LV Predict 2

Cost Benefit Analysis Methodology

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LV Predict 2

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Verification Statement

This work was carried out on behalf of SP Electricity North West (SP ENW) by Frazer-Nash Consultancy and TNEI under Network Innovation Allowance (NIA) project NIA_ENWL_036.

The Cost-Benefit Analysis (CBA) methodology and this accompanying report have been verified for technical consistency. Given the lack of available data, effort has been made to ensure the assumed inputs to the CBA methodology are appropriate and aim to give an outcome representative of the current network. Key assumptions, data sources, and analytical approaches are clearly documented and have been applied consistently to enable repeatability and auditability. This verification relates solely to the CBA methodology and its application as described in this report and does not constitute assurance of specific investment outcomes.

Executive Summary

The two innovation projects, LV Predict and LV Predict 2, have explored the technical challenges and research questions associated with modelling and predicting degradation on Low Voltage (LV) cable joints. This has resulted in a methodology that predicts damage for a given LV joint, given the surrounding network topology, its physical and geographical characteristics and the demand connected in terms of number of customers and adoption of Low Carbon Technology (LCT) (e.g. Electric Vehicle (EV) and heat pumps). It was envisaged that the outcomes of this tool would enable a move to more targeted and proactive maintenance through its ability to predict parts of the LV network most at risk of faults and failures.

However, before considering a change of maintenance strategy towards a more proactive approach and committing to implementing this capability within a Business as Usual (BAU) strategy, it is important to quantify the expected benefit this will bring to the operation and maintenance of the network, both financially and non-financially. This CBA methodology report considers the range of costs and benefits associated with both reactive and proactive maintenance strategies and sets out a CBA methodology that enables SP ENW to quantify the financial benefit of different maintenance approaches. Capital and operational costs, penalties associated with faults and outages, and non-financial factors such as reputational risk and customer satisfaction are detailed.

A reactive maintenance strategy for LV cables is more vulnerable to age related degradation, rising fault rates, and escalating operational costs. The financial burden includes direct repair expenses, customer compensation for outages, regulatory penalties, and street works fines — all compounded by the inefficiencies of an unplanned, urgent response to restore customers supply. Electrification trends in pursuit of widespread LCT adoption further intensify these challenges, increasing peak loads and accelerating asset wear. The reactive scenario also exposes the operator to reputational risk, environmental impact from emergency works, and social disruption due to uncoordinated street works and service outages.

In contrast, a proactive replacement strategy represents a deliberate shift from reactive maintenance to forward-looking asset management. By systematically identifying and replacing high risk LV mains segments before failure occurs, the strategy aims to enhance network reliability, reduce long-term costs, and support broader operational and regulatory objectives. This approach requires the ability of a model such as that presented in the LV Predict 2 Methodology Report [1] to identify LV ways at risk of failure. However, this model has very little validation as the fault and failure data required is unavailable. In lieu of a validated model, this CBA presents the benefit gained from employing models of different skill levels. By targeting the most vulnerable parts of the network, the program ensures that investment is directed where it will yield the greatest reliability improvements and risk reduction. Although this approach requires an additional cost in the form of initial capital investment, the intervention costs are offset over time by a marked decline in fault related service disruptions, repairs and associated penalties. The long-term (a 20-year period is simulated) cost trajectory demonstrates a favourable shift toward predictable, planned expenditures and improved asset performance.

These financial efficiencies could be further enhanced through coordinated planning with internal departments and external stakeholders, enabling cost sharing opportunities and minimising public disruption. The reliability benefits are both immediate and enduring: customers experience fewer outages and improved service quality, while the Distribution Network Operator (DNO) benefits from enhanced performance metrics, regulatory compliance, and reputational gains. Modern replacement cables also support future network demands, including increased electrification and distributed energy integration. Strategically, the proactive replacement program aligns with

SP ENW's commitment to resilience, sustainability, and customer service excellence. It transforms cable replacement from a reactive burden into a strategic investment that safeguards infrastructure, supports economic development, and delivers long-term value to stakeholders.

The presented CBA methodology offers a framework to quantify the relative costs of both reactive and potential proactive maintenance approaches. The CBA methodology is presented alongside results based on reasonable but assumed inputs, from which quantitative insights can be drawn. These quantitative CBA results provide a more detailed and precise view of the financial benefits and shifted costs of a proactive strategy, alongside the qualitative analysis of costs and benefits presented in other chapters. The quantitative analysis is dependent on a specific set of assumed, reasonable parameters that are consistent with the qualitative insights and predictions found elsewhere.

The CBA simulates both LV way replacements and repairs of faults on a set of representative theoretical LV ways over a time span of 20 years. The level of fault rate prediction skill is supplied as an input, meaning the potential benefit of different model skill levels can be explored. Similarly, the volumes of LV way replacement per year are specified as an input, and not only different total levels of investment but also different replacement trajectories can be explored, for example consistent replacement volumes every year vs ramping replacement up slowly or front-loading the replacement schedule.

The CBA methodology demonstration shows financial benefit to a proactive maintenance strategy, even when the level of skill in fault predictions is low. Decreasing marginal financial benefits are then gained as the skill of the predictions increases. Total yearly costs decrease over the 20-year period under all simulated proactive maintenance approaches, mainly due to the reduction in Interruptions Incentive Scheme (IIS) costs. Based on the assumed distribution of fault rates and their evolution through time, with a skill of 0.6 (the correlation between true and predicted fault rate rankings) and with replacements peaking in year 5, a replacement strategy that replaces 40% of all LV ways over the 20-year period is optimal.

The presentation of the CBA methodology, rather than purely the outputs of a conducted CBA, allows SP ENW to take this analysis forward and adapt it to their specific network parameters and test any proposed future proactive maintenance strategies.

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1 Abbreviations

BAU	Business as Usual
CBA	Cost-Benefit Analysis
CI	Customer Interruptions
CML	Customer Minutes Lost
DCF	Discounted Cash Flow
DFES	Distribution Future Energy Scenarios
DNO	Distribution Network Operator
SP ENW	SP Electricity North West
EV	Electric Vehicle
IIS	Interruptions Incentive Scheme
LCT	Low Carbon Technology
LV	Low Voltage
MC	Monte-Carlo
NPV	Net Present Value
NRSWA	New Roads and Street Works Act
PILC	Paper-Insulated Lead-Covered
PV	Present Value
XLPE	Cross-Linked PolyEthylene

2 Introduction, Objectives and Scope Analysis

This piece of work provides SP ENW with analysis of the expected net financial benefit of moving to a proactive maintenance strategy using the outputs of a fault prediction tool such as the deployment of the methodology developed in LV Predict 2. Following discussions with stakeholders at SP ENW, presentation of the CBA methodology for conducting a Cost-Benefit Analysis was determined the most useful output to inform future decisions and give SP ENW the information needed to take this analysis forward and run it on their own assumed inputs in future. A demonstration of this CBA methodology with assumed inputs is also included to illustrate the outputs the CBA methodology gives and the expected magnitude of values. Presentation of the CBA methodology, as opposed to purely the outputs of a conducted CBA, allows SP ENW the flexibility to re-run the analysis periodically as inputs, assumptions or future trajectories change. It also facilitates the conduction of sensitivity analyses to key parameters of a replacement strategy such as the optimal volume of replacements and the expected benefit from investment in improved fault predictions.

This report contains the following chapters, covering the advantages and disadvantages of both reactive and proactive maintenance strategies, before presenting the CBA methodology:

- Chapter 3 describes the reactive maintenance strategy, including the impact to customers and estimated constituent costs and impacts including penalties, reputational risks and non-financial considerations.
- Chapter 4 describes the proactive intervention strategy of full LV way replacement, including selection criteria for replacement and costs and benefits (both financial and non-financial).
- Chapter 5 details and compares the costs associated with each maintenance strategy including capital, operational, indirect and hidden costs.
- Similarly, Chapter 6 details and compares the respective benefits of the reactive and proactive maintenance approaches. Avoided costs and penalties, reputation, resilience and environmental impacts are considered.
- Chapter 7 outlines the sources of uncertainty present and how these have been considered within the CBA methodology design.
- Chapter 8 presents a CBA methodology that quantifies the financial benefit of a given proactive maintenance strategy for a given level of skill in predictions of fault probabilities. This includes a discussion of the CBA methodology's assumptions and a worked example of the outputs of this CBA methodology, showing the calculations of net financial benefit and a sensitivity analysis to replacement volume.
- Chapter 9 concludes the report by summarising the findings and recommendations of the work. It includes a description of how SP ENW could implement the proposed LV way prioritisation methodology, and highlights practical considerations for this implementation.

3 Baseline Scenario

3.1 Overview of the Current Maintenance Strategy

The current approach to managing LV cables is predominantly reactive, with maintenance activities initiated only after a fault or failure has occurred. This strategy relies heavily on customer outage reports and fault detection systems (although even these are a relatively recent development) to identify issues, followed by dispatching repair crews to restore service. While this method minimises upfront capital expenditure, it often results in higher long-term costs due to emergency response premiums and unplanned outages. Additionally, the lack of proactive intervention means that cable degradation is likely not systematically monitored since there is no direct need for this information. This can lead to unanticipated failures that can disrupt service continuity, impact customer satisfaction, and leave the network operator exposed to regulatory penalties. This reactive approach forms the baseline against which the benefits of a proactive replacement strategy will be assessed.

