconfigure the network to share load and increase available capacity. Active network management is modelled as releasing 10% thermal headroom and 3% voltage headroom for a totex cost of £18,704† over its 15-year lifetime. Cheaper solutions exist that release similar levels of thermal or voltage headroom respectively. For example, manual tapping of the HV/LV transformer releases 2.5% voltage capacity at a totex cost of £2,495† over its 40-year lifetime and network data monitoring releases 15% thermal capacity at a totex cost of £7,034* over its 10-year lifetime. In general combining manual tapping and network data monitoring may be a more cost-effective solution than deploying active network management, but active network management proves more effective when thermal headroom is required in addition to between 2.5% and 3% voltage headroom.

It is also valuable in situations where manual tapping to increase thermal headroom isn't a viable solution to release voltage capacity as this would introduce new voltage drop constraints. The PowerFactory Functional Requirements report [5] shows that for the case study urban network, voltages at the remote ends of feeder fall to within 2.5% of the statutory lower voltage limit. Therefore, if manual tapping to increase voltage headroom (by lowering the voltage at the supply substation) were to be deployed in this example, the remote ends of the feeders would drop below the minimum statutory voltage limit. This is an example therefore where manual tapping would be an unsuitable solution, but where active network management could be utilised instead to release voltage headroom.

The ENA ETR140 consultation [10] discussed the impacts of widening the voltage tolerance from 230V +10%/-6% to 230V+/-10%. Further consultation was recommended, but if the voltage tolerance was to be widened, then fewer feeder voltages would drop below the lower statutory minimum voltage. By providing additional legroom through widening the voltage tolerance, this may increase the capability of certain technologies to increase voltage headroom. For example, manual tapping to increase headroom could be accommodated on networks where previously it would not be deployable due to voltages dropping below the statutory voltage minimum limit.

4.3 Active Transformer Cooling

Active transformer cooling is a solution that gets deployed to resolve thermal transformer capacity constraints. It offers a thermal transformer capacity release of up to 22%, for a per feeder totex cost of £6,756† over its 15-year lifetime. For feeders where the only constraint is the thermal capacity of the transformer, active transformer cooling is an attractive option due to its significant thermal release at a relatively modest cost. However, active transformer cooling is assumed to only be applicable to ground mounted transformers.

4.4 RTTR for HV/LV transformers

RTTR for HV/LV transformers is a solution that gets deployed to resolve thermal transformer capacity constraints. It offers a thermal transformer capacity release of up to 15% at a totex cost £22,602† over its 15-year lifetime. It is a more costly option than active transformer cooling, so is most applicable to pole mounted transformers (PMT) where active transformer cooling isn't an option. The LV Voltage Control Selection Methodology [6] shows that RTTR for HV/LV transformers offers the greatest value to network archetypes LV9 (Rural village overhead construction) and LV11 (Rural farmsteads) which are feeders supplied by a PMT, where active transformer cooling isn't an option. While extensive data [8] is available regarding the benefit of RTTR on GMTs, further research is required to understand if the equipment necessary for RTTR can be installed at PMTs and to better understand the extent of potential capacity release.

4.5 Permanent Meshing of Network – LV Urban / LV Sub-Urban

Permanent meshing of the network (in urban and sub-urban environments) is a solution used to address thermal capacity constraints. The solution offers 50% cable headroom together with a smaller 5-10% transformer capacity release, for a totex cost of £48,443† over its 45-year lifetime. The solution is primarily used when significant cable capacity release is required with its 50% thermal cable capacity release. Although costly, it is the highest cable capacity release of all novel solutions, and is cheaper than new feeder or underground minor works which are the BaU solutions deployed. Permanent meshing is deployed to greater or lesser extents to all urban and sub-urban feeders (LV1 to LV8). The PowerFactory analysis showed how given a suitable network topology, feeders from the same transformer could also be meshed, which can be useful to share capacity more evenly between feeders.

However, permanent meshing is only suitable for some feeders where there is the physical opportunity to mesh. Permanent meshing, when retrofitted to a network that was designed as a radial network, comes with significant implications for substation protection and would require significant changes to operating practices to ensure safety for network staff and consumers. For these reasons, while permanent meshing may be suitable in some specific situations (for example in cases of new build network), permanent meshing is not recommended for wide scale deployment as a retrofit solution across National Grid's network and instead has to be visited on a case by case basis.

C1. The novel solutions most commonly deployed across National Grid's LV network and therefore offering value over business as usual solutions are:

- C1.1 Network data monitoring
- C1.2 Active network management (dynamic control of the network by controlling, for example, normally open points)
- C1.3 Active transformer cooling
- C1.4 Real Time Thermal Ratings for HV/LV transformers

C2. Network planners should consider whether flexible solutions can offer a more cost-effective method for resolving network constraints compared to technological solutions. The LV Voltage Control Selection Methodology report [6] quantifies the typical flexibility required per customer to avoid or defer investment by network archetype.

5. Novel Technologies with No Deployment for the Modelled Constraints

This section outlines the novel technologies identified by the RfI process and literature review that were not deployed to resolve the thermal or voltage constraints considered by the Transform model, explaining why these technologies were not deployed. Transform only considered thermal and voltage constraints. Full consideration of additional constraint types such as harmonics or fault level could impact the most appropriate technologies to deploy.

5.1.1 Smart Transformers (Power Electronics)

Smart transformers offer moderate thermal and voltage capacity releases. Smart transformers were modelled to cost an additional £12,267* totex compared to standard transformers, releasing an additional 8% thermal and voltage capacity compared to the capacity release by standard transformers. Other solution sets were more cost effective to resolve thermal or voltage constraints arising on the LV network than deploying smart transformers. For example, deployment of network data monitoring allows maximum utilisation of the existing transformer, increasing confidence in investment decisions. Additional capacity release can then be obtained in confidence from solutions such as active transformer cooling.

The Functional requirements report [3] showed that the majority of voltage rise constraints that are forecast to be encountered on the network required less than 3% voltage rise headroom, which can usually be achieved by the 2.5% voltage headroom released through manual tapping of the distribution transformer. Combining these solutions offers both thermal and voltage release more cost effectively than deploying smart transformers (combined totex cost of network data monitoring* and manual tapping of distribution transformer† is £9,529).

Alternatively, the PowerFactory study [5] discussed additional benefits associated with smart transformers such as harmonic filtering and phase balancing, and where there are network concerns around these issues there is a good use case for smart transformer utilisation.

5.1.2 Smart Transformer (OLTCs)

Smart transformers utilising automatic On Load Tap Changers (OLTCs) are modelled to be able to release 10% voltage headroom and legroom at a totex cost of £20,465*. The Transform and PowerFactory Network Study reports [2, 4] showed that voltage drop constraints were not an issue forecast to be encountered across National Grid's distribution network, but that voltage rise constraints would occur due to the installation of PV across National Grid's distribution network. The Functional Requirements report [3] showed that the majority of voltage rise constraints that are forecast to be encountered on the network required less than 3% voltage rise headroom. The Transform study showed that this was achieved primarily by tapping of the HV/LV transformer, which released 2.5% voltage headroom for a small totex cost of £2,495†. In cases where between 2.5% and 3% voltage headroom is required, manual tapping could potentially be deployed in conjunction with flexible demand that comes online during the solar peak to absorb excess generation and resolve the voltage rise constraint.

In the cases where more than 2.5% voltage headroom release was required, the most common solution deployed was switched capacitors, which were modelled as releasing 5% voltage headroom and legroom at a totex cost of £15,094†. Section 4 of the Functional Requirements report [3] showed that high voltage headroom requirements (above 3%) were most common on urban feeders supplying primarily commercial customers (LV1, LV3, LV4 and LV5). Section 4.3.1 of the Network Study report [2] showed that these network archetypes often were split between feeder that witnessed voltage rise constraints only, and feeders that initially experience voltage rise constraints, followed later by thermal constraints. However, physical spatial constraints in some substations (particularly in dense urban areas) could prevent the installation of switched capacitors. The

Functional Requirements study showed that it is forecast to be very rare that voltage issues will occur requiring headroom releases in excess of 6%, which can be achieved by deploying manual tapping and switched capacitors in parallel for a combined totex cost of £17,589. There was no need for the 10% voltage capacity released by OLTCs, and the voltage release required can be provided at a lower cost by other solutions, thus this solution was not deployed. Where physical constraints prevent the installation of switched capacitors, OLTCs are well positioned as a viable alternative solution to release the required voltage headroom. If totex costs were to be decreased below £17,589, this solution would get deployed ahead of the combination of switched capacitors and manual tapping.

5.1.3 Magnetic Power Flow Controller Transformer

Magnetic power flow controllers are a type of smart transformer that manipulate the magnetic flux within transformer, increasing thermal transformer and voltage capacity .They are modelled as having a totex cost of £54,315* and release 20% thermal transformer headroom at 10% voltage capacity. This high totex means there are alternative solutions already available that release more capacity and therefore this solution was not deployed. There may be specific conditions or circumstances where this solution could be considered as a viable alternative but those would need to be considered during detailed design and lower cost solutions have been excluded.

5.1.4 STATCOMs

STATCOMs were assumed to release 15% voltage headroom and legroom, 5% thermal transformer headroom and 10% thermal cable headroom at a totex cost of £24,633* for overhead circuits or £36,333* for underground circuits (modular solution). The PowerFactory modelling [5] showed that indeed STATCOMs release voltage capacity along the feeder, but the reactive current flow increases losses, reducing thermal capacity. The analysis showed that by installing STATCOMs at the remote ends of feeders, they were able to increase the voltage capacity, while reducing the thermal capacity loss compared to busbar connected STATCOMs. However, physical installation of STATCOMs at remote feeder ends may often be impractical due to a lack of suitable site, space or land ownership requirements for their installation.

The 15% voltage release (by STATCOMs) was shown to be excess to requirements in the Functional Requirements report. Manual tapping of transformers is typically sufficient to release enough voltage headroom at a much lower totex cost of £2,495† and when this isn't sufficient capacity it can be combined with switched capacitors to release sufficient voltage capacity at a totex cost below that of STATCOMs. Similarly, the 5% thermal transformer or 10% thermal capacity release offered by STATCOMs can be achieved at a lower cost by deployment of technologies such as active transformer cooling (thermal transformer), network data monitoring (both thermal constraints) or active network management (thermal constraints and moderate voltage constraints up to 3%). The network operator may opt for a single more costly solution than a combination of solutions that are less costly to minimise repeat visits to substation, staff resource time required and customer disruption. Practically, it may be difficult to install STATCOMs at remote feeder ends due to a lack of suitable installation site and physical space to install the STATCOM units.

5.1.5 Distribution Flexible AC Transmission Systems (DFACTS)-LV

DFACTs are assumed to release 8% voltage capacity and up to 8% thermal capacity. However, the existing forecast totex cost of £82,716† over its 20-year lifetime is prohibitively expensive.