3.2 Asset Condition and Failure Profile

The LV cable network currently in operation comprises a mix of legacy and mid-life assets, many of which are approaching or have exceeded their original design life which is quoted as being at least 60 years for modern cable types [2]. A significant proportion of the cables in the SP Electricity North West operating area were installed in the 1950s and 1960s, with some being over 100 years old [3]. For these assets there is limited historical data on installation practices and environmental exposure. In fact, the additional lack of asset age data means there is significant uncertainty on not only installation conditions for the oldest assets, but also which assets actually are the oldest. As insulation materials and joints degrade over time, the likelihood of faults increases, particularly under stress conditions such as load spikes, water ingress, or ground movement. LV cable failure rates are likely dependent on network age indicating that an ageing network could experience inflated failure rates, especially in legacy cables such as Paper-Insulated Lead-Covered (PILC), which comprises a significant proportion of the current network [4]. While the precise mechanism for PILC cable degradation is complex and poorly understood, it is hypothesised that damage evolution could be non-linear, with failures expected to disproportionally increase as cable loading increases led by LCT adoption. These failures typically manifest as phase-to-earth faults, cable sheath breakdowns, or joint failures, often requiring urgent excavation and maintenance or joint replacement [5].

Compounding this issue is the accelerating impact of electrification, driven by the widespread adoption of LCTs such as EVs, heat pumps, and solar photovoltaics. These technologies are increasing both peak and average loads across LV networks, placing additional strain on ageing infrastructure and accelerating asset degradation and the need for reinforcement. Without proactive intervention, this increased rate of asset degradation is likely to result in more frequent and severe outages. Combined with the absence of systematic condition monitoring, this means deterioration is often undetected until failure occurs, contributing to unpredictable outages and compounding operational risk. This ageing profile underscores the vulnerability of the network and forms the foundation for evaluating the benefits of a proactive replacement strategy.

3.3 Operational and Financial Impacts

The reactive maintenance strategy for LV cables imposes significant operational and financial burdens on the network operator. Emergency fault responses typically require rapid mobilisation of field crews, often outside standard working hours, leading to elevated labour costs and logistical inefficiencies. Excavation, fault location, cable jointing, and reinstatement activities are inherently more expensive when performed under urgent, unplanned conditions. In addition, reactive repairs often involve temporary fixes rather than full asset replacement, increasing (or at a minimum, not reducing) the likelihood of repeat failures and compounding long-term costs.

From a financial perspective, the direct costs of reactive maintenance include materials, labour, equipment hire, and reinstatement. Indirect costs are equally substantial: customer compensation payments under guaranteed standards of performance [6], regulatory penalties linked to reliability indices such as Customer Interruptions (CI) and Customer Minutes Lost (CML), and reputational damage from service disruptions. Street works fines represent another growing cost pressure. Under the New Roads and Street Works Act (NRSWA), utilities may be penalised for overrunning permitted work durations, failing to meet reinstatement standards, or breaching traffic management requirements [7]. These fines can range in value, depending on the severity and location, and are particularly common in urban areas with high traffic sensitivity. Naturally, reactive faults are more likely to breach permit conditions due to their urgency and unpredictability, increasing exposure to these penalties.

3.4 Risk and Reliability Considerations

The reactive maintenance model for LV cables carries significant risk exposure and undermines long-term network reliability. Increasing demand and usage patterns from the adoption of LCTs are expected to accelerate the rates of asset degradation (potentially in a non-linear manner) and consequently reduce the remaining life of cable joints, resulting in an increase in faults on the network. Combined with the effect of weather events such as heavy rainfall triggering faults on damaged joints, the likelihood of fault clustering could significantly increase over time. This would challenge fault response capacity and increase the likelihood of extended outages. Reactive fault repairs often require emergency excavation and reinstatement in public areas, exposing the operator to street works compliance risks. Breaches of the NRSWA, such as overruns, poor reinstatement, or inadequate traffic management, can result in significant fines, particularly in traffic-sensitive areas like city centres. These penalties add to the financial and operational burden and highlight the systemic fragility of an approach focussed primarily on reactive maintenance.

In summary, the reactive maintenance model leaves the LV network exposed to escalating reliability risks, regulatory penalties, and operational inefficiencies. Without proactive reinforcement, the network risks entering a cycle of escalating failures and reactive spending. These vulnerabilities demonstrate the strategic advantages of a proactive replacement program that enhances resilience, predictability, and long-term value.

3.5 Summary of the Baseline Scenario

The baseline scenario comprising of a reactive maintenance strategy for LV cables reveals a network increasingly vulnerable to age related degradation, rising fault rates, and escalating operational costs. With a significant portion of the cable infrastructure exceeding its design life, failures are becoming more frequent and unpredictable, often requiring costly emergency interventions. The financial burden includes direct repair expenses, customer compensation, regulatory penalties, and street works fines — all compounded by the inefficiencies of an unplanned, urgent response.

Electrification trends further intensify these challenges, increasing peak loads and accelerating asset wear. The reactive scenario also exposes the operator to reputational risk, environmental impact from emergency works, and social disruption due to uncoordinated street works and service outages. Reliability metrics such as CI and CML are negatively affected, potentially triggering regulatory consequences.

In conclusion, the reactive approach presents a financially and operationally unsustainable trajectory. It serves as a critical benchmark against which the benefits of a proactive replacement strategy, focused on resilience, predictability, and long-term value will be evaluated.

4 Proactive Replacement Strategy

4.1 Overview of the Proactive Replacement Strategy

The proactive replacement strategy for LV cables represents a shift from reactive fault driven maintenance to a forward looking, risk-based asset intervention model. This approach prioritises the systematic replacement of LV cable infrastructure before failure occurs, aiming to enhance network reliability, reduce long-term operational costs, and support future energy demands such as LCT integration.

The core intervention proposed under this strategy is the full replacement of LV main cable (and associated joints) along an LV way, targeting ways identified as high risk or strategically significant. Rather than waiting for faults to trigger emergency repairs, this method replaces entire cable runs based on predictive indicators and network planning priorities.

Key drivers for this strategy include:

Asset Ageing: Many LV PILC cables in the network are approaching or exceeding their expected service life, with degradation accelerating due to increased loading (potentially both in terms of high demands, and more extreme demand and therefore temperature cycles), exceeding the original cable rating.

Expected increase in fault rates: Reactive maintenance merely patches the fault and does not reduce the underlying failure probability, resulting in outage frequencies and emergency repair costs that increase over time.

Electrification Demands: The rise of EVs and other LCTs is placing new load pressures on legacy infrastructure.

Operational Efficiency: Coordinating cable replacement with other programs such as de-looping and EV upgrades enables cost-sharing and minimises disruption.

By replacing cables proactively, the strategy aims to reduce fault rates significantly, improve customer service continuity, and stabilise long-term cost trajectories. It also aligns with broader asset management goals and regulatory expectations for sustainable, resilient network operations.

4.2 Selection Criteria for Replacement

The effectiveness of a proactive replacement strategy for underground LV cables hinges on the precision and relevance of its selection criteria. These criteria ensure that resources are allocated to the most critical assets, maximising reliability gains while minimising unnecessary expenditure. The output of LV Predict 2 — predictions of damage per joint — would need to be combined with the number of joints on the LV way and existing asset condition to give a proxy for failure rate across the entire LV way.

The following factors form the basis of the selection framework:

Factors included in the CBA prioritisation method: This includes those incorporated into the predictions of per-joint damage that is the output of the LV Predict 2 methodology [1], as well as the aggregate properties of the LV way that are used to create a proxies for failure rate and for the consequence of failure.

- Asset Type and LV way configuration:

- Assets installed using outdated materials, such as PILC, could be flagged for early intervention if indicated by high predictions of damage.
- The total number of joints on the way is used to translate per-joint damage predictions to an overall measure of failure rate for the LV way as a whole.

- Environmental and Installation Conditions:
  - Cables located in high risk environments such as flood prone areas and regions of thermally resistive soil are considered more vulnerable.
- Load and Utilisation Profiles:
  - Cables operating near or above their rated capacity are subject to accelerated ageing and thermal stress.
  - Circuits with high load variability or frequent switching events are assessed for cyclic thermal stresses and associated degradation.
- Risk-Based Prioritisation:
  - The number of customers connected is included in the ranking and prioritisation of replacements, as a proxy for consequence of failure. Of two cables with the same fault rate and replacement cost, the one with more customers connected is prioritised.
  - This approach ensures that high-risk assets are addressed first, aligning with regulatory expectations and reliability targets.

Factors not included in the CBA prioritisation method (or the LV predict 2 model): These relate to the consequence of failure and should be considered separately by SP ENW.

- Historical Performance:
  - If available, fault data should be analysed to identify cables with recurrent failures or degradation patterns that are not flagged by the LV Predict 2 model.
  - Historic data should be used to validate and calibrate the LV Predict 2 predictions, to understand the model's true skill.
- Assumed Asset Age:
  - Since asset age data is unavailable and therefore, does not feed into the LV Predict 2 model, SP ENW should consider prioritising older cable types (PILC) that have historical failures.
- Customer Impact and Criticality:
  - Cables serving higher consequence customers or large customer bases could be given higher priority.
  - Socioeconomic factors, such as the impact of outages on vulnerable populations, could be incorporated into decision making.
- Coordination with Other Infrastructure Works:
  - Opportunities for joint trenching or alignment with planned civil works (e.g. road resurfacing, water main upgrades) can be leveraged to reduce costs and disruption.
  - Replacement is prioritised where possible coordination with other utility programs exist.

This structured selection methodology enables a data-driven, transparent, and justifiable approach to asset replacement. It balances technical, economic, and social considerations, ensuring that the proactive strategy delivers optimal value across the network.

4.3 Expected Reliability Improvements

The proactive replacement of underground LV cables is expected to deliver substantial improvements in network reliability by directly addressing the root causes of recurring faults and service interruptions. By targeting high risk assets before failure occurs, this strategy shifts the operational standard from reactive fault response to preventive asset management, yielding measurable gains in system performance and customer satisfaction.

One of the most immediate benefits is the reduction in fault frequency. Replacing high risk assets with modern, robust alternatives significantly lowers the likelihood of electrical faults, thereby reducing the number of emergency call-outs and unplanned outages. In addition to fault reduction, proactive replacement enhances supply continuity and voltage stability. New cables are sized to account for future load growth within their rated capacity and offer improved thermal performance, lower impedance, and greater resilience to load fluctuations, which collectively contribute to improved reliability. This is particularly beneficial in densely populated urban areas and regions with critical infrastructure, where even brief interruptions can have significant economic and social impacts.