5.1.6 Embedded DC Network

Embedded DC networks have a prohibitively expensive totex cost of £377,194† over its 30-year lifetime. It is more cost effective to deploy other solutions. DC networks have some benefits such as efficiency gains from utilising DC from PV generation directly without converting to AC and direct of DC power for DC load. However, this is associated with increased losses in distribution and inefficiency to the network operator of running separate AC and DC systems.

5.1.7 EAVC HV/LV Transformer Voltage Control

The £54,674† totex cost over EAVC HV/LV Transformer Voltage Control assumed 40-year lifetime releases 9% votlage headroom and 7% voltage legroom. The Functional Requirements report [3] showed that more than 6% voltage headroom release was required very rarely and 7.5% voltage headroom can be released by combining manual tapping [increasing headroom] with switched capacitors for a lower totex cost of £17,589. The forecast uptake of LCTs and historic network design philosophy meant no need for voltage legroom release is anticipated.

5.1.8 EAVC LV Circuit voltage regulators

The £135,650† totex cost over EAVC LV circuit voltage regulators' assumed 20-year lifetime is prohibitively expensive for a minor 1% voltage headroom release.

5.1.9 EAVC LV PoC voltage regulators

The £22,009† totex cost over EAVC PoC voltage regulators' assumed 15-year lifetime is prohibitively expensive for a minor 2% voltage headroom release.

5.1.10 RTTR for LV Underground Cables

RTTR for LV Underground Cables is assumed to release 5% thermal cable headoom, a totex cost of £37,924† over its assumed 15-year lifetime. More cost effective solutions such as network data monitoring can provide the initial improvements in capacity release through better visibility of circuit loading and therefore reduced safety margins without the need for a complete RTTR solution on LV cables.

The typical BaU solution for increasing thermal conductor capacity is splitting feeders or installing new feeders. Both these solutions are expensive (£53,880† for splitting feeders, £59,268† for new feeders), and highly disruptive as they involve excavation work and turning customers off while the new conductors are installed. Future innovative technologies that could offer thermal conductor release without the associated disruption of BaU solutions would be a valuable solution to the network operator.

R2. Innovative solutions that could offer thermal capacity release on underground conductors without the associated disruption of BaU conductor replacement would be a valuable alternative option for the network operator.

5.1.11 Widening of the Design Voltage Tolerance

This solution only offers voltage legroom capacity release which the Transform [2] and PowerFactory [4] Network Study reports showed not be a significant constraint on the LV network under any of the forecast DFES scenarios. However, the PowerFactory study has shown that the uptake of LCTs causes the remote ends to come close to the existing lower statutory voltage limit. Widening the design voltage tolerance could facilitate wider use of solutions that release additional voltage rise capacity while reducing voltage legroom without causing voltages to stray outside statutory limits.

6. Requirements for LV Voltage Control not currently addressed

6.1 Networks with No Suitable Novel Solutions

Section 7 of the Functional Requirements report [3] showed LV archetypes for which the solutions deployed were dominated by BaU solutions rather than novel technologies. Two cases were identified.

Urban Circuits Serving Commercial Customers

The first case was for urban circuits serving many commercial customers namely LV1 (Central Business Districts), LV3 (Town Centres), LV4 (Business Parks) and LV5 (Retail Parks). The dominant solution for these network archetypes, which were primarily concerned with voltage rise issues caused by PV uptake, was manual tapping. This offered 2.5% voltage headroom for totex cost £2,495†. At such low totex cost, none of the novel technologies are able to more cost effectively resolve the constraint. However, flexibility, for example through Demand Side Management, should be considered as an alternative option particularly where the net export causes voltages to rise outside limits rarely.

Rural Overhead Feeders Supplied from PMTs

The second case was for rural overhead feeders supplied from PMTs for network archetypes LV9 (Rural village overhead construction) and LV11 (rural farmstead small holdings). These feeders primary concern was thermal issues caused by adoption of EVs and heat pumps. The typical solutions deployed were new pole mounted transformers and overhead minor works which release 80 to 100% thermal capacity. It is unlikely that any novel solution will be able to more cost effectively release such high levels of capacity. When very significant levels of LCTs are deployed in a highly clustered manner, new feeders and transformers will need to be installed to meet the required capacity.

6.2 Case for Solutions Releasing Intermediate Headroom

In some situations solutions were deployed which ensured the network remained within limits but potentially released significantly more capacity than the minimum amount required. Figure 3 shows an example for LV10 feeders (rural village) in the South West. In the year 2044 LV Underground Network Split Feeder is deployed, releasing vast additional thermal capacity (excess to requirements) at high cost. The figure shows that the capacity released was over procured, even by 2050 the loading through the cable remains well below its capacity limit. Section 4.2 of the LV Voltage Control Selection Methodology report [6] showed that over procurement is a common issue across a range of network archetypes, including for domestic sub-urban underground feeders and rural overhead feeders. Over procurement occurs as a result of a lack of alternative, viable solutions availability to release sufficient headroom.

Table 2 below details where there are solutions with a significant range in the capacity release available. If capacity release is required marginally above the lower bound solution, the network must invest in the next available solution and may release excess capacity surplus to requirements. This presents an opportunity for technological providers to develop technologies that offer value to the network with intermediate options for capacity release. Sections 7.1.1 and 7.1.2 of this report discuss the potential for future innovative technologies to fill gaps in available headroom release. The development of innovative technologies to fill these gaps would reduce over procurement and give the network operator more cost efficient options with which to resolve network constraints.

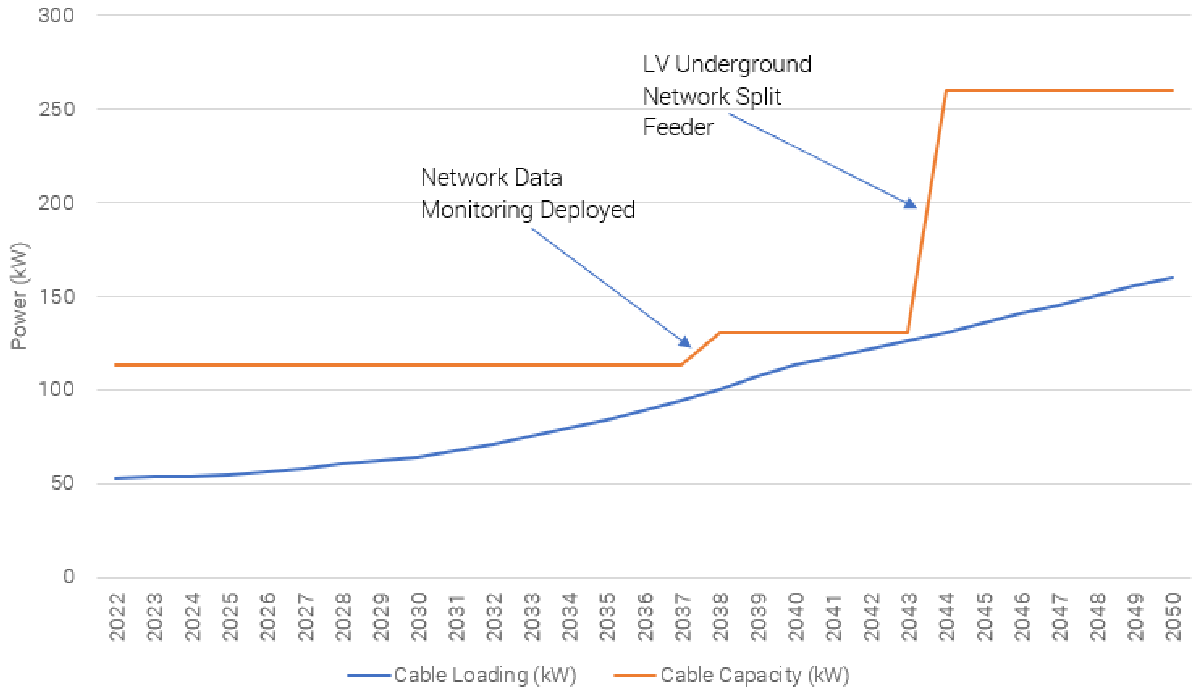

Figure 3: Example of over procurement of thermal cable capacity, taken from LV10 South West Steady Progress

In cases where the required headroom release is marginally exceeded, network operators should consider whether combining the lower cost technological intervention with a flexible service to provide the extra headroom required would be a more cost-effective solution to the network constraint. Figure 4 shows an example where active transformer cooling is deployed in 2050 to resolve a thermal transformer constraint, where the transformer capacity is exceeded by a small margin. Flexible solutions offer the potential to resolve this constraint by reducing load through the transformer rather than investing in costly network interventions.

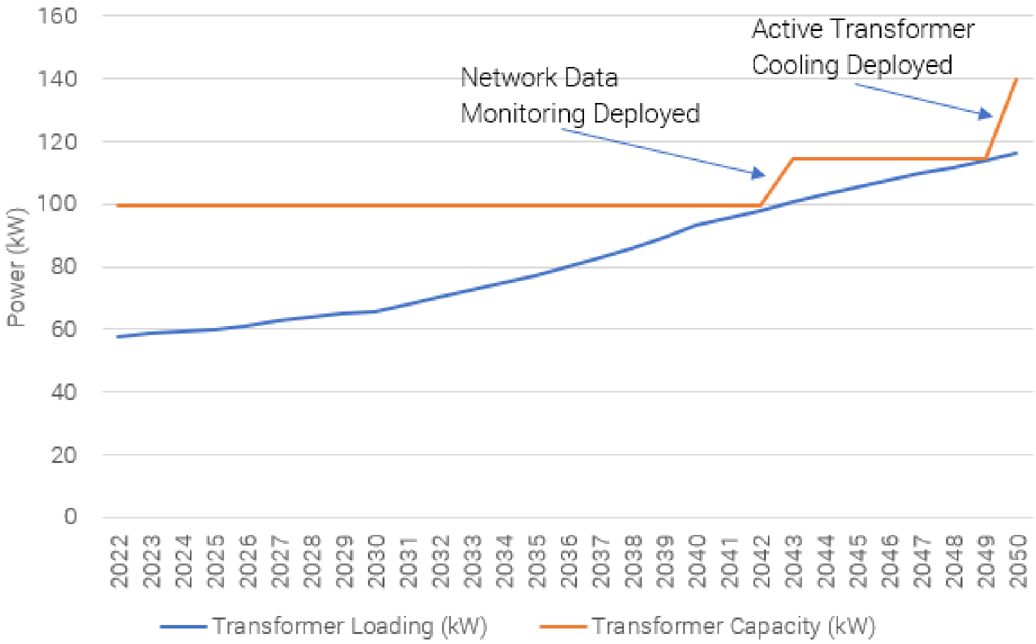

Figure 4: Example where flexibility should be considered, taken from LV10 West Midlands Steady Progress

The LV Voltage Control Selection Methodology report [6] considers deploying flexibility in two particular applications. It considers deploying flexibility as a means to defer network investment, and deploying flexibility as an enduring solution to avoid the need for network reinforcement. This report discussed the flexibility required per customer on each feeder type for these applications of flexibility. As understanding of customer willingness to participate in flexibility emerges, the network operator will improve its understanding of whether the flexibility required is achievable and hence viable as an alternative to network reinforcement.