Using this strategy could also lead to improvements in fault location and restoration times. The planned replacement of high risk assets with modern cable systems offers the possibility of simultaneously installing enhanced monitoring which simplifies diagnostics and accelerates the repair process in the event of a failure. This would lead to shorter outages and reduced disruption for customers going forward.

From a network-wide perspective, proactive replacement contributes to improved reliability indices, such as CI and CML. These metrics are closely monitored by regulators and stakeholders, and sustained improvements can strengthen the utility's performance standing, regulatory compliance, and public trust.

Moreover, the reliability gains are not limited to the replaced segments alone. A fault on the network can cause increased levels of stress on adjacent assets such as transformers, switchgear, and upstream feeders. This will most likely be due to increased level of thermal degradation as most faults tend to causes excessive heating. By reducing the stress on adjacent assets, the strategy helps stabilise the broader distribution system. This cascading effect supports long-term asset health and reduces the risk of compound failures.

In summary, the proactive replacement of underground LV cables is a strategic investment in reliability. It mitigates the risk of future faults, enhances service quality, and supports SP ENW's commitment to delivering safe, dependable electricity to its customers. These improvements form a critical part of the overall value proposition for the replacement program and underpin its long-term justification.

4.4 Summary of the Proactive Replacement Strategy and Strategic Justification

The proactive replacement strategy for underground LV cables represents a deliberate shift from reactive maintenance to forward-looking asset management. By systematically identifying and replacing high risk cable segments before failure occurs, the strategy aims to enhance network reliability, reduce long-term costs, and support broader operational and regulatory objectives.

This approach utilises the ability of the LV Predict model to identify cables at risk of failure. By targeting the most vulnerable segments, the program ensures that investment is directed where it will yield the greatest reliability improvements and risk reduction. Although the initial capital investment is substantial, the intervention costs are offset over time by a marked decline in emergency repairs, fault related service disruptions, and associated penalties. The long-term cost trajectory demonstrates a favourable shift toward predictable, planned expenditures and improved asset performance. These financial efficiencies are further enhanced through coordinated planning with internal departments and external stakeholders, enabling cost sharing opportunities and minimising public disruption.

The reliability benefits are both immediate and enduring. Customers experience fewer outages and improved service quality, while the DNO benefits from enhanced performance metrics, regulatory compliance, and reputational gains. Modern replacement cables also support future network demands, including increased electrification and distributed energy integration.

Strategically, the proactive replacement program aligns with SP ENW's commitment to resilience, sustainability, and customer service excellence. It transforms cable replacement from a reactive burden into a strategic investment that safeguards infrastructure, supports economic development, and delivers long-term value to stakeholders.

5 Qualitative Cost Breakdown

This section provides a qualitative analysis of the costs associated with the proactive replacement of underground LV cables, comparing them against a reactive maintenance strategy. It examines both direct and indirect financial impacts across the full asset life cycle from initial capital investment to long-term operational savings and hidden liabilities. A holistic view of the economic implications of each approach is provided by categorising costs and analysing their interdependencies. The goal is to support informed decision making by highlighting not only the immediate financial requirements but also the strategic value and long-term efficiencies gained through proactive intervention.

5.1 Capital Expenditure

The proactive replacement of underground LV cables entails a significant capital investment, encompassing a range of direct and indirect costs required to execute the program effectively. While the majority of these costs are replicated under the reactive maintenance strategy, the overall magnitude of capital investment is greater for proactive replacement. These costs begin with materials, where the primary expense is the procurement of new LV cables. These are typically priced per meter, depending on the cable specification and installation context. In addition to the cables themselves, ancillary materials such as joints, connectors, and enclosures are essential to ensure safe and reliable connections throughout the network.

Labour costs form another substantial component of the capital expenditure. These include the wages or fees for installation crews, whether sourced internally or through external contractors. In many cases, specialist services are also required such as traffic management, excavation, and utility detection which add complexity and cost to the overall operation, particularly in urban or congested environments.

The use of equipment and machinery introduces further capital costs. This includes the hire or depreciation in value over time of cable pulling rigs, trenching tools, and other mechanical aids necessary for efficient and safe installation as well as their upkeep and maintenance costs.

Street works and reinstatement costs are particularly relevant in public or shared spaces. These include fees for permits and traffic disruption levied by local authorities, as well as the cost of restoring affected surfaces such as tarmac, paving, curbs, and landscaping to their original condition or better. These reinstatement activities are often subject to strict regulatory standards and community expectations.

Together, these elements represent the full spectrum of capital investment required for a proactive cable replacement strategy. While substantial, these costs must be weighed against the ongoing operational savings, reliability improvements, and risk mitigation benefits outlined in subsequent sections of this report.

5.2 Operational Expenditure

While capital expenditure captures the upfront investment in proactive cable replacement, operational expenditure reflects the ongoing costs and savings associated with maintaining and managing the LV network over time. These costs are influenced by the extent of replacement, the condition of remaining assets, and the operational efficiencies gained through modernisation.

One of the most significant impacts of proactive replacement is the reduction in fault-related maintenance costs. New LV cables are less prone to failure, which translates into fewer emergency call outs, lower repair costs, and reduced disruption to customers and field teams. This improvement in reliability also decreases the frequency and intensity of monitoring and inspection activities, although some level of routine asset surveillance remains necessary to ensure long-term performance.

In scenarios where only partial replacement is undertaken, reactive repair costs persist for segments of the network that remain untouched. These costs include fault detection, emergency response, and temporary reinstatement, which can be unpredictable and often more expensive than planned interventions. The continued presence of legacy infrastructure may also complicate fault diagnosis and increase the likelihood of repeat issues.

Customer service costs are another important component of operational expenditure. These include the resources required to manage fault-related call outs, handle complaints, and process compensation claims for service interruptions. Proactive replacement tends to reduce these costs over time by improving service continuity and customer satisfaction, though short-term increases may occur during the transition phase due to planned outages or construction-related inconvenience.

Project management and overheads round out the operational expenditure profile. Planning, supervision, and administrative support are critical to ensuring the program is delivered on time, within budget, and in compliance with safety and quality standards. These costs also include stakeholder engagement, procurement coordination, and documentation. To account for unforeseen challenges such as adverse weather, underground obstructions, or scope changes a contingency allowance is also typically included.

Overall, operational expenditure under a proactive strategy is characterised by a shift from the reactive maintenance strategy with high cost variability to more predictable and manageable maintenance profiles. This transition supports better budgeting, enhances customer experience, and contributes to long-term network resilience.

5.3 Indirect and Hidden Costs

Beyond the visible capital and operational expenditures, the proactive replacement of underground LV cables carries a range of indirect and hidden costs that can significantly influence the overall cost-benefit profile. These costs, while less tangible, are critical to understanding the full financial and strategic impact of the intervention.

One of the most consequential indirect costs is the potential for regulatory penalties in the form of CI and CML through the IIS mechanism where penalties are linked to customers' perceived value of lost load [8, 9]. The cost of these penalties are quantified in the CBA methodology through a combination of CI and CMLs. Faults and service interruptions in ageing cable infrastructure can lead to breaches of performance standards, resulting in fines or other sanctions from regulatory bodies. By proactively replacing vulnerable assets, the penalties associated with unplanned outages can be significantly reduced. While IIS penalties may also apply to disconnections that are part of planned replacements, the incentive rate is lower and this work can be planned to minimise customer interruptions. This represents a form of cost minimisation that strengthens the business case for early intervention.

Reputational impact is another important consideration. Frequent faults and prolonged outages can erode customer trust and damage the brand. Although difficult to quantify directly, proxy measures such as customer complaint volumes, satisfaction scores, and survey feedback can be used to estimate the financial implications of reputational harm. These costs may manifest as decreased customer satisfaction, reduced stakeholder confidence, or diminished public support for future infrastructure programs.

Coordination costs also play a role in shaping the hidden expenditure landscape. Proactive replacement programs must be carefully integrated with other ongoing initiatives, such as EV de-looping, service upgrades, or smart grid deployments. Failure to align these efforts would result in duplicated work, missed efficiencies, and opportunity costs associated with uncoordinated interventions. Conversely, well timed coordination can unlock opportunities that reduce overall program costs and enhance long-term value.

These indirect and hidden costs underscore the importance of a holistic approach to cost analysis. While they may not all be easily quantifiable, their influence on financial outcomes, customer experience, and strategic alignment is substantial. Recognising and accounting for these factors ensures a more accurate and comprehensive evaluation of the proactive replacement strategy.

5.4 Comparative Cost Summary

The financial case for proactive replacement of underground LV cables is best understood through a comparative analysis of cost trajectories under both proactive and reactive strategies - essentially what the CBA methodology enables. This section compares the cumulative cost profiles, performance metrics, and geographic variations that influence investment prioritisation and long-term value.

Over time, the proactive approach would almost surely demonstrate a more predictable and declining cost curve as is the case in the CBA methodology demonstration results in section 8.3. This would be driven by reduced fault frequency, lower emergency repair costs, and improved asset reliability. In contrast, the reactive strategy typically incurs escalating costs due to ageing infrastructure, increasing fault rates, and compounding service disruptions. While the expenditure on a proactive replacement strategy would inevitably be higher for the first few years, cost curves are very likely to show a break even point after which the proactive strategy begins to deliver net financial benefits. When running the quantitative CBA for a reasonable set of assumptions, including for the distribution of initial asset condition and the scale and profile of replacements, the‘payback period’ for the initially higher capital outlay provides a useful benchmark for evaluating investment timing.

To support prioritisation, cost effectiveness can be expressed in terms of cost per LV way replaced or cost per fault avoided. These metrics allow for benchmarking across different asset types and regions, helping to identify high-risk areas where proactive intervention yields the greatest return. For example, urban zones with dense customer populations and high fault incidence may justify earlier replacement, while rural areas with lower fault rates might be scheduled later in the program.