C3. Significant steps in headroom release exist between solutions available to the network operator. If insufficient flexibility services are available to avoid additional investment, the network operator will have no choice but to over procure headroom at a higher cost. Any solution that can cost-effectively provide intermediate steps in headroom release could offer valuable alternative options to the networks.

Table 2: Steps in thermal capacity release available that may lead to significant capacity overprocurement

Constraint Type	Solution with lower capacity release (Lower Bound Solution)	Lower Bound Solution Headroom Release	Lower Bound Solution Totex	Solution with higher capacity release (Upper Bound Solution)	Upper Bound Solution Headroom Release	Upper Bound Solution Totex
Thermal Cable	Network Data Monitoring	15%	£7,034*	Permanent Meshing of Networks (LV Urban / LV Sub-Urban)	50%	£48,433†
Thermal Cable	Permanent Meshing of Networks (LV Urban / LV Sub-Urban)	50%	£48,433†	LV Underground Network Split Feeder	100%	£53,880†
Thermal Cable[6]	Network Data Monitoring	15%	£7,034*	LV Underground Network Split Feeder	100%	£53,880†
Thermal Transformer	Active Transformer Cooling	22%	£6,756†	LV Ground Mounted 11/LV Tx	80%	£15,987†
Thermal Transformer	Network Data Monitoring	15%	£7,034*	LV Pole Mounted 11/LV Tx	80%	£7,470†

[6] Permanent Meshing of Network (LV Urban / Sub-Urban) is not available for LV10 (rural village feeders of underground construction).

7. Recommended Solution Development

Following the literature review, analysis and assessment carried out in this project, this section sets out the proposed approaches for National Grid to further understanding of the novel solutions for use on their network. It also sets out areas where potential innovative technological development could provide significant benefits to network operators.

7.1 Areas for Future Technological Innovation

Table 2 shows significant steps in headroom release available from existing solutions. Section 4.2 of the LV Voltage Control Selection Methodology report [6] shows that this may result in significant over procurement of capacity. Technological innovations that can reduce the steps in headroom release at a competitive price point would offer significant value to the network operator by reducing necessary over procurement and reducing the necessary network investment required.

7.1.1 Thermal Cable Capacity

No solutions exist that release thermal cable capacity between 15% (from network data monitoring) and 50% (from permanent meshing). Innovative technologies that could provide intermediate thermal cable capacity headroom at totex cost[7] below the £48,433† cost of permanent meshing would offer significant value to the network operator. While Transform has selected permanent meshing as a cost-effective solution, practical difficulties in retrofitting to existing feeders together with implications on substation protection, safety and operational practice means that it is unlikely to be suitable for wide scale role out. Where network meshing is not a practicable solution, the next logical solution is splitting the feeder at totex cost[8] £53,880† and also technically challenging.. Therefore, this is an area for innovation with any technologies developed that could release greater than 15% thermal cable capacity with less cost and technical challenge than that of permanent meshing or splitting feeders would offer significant value to the network operator.

Alternatively, innovative solutions that could release a similar level of thermal cable capacity to network data monitoring and were compatible such that the total thermal cable capacity of network data monitoring and the innovative solutions together summed linearly. The price point required for this to be cost effective is the difference in costs between network data monitoring and the alternative solution (permanent meshing or splitting feeder).

Any solution that could fill these gaps without requiring extensive excavation and associated disruption would be particularly favourable for the network operator to employ, particularly if the solution could be deployed without a requirement for consumers to be turned off supply.

R3. Innovative technologies that could offer between 15% and 100% thermal cable capacity release for a totex cost below approximately £50,000 would provide significant value to the network operator. Innovation activity could investigate solutions able to fill this gap.

7.1.2 Thermal Transformer Capacity

No solutions exist that release thermal transformer capacity between 22% (from active transformer cooling) and 80% (from transformer upgrade). Innovative technologies that could provide intermediate thermal

[7] Assumed lifetime of permanent meshing is 45 years.

[8] Assumed lifetime of splitting feeder is 45 years.

transformer capacity headroom release at a totex cost per feeder below £15,987† (for feeders supplied by GMTs) or £7,470† (for feeders supplied by PMTs) would offer significant value to the network operator.

R4. Innovative technologies that could offer between 20% and 80% thermal transformer capacity at less than approximately £16,000 per feeder (for feeders supplied by GMTs) or £7,500 per feeders (for feeders supplied by PMTs) would provide significant value to the network operator. Innovation activity could investigate solutions able to fill this gap.

7.1.3 Alternative Solution to Manual Tapping

Section 6.1 and section 7 of the Functional Requirements report [3] showed that for urban circuits supplying primarily commercial customers manual tapping of the transformer, at totex cost £2,495† was the dominant solution deployed to resolve voltage rise constraints caused by high levels of PV deployment. Any innovative solution that could release similar levels of headroom at lower cost would be favourable to the network operator. Alternatively, any solution that could offer a similar level of headroom release without disrupting customers by temporarily taking them off supply, could be a preferential solution for the network operator, at equal or even potentially slightly higher cost to manual tapping. Flexible solution such as demand turn up to absorb excess solar PV generation could offer an alternative method for resolving the voltage rise constraint.

7.1.4 Alternative Solutions to Traditional New Build Assets

Section 6.1 and section 7 of the Functional Requirements report [3] showed that for rural overhead feeders, deployment of LCTs drove the need for new pole mounted transformers and in many cases complete overhead minor works (new transformer and new conductors). While today no technology exists that can compete with these traditional technologies, any technology that could release 100% thermal capacity for less than the assumed totex cost of overhead minor works (£35,920†). It is also recognised that this study only considers costs of reinforcements required at LV level, additional costs may also be incurred due to the growth of LCTs through reinforcements needed at, for example, the high voltage levels.

Although beyond scope for this project, in this instance solutions that can avoid needs for costly HV upgrades such as potential microgrids with distributed generation and storage may prove more cost effective than traditional upgrades. To enable solutions such as these to be considered, regulatory change may be required to allow the network operator to own storage and generation assets, or some other model would have to be explored such as consumer ownership.

7.2 Technologies for Further Trials

7.2.1 Active Transformer Cooling

Active transformer cooling was a solution commonly deployed to resolve thermal transformer constraints. Electricity North West (ENW) have conducted the Celsius [11] trial to investigate the potential for active transformer cooling to release headroom of distribution GMTs. National Grid currently employ active transformer cooling at primary substations and above, but not at distribution subs. It is recommended that National Grid conduct a trial of active transformer cooling on a sample of their distribution GMTs to ascertain if the anticipated headroom release is replicated before incorporating into BaU deployment if the trial is successful. Indicative timelines from the LV Voltage Control Selection Methodology report [6] suggest that active transformer cooling is required in sub-urban feeders by the early 2030s. Therefore, it is recommended that a verification trial of active transformer cooling is completed by the late 2020s across a subset of National Grid's heavily loaded GMTs.

R5. Verify performance of active transformer cooling technology across a subset of National Grid's heavily loaded distribution Ground Mounted Transformers by the late 2020s.

7.2.2 RTTR for HV/LV Transformers

The analysis has shown RTTR for HV/LV transformers as being a highly valuable option for LV feeders supplied by PMTs, i.e. where active transformer cooling is not viable. RTTR is being trialled across National Grid's 132kV and 33kV overhead lines [12], but has not been trialled for distribution transformers. Therefore, it is recommended that National Grid conduct a trial of RTTR for HV/LV transformers at a sample of sites where their PMTs are operating close to their thermal limits by the early 2030s. The trial should aim to demonstrate the effectiveness of the technology, and verify or otherwise the assumed 15% thermal transformer capacity release utilised in the modelling.

R6. By the early 2030s trial Real Time Thermal Ratings for HV/LV Transformers across a sample of National Grid's pole mounted transformers forecast to become thermally constrained. Trials should focus on how to install equipment necessary for RTTR on PMTs and on quantifying the benefit of RTTR on thermal PMT capacity.

7.2.3 Active Network Management

Active network management (of the LV network by control of, for example, normally open points) is not in use on the LV network, nor has it been trialled at significant scale on National Grid's LV distribution network. It is recommended that National Grid conduct a trial of active network management to gain an understanding from a real world trial regarding the levels of thermal and voltage capacity release that can be achieved from active network management. The LV Voltage Control Selection Methodology report [6] indicative timelines showed that active network management will be required for rural underground feeders by 2040, suggesting a trial should be underway by the mid-2030s. The Case Studies from the Transform analysis in this report suggest active network management is widely deployed across different archetypes and licence areas, therefore the network operator may want to bring forward the trial timings to ensure active network management is ready to be deployed when required.

R7. By the mid-2030s trial active network management across a section of National Grid's LV network and quantify the thermal and voltage headroom release achieved.

7.3 Proven Technologies for Continued Deployment

7.3.1 Manual Tapping of Transformers

Manual tapping of transformers was shown to be an effective means to increase voltage rise capacity by the PowerFactory and Transform studies, which will allow greater deployment of solar PV on the distribution network. The PowerFactory studies showed that for the case study networks, manual tapping does not introduce new voltage drop constraints for the three case study networks. Manual off load tapping at scale will necessitate significant staffing time and resource to conduct the procedure with the potential need to recruit and train more staff to carry out the procedure. Time off supply for customers fed by the transformers where manual tapping is carried out will also be required. Analysis conducted in the PowerFactory modelling has suggested that only a single tap operation is required, which will limit the time off supply to customers.

On feeders at the upper end of statutory voltage limits, manual tapping should be deployed in order to facilitate increased levels of PV deployment on the LV network.

7.3.2 PMTs, GMTs, New Feeders and Substation Minor Works

The Transform analysis showed that on feeders where high levels of LCTs were clustered, major BaU network interventions such as new PMTs and GMTs, new feeders and LV Minor Works (new transformers and new feeders) were unavoidable, although in some cases novel technologies could be used to defer the point in time when these were required. In these instances, the network operator will need to augment their network using traditional technologies, unless suitable alternative technologies are developed.

C4. Major network interventions using business as usual solutions such as new transformers, new feeders and new substations will be required for feeders with very high penetrations of low carbon technology deployment, unless suitable alternative technologies are developed.