Geographic and asset type variations further refine the comparative analysis. Soil conditions, access constraints, and legacy network configurations can significantly influence installation costs and fault behaviour. By mapping these variations, the replacement strategy can be tailored to local conditions, optimising resource allocation and minimising disruption.

In summary, the comparative cost analysis underscores the long-term financial and operational advantages of proactive cable replacement. While the initial investment is substantial, the cumulative savings, improved service quality, and reduced risk profile make it a compelling strategy for sustainable network management. This is highlighted in Table 1 which presents a qualitative comparison of the different costs associated with the two replacement strategies.

Table 1: Comparison of different qualitative costs associated with proactive and reactive LV cable replacement.

Cost Description	Proactive Replacement	Reactive Replacement
Capital Expenditure	High upfront investment in materials, labour, equipment, and reinstatement	Minimal initial investment; costs incurred only when faults occur
Operational Expenditure	Lower long-term maintenance and fault repair costs; predictable budgeting	Higher ongoing fault response costs; unpredictable and often urgent repairs
Timing of Spend	Planned and scheduled investment	Unpredictable, triggered by failure
Labour Costs	Standard rates, efficient crew deployment	Premium rates due to emergency call outs
Material Procurement	Bulk purchasing and standardised components	Ad hoc purchases, potentially at higher unit cost
Civil Works Coordination	Aligned with other infrastructure projects	Isolated works, no cost-sharing opportunities
Customer Impact	Scheduled outages with advance notice mean fewer call outs and complaints; improved satisfaction	Unplanned outages, higher risk of frequent call outs, increased complaint volumes, and compensation payouts
Budget Predictability	High predictability, supports long-term planning and resource allocation	Low predictability, requires flexible budgets and contingency reserves
Asset Longevity	High longevity, as new cables installed with modern standards	Variable longevity, as repairs may not address underlying degradation
Operational Efficiency	Streamlined workflows and fewer repeat interventions	Frequent fault repairs and fragmented asset records
Regulatory Risk	Lower risk, as improved reliability metrics and compliance	Higher risk, including risk of penalties due to service interruptions
Life cycle Cost	Lower overall cost due to reduced fault frequency and extended asset life	Higher cumulative cost from repeated emergency interventions
Penalties	Reduced IIS costs and risk of other regulatory fines due to improved reliability	Increasing IIS costs as fault rates increase, with possibility for further penalties from service disruptions and safety breaches
Reputational Impact	Enhanced brand perception and customer trust	Risk of reputational damage from repeated outages and poor service
Geographic/Asset Variability	Enables targeted investment in high-risk areas	Reactive approach lacks strategic prioritisation; may overlook critical assets

6 Benefit Breakdown

Proactively replacing low voltage cables could bring a wide range of benefits that stretch beyond the immediate financial savings resulting from avoiding fault repairs. While the baseline scenario of reactive maintenance is characterised by uncertainty, high emergency costs, and reputational risks, a planned replacement strategy aims to improve operational efficiency, regulatory perception, customer satisfaction and environmental impact. There are both direct and indirect advantages of proactive replacement, ranging from reduced operating costs by avoiding emergency repairs and penalties to an improvement in perception and quality of service from both the regulator and customers.

This section provides a review of the key benefit categories ranging from benefits that have associated quantitative costs such as avoided fault repair costs and reduced penalties to those connected with enhanced social value, such as improved customer satisfaction, reputational value, and environmental performance. The strategic advantages of proactive maintenance including network resilience, future proofing, and coordination with other infrastructure works will also be explored. These benefits illustrate how proactive replacement shifts the focus of cable management from reactive response, with escalating uncertainty in costs, to a strategic investment that ensures long-term reliability, sustainability, and stakeholder confidence.

6.1 Reduced Penalties

An advantage that emerges from a proactive cable replacement strategy is the reduction of regulatory penalties and compliance risks. DNOs must adhere to performance standards that are directly related to reliability, the number of outages, and restoration times. Under a reactive maintenance strategy, faults are likely to be more frequent and therefore also more likely to cluster in a short period. Breaches can lead to financial penalties, obligatory compensation payments, and increased regulatory scrutiny, all of which carry direct and indirect costs. A proactive replacement strategy aims to reduce such risks by decreasing the likelihood of unplanned outages and thus ensuring that service continuity stays within permissible levels. By carefully selecting high-risk assets that are close to failure for replacement, compliance with reliability targets can be demonstrated and the reputational damage associated with regulatory intervention is avoided.

The benefits gained from a reduction in penalties are not only financial. Other indirect benefits include increased operational freedom, a reduction in administrative workload related to claims and disputes, and greater levels of regulator trust that the network is being managed in a responsible way. In qualitative terms, the avoidance of penalties is one of the many factors that contribute to the overall value of the proactive replacement as it ensures not only financial savings but also a more stable regulatory relationship.

6.2 Enhanced Customer Satisfaction and Reputational Value

Improving the reliability and quality of service through the proactive replacement of low voltage cables can lead directly to increases in customer satisfaction and builds stakeholder confidence in the competence and responsibility of the network operator. Under the current strategy of reactive maintenance, customers are subject to unplanned outages, service interruptions, and the inconvenience of having to deal with emergency repairs. These factors can erode the confidence of both customers and stakeholders and create complaints and compensation claims, particularly when outages impact critical infrastructure such as hospitals, schools and businesses that rely on a continuous source of power. In contrast to this, implementing a proactive replacement strategy reduces the probability of these types of disruptions. Customers will benefit from a more stable and predictable service with fewer interruptions which will decrease the frustration and uncertainty that leads to complaints. Simultaneously, long-term investments demonstrate a dedication to network resilience improving the levels of trust between stakeholders and the DNO.

6.3 Lower Future Maintenance Burden

Proactive replacement of low voltage cables also delivers significant benefits in terms of reducing the future maintenance burden. Under the reactive maintenance model, cables are brought back into service by patching the existing infrastructure, which tends to be very inefficient. Repeated interventions on deteriorating assets rarely provide lasting solutions, meaning that the same sections of network may require attention multiple times over their remaining life.

In contrast to this, proactive replacement resets this cycle by completely reinstating whole LV ways. New assets are more reliable, require fewer interventions, and can be incorporated into long-term asset management plans. By integrating proactive replacement into the existing reactive maintenance strategy, benefits can be gained that extend beyond cost savings associated with a reduction in urgent reactive maintenance. A lighter maintenance burden improves workforce efficiency, reduces stress on field crews, and enhances the overall stability of the network. In effect, proactive replacement transforms maintenance from reactive firefighting into a more controlled and sustainable process, ensuring that resources are deployed where they add the greatest value.

6.4 Network Resilience and Future Proofing

Proactive cable replacement strengthens the resilience of the network and positions it for future success by reducing the risk of unexpected failures. When faults and failures do occur, they can cascade across interconnecting systems causing an amplification in the level of disruption. The reactive approach leaves the network exposed to these risks, as interventions are only made after failures have already compromised service. Proactive cable replacement allows for the construction of more robust and dependable infrastructure that will have a greater ability to withstand network stresses. This resilience is especially important in the context of climate change and future electrification as the network is at greater risk of failure during extreme weather events and periods of prolonged high demand. Proactive cable replacement also supports network modernisation initiatives to prepare for electrification of transport and heating, smart grid deployment and distributed generation, all of which demand a more adaptable network.

In addition to providing an immediate increase in reliability, proactive cable replacement also allows the DNO to be positioned to address potential long-term challenges, reduce the risk of widespread outages and create a platform for integrating new technologies and services. Ultimately, proactive replacement transforms the network from a system that reacts to failures into one that anticipates and withstands them, providing a dependable foundation for future energy needs.

6.5 Potential Carbon Savings and Environmental Benefits

Proactively replacing LV cables yields significant positive environmental benefits, particularly in the form of reduced carbon emissions. By comparison, when LV cables are replaced reactively, emergency call outs are typical which are characterised by inefficient deployment of resources. Such inefficiencies compound and contribute to an increase in overall fuel consumption and associated greenhouse gas emissions. Additionally, reactive maintenance usually requires repeat repairs on the same parts of the network as under this strategy, the main goal is to restore service, not improve network longevity. The need for repeated repairs on assets generates a significant amount of waste material due to the partial replacement of components, sometimes within a short time frame. Using new, modernised cable installations will significantly reduce the amount of waste created when a proactive replacement plan is used as whole problem sections of the network can be completely replaced, thus greatly reducing the risk of faults and failures on that section.

Proactive replacement employs a different approach from the reactive method of responding to emergencies by consolidating the replacement of full LV ways into planned, efficient projects. Through this optimised approach, the total number of vehicle trips will decrease and the use of temporary components and materials will be minimised. Hence, both emissions and waste will be reduced. In addition, new installations have longer lifespans, which reduces the need for repeated interventions and further supports sustainability goals. A proactive replacement strategy also aligns with broader environmental commitments, such as net-zero targets and regulatory frameworks that increasingly emphasise sustainable asset management.

Although many positive environmental benefits come from proactive replacement, it is also possible to introduce negative benefits by replacing cables with operating life remaining. The level of this negative impact will be highly dependent on the ability of the cable selection model to accurately predict the likelihood of cable failure.

The overall environmental benefits of proactive replacement include waste reduction, improved resource efficiency, fewer interruptions to surrounding communities caused by repeated excavations, and increased alignment with local communities' expectations around sustainability. Proactive replacement of LV cables is a key component to the organisation's overall environmental sustainability strategy.

6.6 Coordination Savings

A further benefit of proactively replacing cables is the potential to coordinate works with other infrastructure projects. Naturally, reactive maintenance is unplanned and usually requires an urgent response, meaning repairs are often carried out in isolation from other works. This lack of coordination can result in duplicated costs due to repeated excavations, traffic management measures and reinstatement works, all of which could have been shared had the interventions been scheduled alongside other planned activities.

A proactive strategy allows for scheduled replacements to coincide with wider infrastructure projects that are undertaken either by the DNO itself or by external stakeholders, such as municipalities, transport authorities and other utilities. Coordinated intervention reduces community disturbances as there are fewer instances of road closures and excavations. This also lowers the cost for all parties involved through the consolidation of labour, materials, and equipment.

The benefits from coordinating infrastructure works extend beyond direct financial savings. Coordinating projects helps develop stronger relationships between utility companies, local authorities and partner organisations, resulting in a better public perception due to less visible disruption, and contributes to smoother overall delivery of utilities infrastructure.

6.7 Summary

The advantages of proactively replacing LV cables stretch beyond avoiding repair expenses associated with faults and failures. Benefits include greater capability in meeting regulatory requirements, reductions in penalties and future maintenance costs, and improved customer satisfaction. These operational improvements are supported by increased reputational value, enhanced network resilience, and conformity with long-term modernisation and sustainability goals. Environmental benefits, such as lower carbon emissions and less material waste, are also realised, while coordination savings emphasise the efficiency gains that can be achieved if replacements are planned together with other infrastructure works. The cumulative effect of these benefits is substantial. Adopting a proactive replacement strategy positions the DNO to demonstrate financial stability, operational efficiency, customer trust, and environmental responsibility. This holistic view emphasises the importance of proactive cable replacement to ensure sustainable network management.

7 Risk and Uncertainty Analysis

Uncertainties are present on several parameters used as inputs for the quantitative CBA methodology, which has been designed to incorporate these uncertainties. Even if it were possible to perfectly know the true underlying failure probabilities, there is still an element of randomness in the materialisation of failures. This is accounted for through the adoption of a Monte-Carlo (MC) simulation approach, where fault outcomes are sampled from probabilities and the complete 20-year study period is simulated many times to capture the overall behaviours. Furthermore, the output of this approach, where many runs have been undertaken, allows for not only the calculation of mean financial benefits, but also probabilistic analysis of the results. For example, if some MC simulation runs return a net positive and some a net negative financial benefit, it is possible to quantify the probability of a net positive outcome.

Best efforts have been taken to accurately quantify all inputs to the CBA methodology and, where appropriate, LV way properties are sampled from a distribution to represent variability in properties across the network. Conducting a CBA that is directly based on the output failure probabilities from a prediction model such as that developed in LV Predict 2 would limit the usefulness of the outputs as the results would be entirely dependent on the skill of the failure probability inputs. Given the lack of failure rate data to validate and calibrate these predictions within this project, this would lead to CBA results that are based on a model of unknown real skill. Because of this, the CBA was structured to calculate the potential benefit from any possible failure prediction model, given its skill. This means a range of possible skill levels can be tested and allows greater flexibility and interpretation of the CBA results, enabling it to answer questions such as 'is there any benefit from proactive replacement when there is no skill in failure predictions?' and 'what is the likely return on investment of improving the skill of failure predictions?'.

The DNO's capacity to undertake proactive replacement work may be limited by supply chain or budget constraints. The overall trajectory of numbers of proactive replacements per year is specified as an input to the CBA, allowing a sensitivity analysis on replacement volume to be carried out. This showed the boundaries at which costs increase due to under-investment when proactive replacements are too low, or where costs increase due to over-investment (when the cost of additional proactive replacements is greater than the resulting reduction in fault costs).

Future load growth, in particular the uptake of LCTs, is assumed to increase fault rates. A simplistic percentage increase in fault rate per year has been used to simulate this effect in the CBA methodology demonstration, but futher work to refine the relationship between load growth and fault rates and quantify the sensitivity of the CBA results to this would be beneficial. There is also uncertainty in the trajectory of future LCT uptake; use of the different scenarios from the Distribution Future Energy Scenarios (DFES) and translation of these into fault rate 'scenarios' could give insight into the range of possible future trajectories. Uncertainty in future policy changes and their effect on LCT uptake is partially represented in the DFES, but this uncertainty may also need to be considered separately to ensure it is fully encapsulated.

Some of the technical characteristics of faults are not represented in the CBA, where behaviour has been simplified to the two-stage process of 'fault occurs' → 'fault repaired'. In particular, this does not account for repeated faults around a single location as a larger failure develops, or fault propagation leading to an increased likelihood of nearby faults after a repair. Nor does it account for the risk of further faults introduced upon reclosing. The CBA methodology could be further developed to incorporate some of these effects, but this simplified representation was deemed sufficient for this analysis. If anything, this means the current CBA methodology underestimates the probability of repeated faults and therefore slightly underestimates the benefit of proactive replacement.

8 Methodology

The CBA methodology is a framework to establish the cost, in terms of Net Present Value (NPV), of any given cable replacement strategy, depending on the level of skill expected in prioritisation and ranking of the annual probability of a failure on each LV way. It is assumed that failure rates are directly linked to accumulated damage at joints, so that those joints with higher predicted damage will be the joints with highest failure probability.

It is based on a sequential MC simulation of a set of N LV ways with properties sampled from defined distributions. Failures and repairs are then simulated year-by-year for a 20-year period. Two actions are modelled: repair of a joint when a failure occurs, which is assumed to fix the immediate fault but leave the failure probability of the LV way unchanged; and planned replacement of the LV mains on a way, which resets the failure probability to 1% per year (i.e. an assumed 1 in 100 year failure rate for new LV mains). The total number of planned replacements over the 20-year period is a pre-determined input to the CBA and the specific set of LV ways that are planned to be replaced in the year are determined at the start of the year.

The skill of predictions of failure probability is represented by the correlation ρ between predicted values and the true underlying failure probability. While in reality the true failure probabilities are not known, this CBA creates a hypothetical set of LV ways with assigned true failure probabilities, and then creates estimated failure probabilities based on the underlying failure probability and the correlation of the estimated failure probabilities to the true probabilities. This allows assessment of any level of skill in estimating the relative (ranked) failure probabilities of the set of LV ways.

The simulation is run multiple times, each on a set of N ways, and the distribution across simulations gives average expected costs for the given scenario. The simulation process is as follows:

1. Define distribution parameters for number of customers $n_{\text{customers}}$, failure probabilities, repair cost C_{repair}, replacement cost C_{replace} and outage duration T. Sample a value for each of these parameters for every simulated LV way.
2. Sample a base 'true' failure rate b_t (the failure rate in year 1) for every LV way, and perform an outer merge with the range of correlation values to test, so the resulting table has a row for every combination of LV way and correlation, where the base failure rate is the same for a given LV way for every correlation value.
3. The next step is to generate estimated base failure probabilities b_e (the equivalent of failure probability predictions from a tool like LV predict) from the true base failure probability b_t and the correlation ρ using the Gaussian copula. Mathematically, the true base failure probability b_t is first transformed to a standard normal distribution by calculating the out-turn probability of b_t against the distribution it is sampled from, and then calculating the equivalent value of a standard Gaussian distribution (with mean 0 and standard deviation 1) that has the same out-turn probability. This value is denoted g_t. The formulae for a bivariate Gaussian copula[1]can then be used to calculate the conditional mean μ_e and variance σ_e^2 of the *estimated* base failure rate in standard-normal space :

$$\begin{aligned} \mu_e &= \rho g_t \\ \sigma_e^2 &= 1 - \rho^2 \end{aligned} \tag{1}$$

[1] See the bivariate conditional expectation section of https://en.wikipedia.org/wiki/Multivariate_normal_distribution using a standard normal, so $\mu_1 = \mu_2 = 0$ and $\sigma_1 = \sigma_2 = 1$.

A value is then drawn randomly from this distribution and converted back to an out-turn probability g_e. This can then be combined with the original distribution for failure rates to give the estimated base failure rate b_e. Over the whole set of LV ways, this gives a set of pairs of true and estimated base failure rates that both follow the same distribution and have the specified correlation as shown in Figure 1.

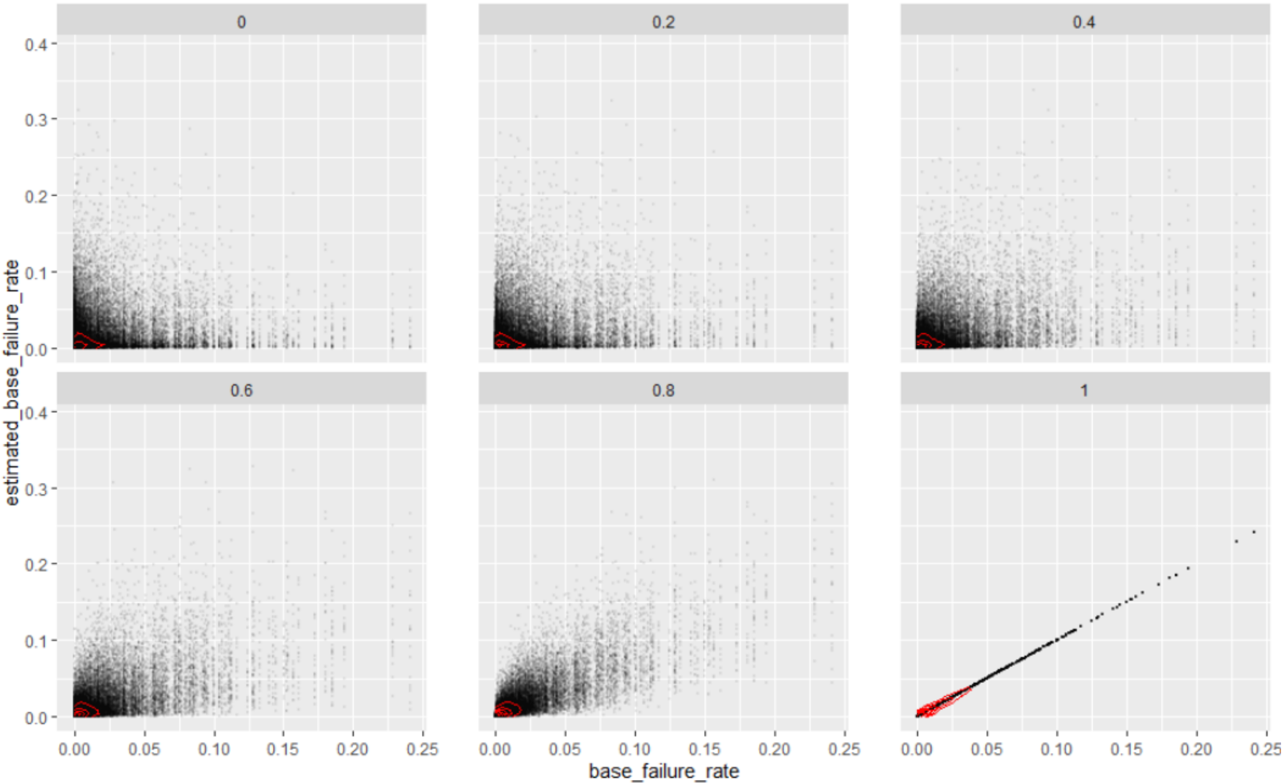


Figure 1: The bivariate distribution of true and estimated failure rate, for different correlations. Contour lines showing the 2D density are in red.