7.3.3 Network Data Monitoring

National Grid first trialled LV monitoring in lab conditions in the LV Sensors [13] project from 2011 to 2013, and have installed LV monitoring equipment on their network for a number of years. Increasing installations of LV monitoring equipment is included within National Grid's RIIO-ED2 business plan. This project provides further confidence in the value of that strategy, such that increased visibility of the LV network can enable National Grid to make informed decisions regarding true capacity limits. This will enable them to be efficient and confident in the benefit available from the next technological solutions to deploy and in which locations to most effectively resolve network constraints. Continued innovation in the development of applications and algorithms deployed to LV monitoring to increase utilisation of existing assets based on the data from LV monitoring is advised to maximise the benefit from the technology. This development may wish to consider how algorithms from LV monitoring equipment can dynamically communicate with flexible demand to ensure the network remains within limits.

R8. Continue to deploy targeted LV Network Data Monitoring equipment across National Grid's network. Continue to innovate applications and algorithms deployable to LV monitoring equipment the benefits from the monitoring equipment and to maximise utilisation of existing assets.

7.4 Policy, Safety and Design Implications

Novel technologies such as network data monitoring present new risks to network operators. Data security is becoming increasingly important as an increasing proportion of the LV network is monitored. Active network management would allow the network operator to remotely manage and reconfigure their network. The communications protocol to do this must be secure so as to prevent malicious actors from potentially taking control of network assets. As novel solutions are deployed that provide more network data and greater remote control of network assets, cyber security must be continuously reviewed and enhanced to ensure that malicious actors can't access the data or control network assets. It is also always important to consider that systems will fail and ensure the impact of that happening is limited and understood.

If permanent meshing is considered as a solution, there are implications to the design methodology. It is important when meshing networks that full consideration is made regarding fault levels, substation protection implications and operator understanding. Safety considerations are also critical, whenever work is performed on meshed sections of network, it is vital to ensure that the work is conducted having been isolated from all supply routes. Reconfiguration of open/closed points may be possible to reduce the number of customers off supply while the work is conducted and therefore could benefit further from integration of active network management schemes.

7.5 Flexibility

This project has considered only technological based solutions to release headroom on the LV networks. National Grid are pursuing a "flexibility first" strategy to managing the LV network ensuring that customer provided demand/generation flexibility is considered first when there are network constraints. For flexible solutions to be the most cost effective, the annual cost must be less than the annualised totex cost of deploying the least costly technological solution (or set of solutions) required to resolve the constraint. The SILVERSMITH project has identified the most cost effective technological solution(s) for particular network constraint types. Therefore, when network planners consider flexible solutions, they should compare the cost of procuring the necessary flexibility to the cost of the most cost effective technological solution(s).

Flexibility may also be considered even when it may not be the most cost effective solution. For example, at times when there is a resource constraint (e.g. staffing / supply chain), flexibility can be used to postpone the need for the technological solution until the resource constraint eases.

C5.	Flexible solutions should be considered both as an alternative and complementary solution set to technological solutions.

R9.	Before investing in any technological solution, the network operator should consider whether a flexible solution could be used to more cost-effectively resolve the network constraint.

8. Conclusions and Recommendations

This project has utilised Transform and PowerFactory to perform analysis exploring how novel technologies can be used to increase capacity of the archetype LV network. The Transform model was used to perform a CBA to identify the most cost effective solutions to resolve typical thermal and voltage constraints anticipated across National Grid's network. The PowerFactory analysis showed the effect of novel technologies on voltage and loading, but in addition discussed additional technical parameters such as fault level and harmonics not assessed in the Transform analysis, which could impact the most effective technologies to deploy.

While it is envisaged that the solutions recommended below may be cost effective for network deployment, trials are advised to ensure real-world performance aligns with the modelled behaviour and to identify issues (such as physical constraints) not identified at this modelling stage which could lead to conditions where other solutions are well suited. There may also be occasions where other constraints such as supply chain issues and staffing availability may mean it is desirable to deploy a solution that is not strictly the most cost effective but minimises disruption or delays.

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. The novel solutions most commonly deployed across National Grid's LV network and therefore offering value over business as usual solutions are:

- C1.1 Network data monitoring
- C1.2 Active network management (dynamic control of the network by controlling, for example, normally open points)
- C1.3 Active transformer cooling
- C1.4 Real Time Thermal Ratings for HV/LV transformers

C2. Network planners should consider whether flexible solutions can offer a more cost-effective method for resolving network constraints compared to technological solutions. The LV Voltage Control Selection Methodology report [6] quantifies the typical flexibility required per customer to avoid or defer investment by network archetype.

C3. Significant steps in headroom release exist between solutions available to the network operator. If insufficient flexibility services are available to avoid additional investment, the network operator will have no choice but to over procure headroom at a higher cost. Any solution that can cost-effectively provide intermediate steps in headroom release could offer valuable alternative options to the networks.

C4. Major network interventions using business as usual solutions such as new transformers, new feeders and new substations will be required for feeders with very high penetrations of low carbon technology deployment, unless suitable alternative technologies are developed.

C5. Flexible solutions should be considered both as an alternative and complementary solution set to technological solutions.

8.2 Recommendations

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

R1. Consider the viability of flexible solutions to defer or avoid investment ahead of any decision to invest in the network. Assess likelihood of being able to procure sufficient flexibility to defer investment for each archetype as outlined in LV Voltage Control Selection Methodology [6].

R2. Innovative solutions that could offer thermal capacity release on underground conductors without the associated disruption of BaU conductor replacement would be a valuable alternative option for the network operator.

R3. Innovative technologies that could offer between 15% and 100% thermal cable capacity release for a totex cost below approximately £50,000 would provide significant value to the network operator. Innovation activity could investigate solutions able to fill this gap.