4. Define the number of LV ways to be replaced in each year over the 20 year period, based on the total number to be replaced n_{TOT} along with the peak replacement year y_c and the parameter ϕ which describes the peakiness of the LV way replacement trajectory. Then the number of LV ways to be replaced in year y is given by $n_y = n_{\mathrm{TOT}} * \omega_y$ where

$$\omega_y = \frac{\max(1 - \phi|y - y_c|, 0)}{\sum_{j=1}^{H} \max(1 - \phi|j - y_c|, 0)} \tag{2}$$

and H is the total number of years simulated. This gives a trajectory of replacement volumes such as in Figure 2.

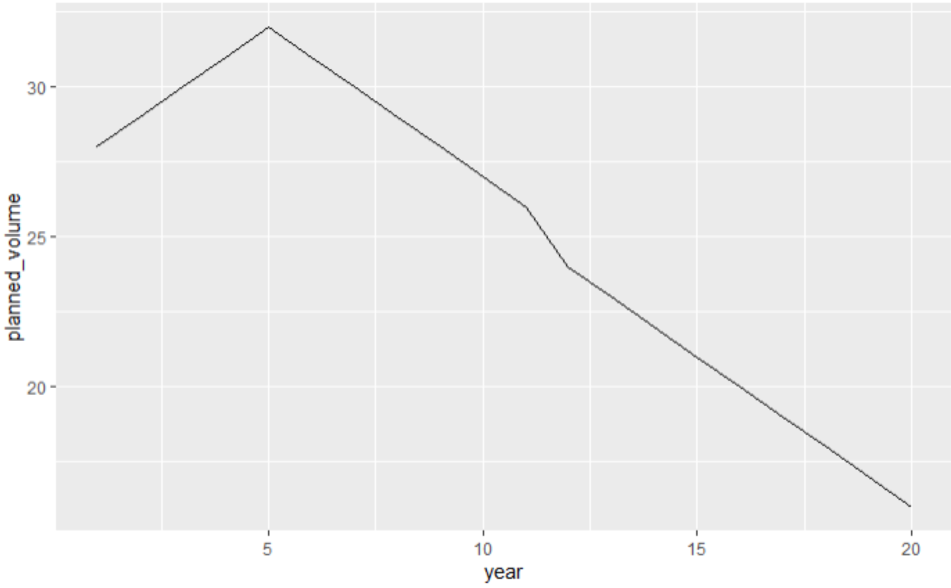


Figure 2: Trajectory of volume of planned replacements per year, for $n_{\text{TOT}} = 500$, $y_c = 5$ and $\phi = 2/3$. The slight jump around year 12 is due to rounding each year's planned volume to the nearest integer.

5. Perform an outer merge of planned volumes per year with the table of base failure rates from step 2, giving a table with a row for every combination of LV way, correlation, and year. Calculate estimated failure probabilities for each year, p_y, from the estimated base failure probability b_e in year 1, increased by 10% of this base value per year: $p_y = b_e + b_e \times 0.1 \times (y - 1)$. These per-year failure probabilities are capped to a minimum of 0.01 (1-in-100 year failure) and a maximum of 1 (guaranteed to fail). Now we have a failure probability for every LV way for every year, and a planned volume of replacements for every year.
6. Calculate a metric of 'merit', M, on which LV ways will be ranked and prioritised for replacement. This value is

$$M = (p_y \times n_{\text{customers}})/C_{\text{replace}} \, . \quad (3)$$

   In this metric, $p_y \times n_{\text{customers}}$ is a proxy for risk (probability × consequence) and the factor C_{replace} ensures LV ways with the same risk but a lower replacement cost are prioritised.
7. Iterate over years sequentially, and:
   - Calculate the merit order of all LV ways that have not yet been replaced: this is a rank where the highest priority rank is given to the cable with the highest M.
   - Mark the top n_y LV ways as for replacement in that year, based on the merit order with an indicator variable R which is 1 for LV ways that are replaced that year and 0 otherwise.
   - For LV ways not selected for replacement, simulate failures by sampling from a binomial with probability equal to p_y, and record which LV ways have a failure. Create an indicator variable F which is 1 for LV ways that fail that year and 0 otherwise.
   - For LV ways that are selected for replacement, simulate the case where an LV way would have failed, but was replaced before this occurred within the year. This is done by sampling from a binomial with probability equal to 0.75, and LV ways where this sample is 'successful' are labelled as 'saved' and the failure probability for that year is set to 0. Here the probability of replacement before failure is assumed

to be greater than 0.5 due to the use of pre-fault sensing to inform and prioritise replacements within the year.

- Update the cumulative set of LV ways that have been replaced in all years up to year y and update the failure probabilities for LV ways that have been replaced in year y.

8. Group by year and failure prediction correlation and calculate:
   - The total annual CIs as the sum of $F \times n_{\text{customers}}$ and CMLs as the sum of $F \times n_{\text{customers}} \times T \times 60$. Then the total cost associated with the IIS is given by $15 \times \text{CI} + 20 \times \text{CML}$ where these are assumed CI and CML rates.
   - The total annual spend on LV way repairs as the sum of $C_{\text{repair}} \times F$
   - The total annual spend on LV way replacement as the sum of $C_{\text{replace}} \times R$
   - Total cost for the year, Discounted Cash Flow (DCF), as the sum of IIS + total repair spend + total replacement spend
   - The Present Value (PV) for year y of that DCF;

$$\text{PV} = \frac{\text{DCF}}{(1+d)^{y-1}} \tag{4}$$

   where d is the social time preference rate, set to 3.5%.

This entire process is repeated many times with different binomial samples in step 7 to produce the full set of simulations from which to derive results. From this, we can examine the volumes and costs of failures and replacements over the years under different levels of skill in predicting annual failure probability for each LV way.

8.1 Input Values and Parameters

Several values and distributional parameters must be defined as inputs for the demonstration of this CBA methodology. A value of 3.5% has been used for the social time preference rate d when calculating the present value of future spending. The trajectory of cable replacement uses the parameters $n_{\text{TOT}} = 500$ (i.e. proactive replacement of 50% of modelled LV ways over the 20-year period), $y_c = 5$ and $\phi = 2/3$ as plotted in Figure 2. In this example, initial replacement volumes are high with replacements peaking in year 5, meaning a rapid ramp up in supply chain in the initial years, and then a gradual tail off in annual replacements after that point.

Analysis has been carried out for 6 values of fault prediction skill, with values of correlation between the true underlying fault probability and the predicted fault probability of $\rho = 0$ (no skill), 0.2, 0.4, 0.6, 0.8 and 1 (perfect skill).

The CBA methodology defines distributions for key LV way parameters such as the number of customers; the exact numbers per simulated LV way are then sampled from these distributions. The exact type of distribution for each parameter has been assumed based on what is deemed most reasonable. The assumed parameters of these distributions used for the CBA methodology demonstration are presented in this section. These are reasonable values to provide a demonstration that broadly reflects SP ENW's real operational situation, but these inputs should be verified before use of the CBA outputs for decision making.

Firstly, the distribution of annual failure probability — the probability of a failure at any joint on the LV way within a one year period — is defined as a gamma distribution with a mean failure rate of 2.5% and variance of 0.1%. Failure probabilities of each LV way are sampled from this distribution for the first year, and then these probabilities are increased by 10% of this base failure rate for every subsequent year. This assumption allows demonstration of the CBA methodology and starts from the real failure rates, using these to calculate estimated failure rates for a model of a given skill level. In real application to determine which LV ways to replace, only estimated failure probabilities would be known; these come from the output of a prediction model such as demonstrated in the methodology report of LV Predict 2, and would require calibration to observed failure rates.

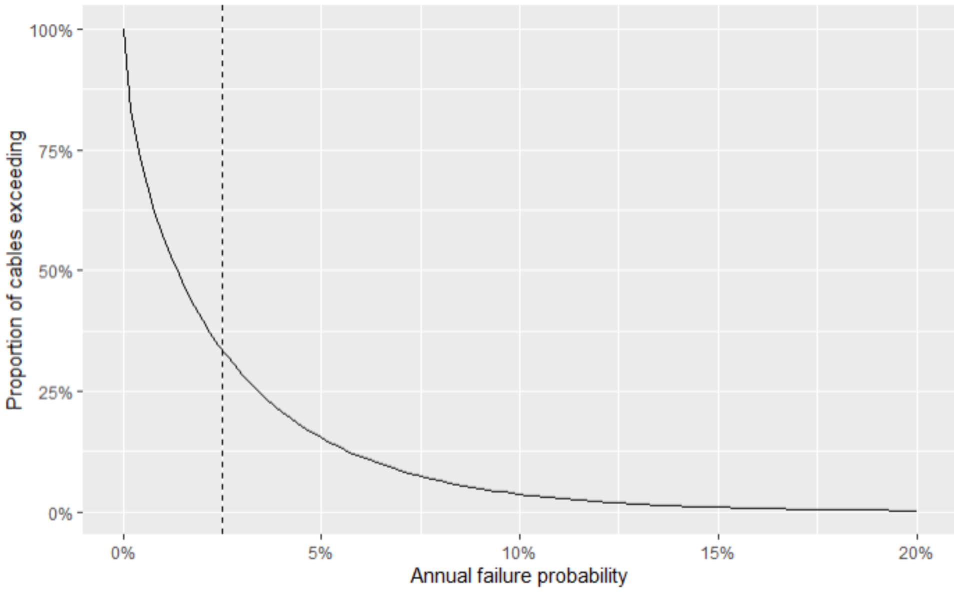


Figure 3: Distribution of LV way annual base failure rates

We define the number of customers per LV way as a gamma distribution with a mean of 50 customers and variance of 5,000, which gives the distribution shown in Figure 4.

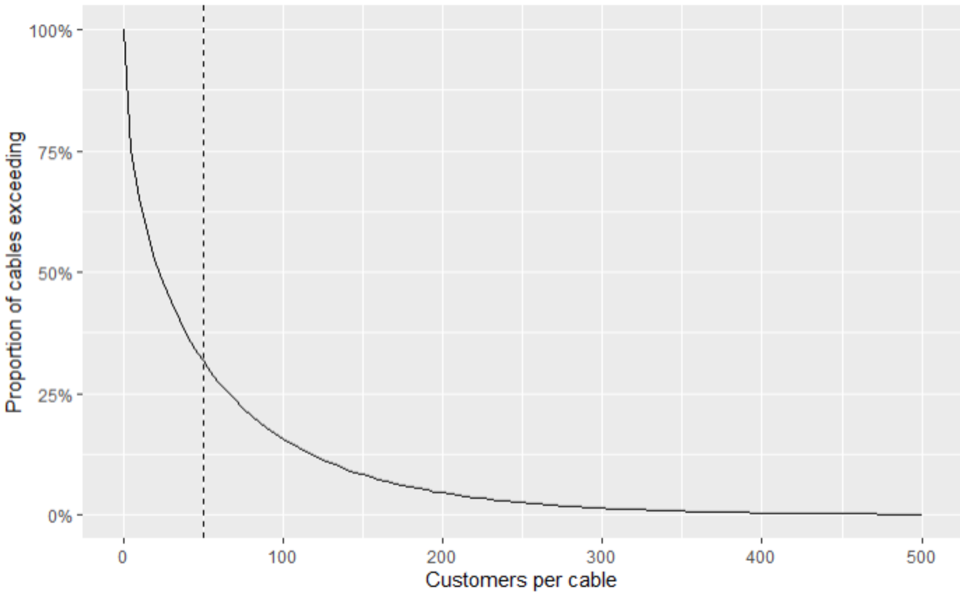


Figure 4: Distribution of customers connected to each LV way

The costs of both planned LV way replacement, and joint repair, are defined as triangular distributions where the minimum, mode and maximum costs are specified. Planned replacement costs are significantly higher as they represent replacement of the main cables (excluding service cables) on the entire LV way, so have a minimum cost of £20,000, mode of £50,000 and maximum of £100,000. This gives the distribution seen in Figure 5.

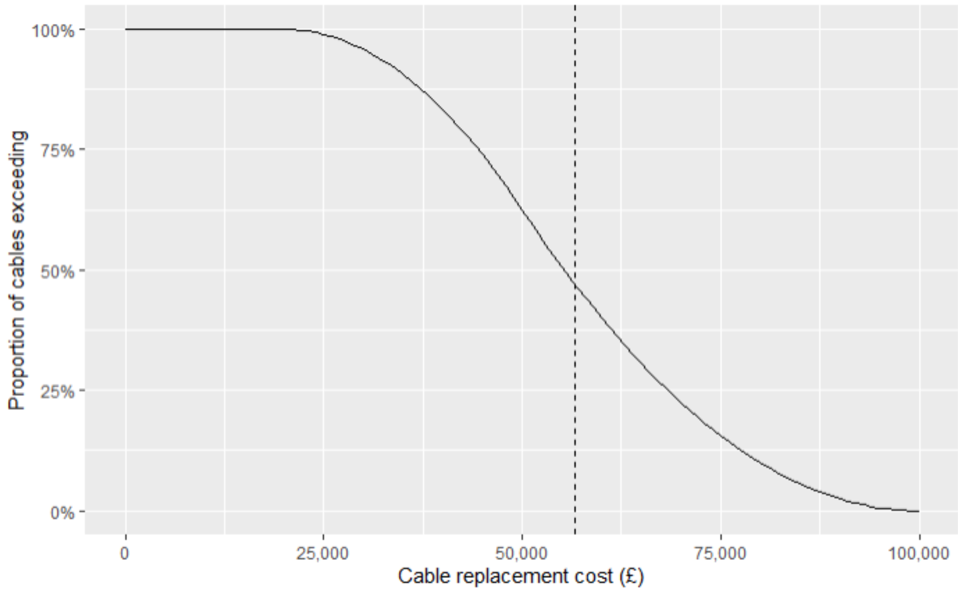


Figure 5: Distribution of LV way replacement cost

Unplanned repairs (repairs carried out when a fault occurs) are defined to have a minimum cost of £2,000, mode of £4,000 and maximum cost of £12,000.

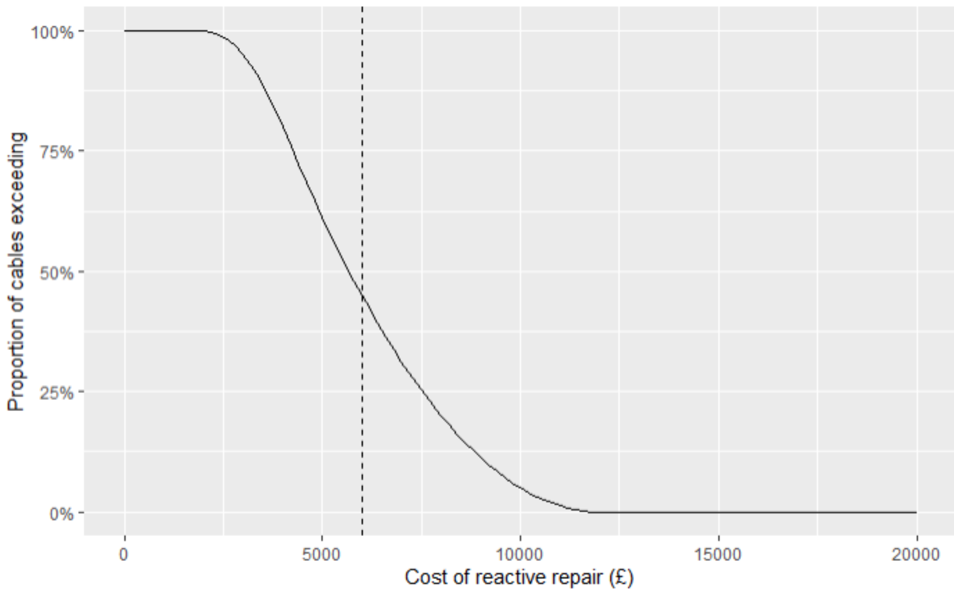


Figure 6: Distribution of LV way unplanned repair cost

Finally, the distribution of length of customer outages is defined. This has a gamma distribution again, but with a minimum duration of 1 hour, mean duration of 2.5 hours and variance of 3 hours giving the distribution in Figure 7.

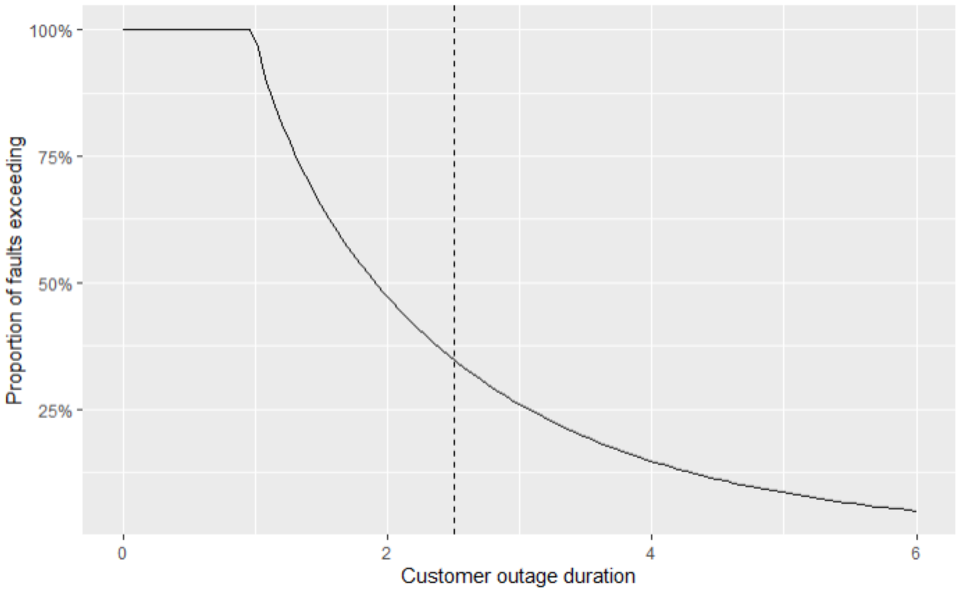


Figure 7: Distribution of outage durations resulting from a fault

In the demonstration, values of each of these parameters are sampled randomly for each modelled LV way; this sampling is conducted independently for each parameter, meaning there is no correlation between values. In reality, some correlation between (e.g.) number of customers connected and failure probability is likely, but this is difficult to quantify without data on faults and the properties of the LV ways they are on.