R4. Innovative technologies that could offer between 20% and 80% thermal transformer capacity at less than approximately £16,000 per feeder (for feeders supplied by GMTs) or £7,500 per feeders (for feeders supplied by PMTs) would provide significant value to the network operator. Innovation activity could investigate solutions able to fill this gap.

R5. Verify performance of active transformer cooling technology across a subset of National Grid's heavily loaded distribution Ground Mounted Transformers by the late 2020s.

R6. By the early 2030s trial Real Time Thermal Ratings for HV/LV Transformers across a sample of National Grid's pole mounted transformers forecast to become thermally constrained. Trials should focus on how to install equipment necessary for RTTR on PMTs and on quantifying the benefit of RTTR on thermal PMT capacity.

R7. By the mid-2030s trial active network management across a section of National Grid's LV network and quantify the thermal and voltage headroom release achieved.

R8. Continue to deploy targeted LV Network Data Monitoring equipment across National Grid's network. Continue to innovate applications and algorithms deployable to LV monitoring equipment the benefits from the monitoring equipment and to maximise utilisation of existing assets.

R9. Before investing in any technological solution, the network operator should consider whether a flexible solution could be used to more cost-effectively resolve the network constraint.

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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 Business as Usual Solutions

Headroom releases and costs associated with BaU solutions were agreed by GB network operators during development of the Transform model. These costs have been adjusted for inflation and were agreed by National Grid and EA Technology during the analysis for the Functional Requirements report [3].

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

Solution Id	Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
BaU_T1	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%
BaU_T2	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%

Solution Id	Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
BaU_T3	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%
BaU_T4	LV underground Minor works†	The cost is composed of a new ground mounted distribution transformer, 100m of HV cable to supply the new transformer and associated jointing to connect this to the network; 600m of new LV cable to supply two new circuits at an average length of 300m each.	£133,288	£1,333	£179,599	45	100%	100%	1%	10%
BaU_T5	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;	£333,220	£3,332	£448,997	45	500%	500%	1%	15%

Solution Id	Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
		1.8km of new LV cable to supply six new circuits at an average length of 300m each.								
BaU_T6	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%
BaU_T7	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%
BaU_T8	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%

Solution Id	Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
BaU_T9	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%
BaU_T10	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%
BaU_T11	Manual phase balancing - LV†	Rebalancing phases by changing which phases customers are connected to	£22,440	£224	£41,232	45	20%	20%	20%	0%

Solution Id	Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
BaU_T12	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%
BaU_T13	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 III Novel Solutions

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

The literature review [1] identified additional novel solutions that the network operator might consider deploying to increase LV network capacity. Headroom releases and costs associated with these technologies were agreed by GB network operators during development of the Transform model. The same methodology has been applied to cost the BaU solutions. These costs have been adjusted for inflation and were agreed by National Grid and EA Technology during the analysis for the Functional Requirements report [3]. These solutions are marked throughout this appendix with a dagger (†).

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

Solution ID	Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
NT1	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%
NT2	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%

Solution ID	Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
NT3	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%
NT4	EAVC - HV/LV TransformerN Voltage Control†	As the network starts to operate closer to these limits, DNOs may opt to introduce additional automatic voltage control devices over and above those located at the grid and primary transformers. Together these new and existing voltage control devices will constitute an EAVC system.	£42,057	£0	£54,674	40	0%	0%	9%	7%
NT5	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	£104,346	£0	£135,650	20	0%	0%	1%	1%

Solution ID	Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
		transformers. Together these new and existing voltage control devices will constitute an EAVC system								
NT6	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%
NT7	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	£23,181	£2,318	£40,376	5	10%	10%	3%	3%

Solution ID	Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
		generators (e.g. supermarkets, commercial buildings) connected to the LV network - it is not deemed to be a residential solution								
NT8	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%
NT9	Permanent Meshing of	Converting the operation of the LV network from a radial feeder (with split points) to a solid	£23,181	£927	£48,443	45	10%	50%	0%	2%

Solution ID	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†	mesh configuration. Costs include labour, excavation, joints, any additional cabling and LV circuit breakers, plus modelling costs for new network configuration. Does not include costs for change to design policy, additional staff training, costs associated with changing operating practices.								
NT10	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%
NT11	RTTR for HV/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%

Solution ID	Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
NT12	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%
NT13	RTTR for LV Underground Cables†	The use of measurement and ambient forecasting data to predict the rating (and hence current carrying capacity) of assets in a real-time mode. This variant considers RTTR for LV underground cable circuits	£29,172	£0	£37,924	15	0%	5%	0%	0%
NT14	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%

Solution ID	Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
NT15	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%
NT16	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%
NT17	Widening of the design voltage tolerance - LV†	Changing voltage limits from +10% / -6% to +/-10%	£78	£0	£117	60	0%	0%	0%	20%
NT18	Smart Tx (Power Electronics)*	Smart Tx technology utilising power electronics	£10,000	£100	£12,267	15	8%	0%	8%	8%
NT19	Magnetic Power Flow Controller (Tx)*	Smart Tx technology controlling magnetic flux through transformer	£40,000	£800	£54,135	15	20%	0%	10%	10%
NT20	Smart Tx (OLTCs)*	Smart transformer using automatic OLTCs	£6,950	£820	£20,465	20	0%	0%	10%	10%

Solution ID	Solution	Description	Capex (£)	Opex (£/year)	Totex (£)	Lifetime (Years)	Thermal Transformer Capacity Release (%)	Thermal Cable Capacity Release (%)	Voltage Headroom Capacity Release (%)	Voltage Legroom Capacity Release (%)
NT21	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%
NT22	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%
NT23	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%
ES	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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