8.2 Assumptions

This CBA methodology and its demonstration is based on a set of assumptions intended to provide a consistent framework for comparing reactive maintenance with proactive replacement of LV cables. While every effort has been made to ensure accuracy, certain limitations apply due to data availability, forecasting uncertainty, and operational variability. The following assumptions and limitations should be considered when interpreting the results and assessing the robustness of the proposed proactive strategy. The key assumptions are:

Asset Age Profile: Asset age is not included as a factor in the CBA methodology, beyond the complete set of LV ways having a distribution of base failure rates. If a joint has a very low predicted annual accumulation of damage, this is likely to hold historically (and therefore the total cumulative damage will be low), whereas a high predicted annual accumulation of damage is likely to lead to rapid ageing: as such, the rate of damage accumulation is deemed generally more important than the historical accumulation of damage. Asset age is not available to SP ENW, so a CBA methodology requiring asset age as an input would not be implementable.

Failure Rates and outages: The CBA methodology assumes that in practice, the true failure rates are unknown but that we can estimate them with imperfect accuracy. To model this, sets of 'true' underlying failure rates and estimated failure rates for varying levels of accuracy are simulated. The true underlying failure rates and outage durations are both sampled from Gamma distributions, to represent variability across LV ways.

Replacement prioritisation through merit order: The merit order used is based on risk and replacement cost, but does not take into account outage duration. It is assumed outage durations are not known ahead of a fault occurring, and that they are random and independent for every LV way. A different relative weighting of risk vs cost could be used if there was a strong preference to either prioritise the LV ways most at risk of failures, or those with lowest replacement cost. Use of this merit-order system for LV way replacement relies on having predicted failure probabilities for every LV way on the network.

Cost Estimates: Unit costs for reactive repairs and proactive maintenance works (the replacement of an entire mains cable on an LV way) are defined by distributions to represent variation in these quantities across the network, including variation by region, fault type and response conditions. Regulatory penalties under the IIS are based on assumed CI and CML rates for reactive repairs, whereas any IIS costs associated with proactive replacement are assumed to be known before the work is scheduled and therefore included in the total replacement cost. All other costs associated with repair or replacement (e.g. street works, materials etc) are contained within the total reactive repair and proactive maintenance costs respectively.

Demand growth: Future demand growth is represented by a basic year-on-year increase in fault rates as a proportion of the starting fault rate of each LV way. If a proactive maintenance strategy were adopted, this effect would be included through changing the inputs to the damage prediction model based on future energy scenario modelling.

Discount Rate and Time Horizon: The Spackman CBA approach has been adopted, in line with Ofgem's preferred modelling of NPV, but for simplicity all replacement costs are fully capitalised. Financial benefits are calculated using a social time preference rate d of 3.5% and a 20-year horizon to evaluate long-term cost-effectiveness. However, additional cost savings from proactive maintenance would continue to be seen beyond the 20-year horizon.

Supply chain limiting factors: Workforce capacity or material supplies were not deemed limiting factors, so a constraint on total number of repairs or replacements has not been included in this CBA methodology but could be incorporated in future when defining the trajectory of planned replacement volumes.

Repeated replacement: A way can fail, be repaired, and then later be replaced in the same year. Failures and replacements can only occur once per year under the proposed CBA methodology.

The limitations associated with the CBA methodology are:

Independence of input parameters for each LV way: The failure rate, number of customers, repair and replacement costs and outage durations for each LV way are sampled independently. In reality, there is likely to be some level of correlation between these. For example, geography (rural/urban, topology etc) could influence all of these factors. If implemented in practice, this limitation would be alleviated by the use of geographic and network topology features in the predictions of damage, and real customer numbers. Some additional work on the factors influencing replacement cost could also improve these estimates and distinguish LV ways that are relatively more or less expensive to replace.

Data Gaps: Fault record and asset condition data is either unknown or unavailable. It is proposed that asset condition predictions are made by the LV Predict 2 model, and it is assumed that higher predicted damage corresponds to higher failure probabilities. However, the ability to calibrate and verify would require historic records of faults.

Regulatory Changes: Future adjustments to compensation schemes, street works legislation, or reliability targets could materially affect cost structures.

Behavioural Uncertainty: Future uptake of low carbon technologies and their impact on load profiles is uncertain. This is encapsulated through the range of scenarios in future energy scenario modelling, including DFES. However, there is no single clear method to make a decision across those scenarios, and the likelihood of each scenario is dependent on future policy which is uncertain and subject to change.

Non-Financial Impacts: While environmental and social factors are discussed qualitatively, they are not monetised and quantified in the cost-benefit model.

8.3 Demonstration of Results

This section presents results from the implementation of the described CBA methodology, based on the assumed parameters and distributions described in Section 8.1. While effort has been taken to ensure these inputs and therefore the results are generally sensible estimates reflecting real-life values, the purpose of these results is to show the type of output and insights the CBA methodology can provide, and should be repeated with verified inputs when used by SP ENW. 1000 LV ways have been simulated, with 500 (50%) of these planned to be replaced over the simulated 20 year time span. Costs shown have been scaled to an assumed total number of 58,000 LV ways to represent the estimated total cost across SP ENW's network.

Before simulating failures and replacements, the set of failure rates for the whole set of LV ways is sampled from the probability distribution defined in Figure 3 and the values shown in Figure 8. This shows the long-tailed nature of the distribution: while most failure rates are low, a minority of LV ways have much higher failure probabilities, up to 19% — a failure every 5 years — in the base year. The year-on-year increase in failure rates (assuming no LV way replacement) can also be seen in this figure with the mean annual failure rate increasing from 1 in 40 to approximately 1 in 15 after 20 years.

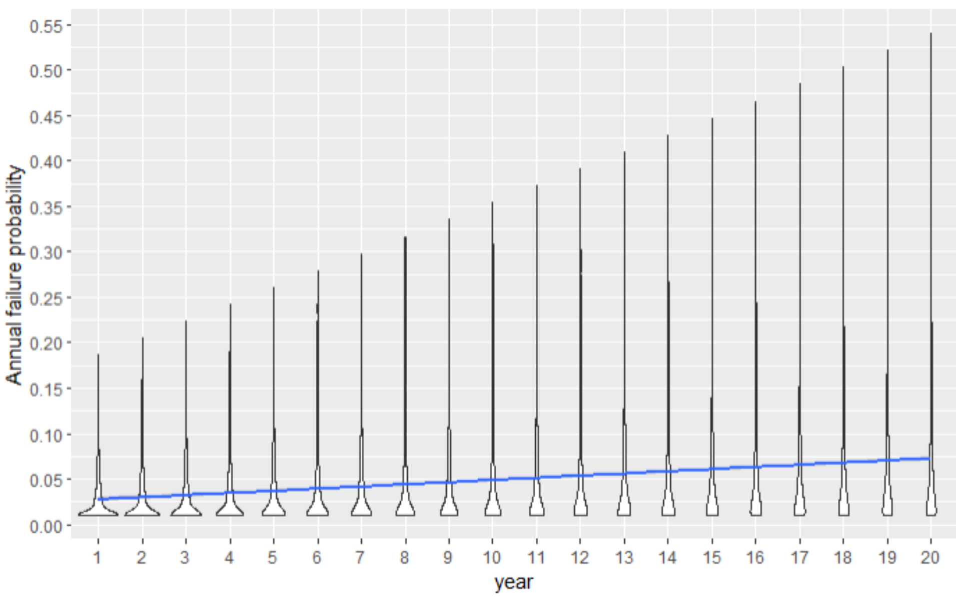
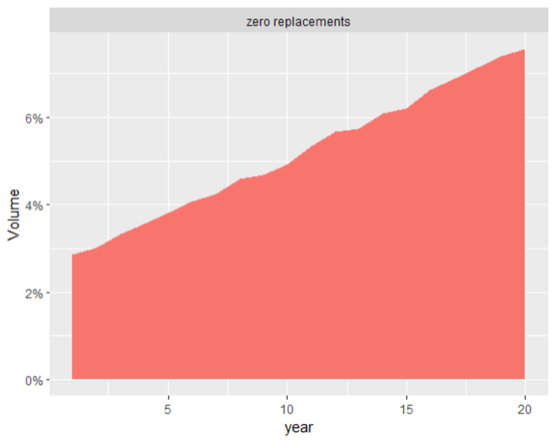
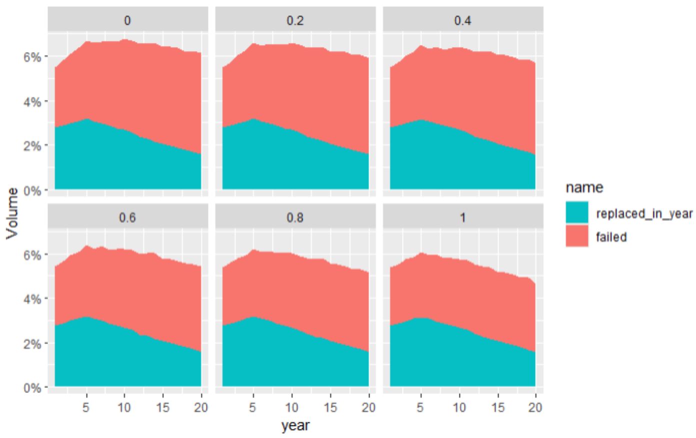


Figure 8: Distribution of annual LV way failure probability

After 100 MC simulations of LV way failures and replacements, each for 6 different prediction skill (correlation) levels, the total repair and replacement volumes and costs can be assessed. Figure 9 shows the volume of repairs and replacements in each year, under both a scenario with no proactive replacements (9a) and the different prediction skill levels (9b). There is very little difference in the volume of planned replacements between skill level scenarios, as the volume of proactive replacements is determined separately and is fixed across all skill levels. However, the choice of exactly which LV ways are replaced is determined by the ranking of predicted failure probabilities, and this figure shows lower volumes of failures — particularly in future years — for the scenarios with higher predictive skill. This is because the LV ways most likely to fail are more likely to have been correctly identified for earlier replacement in these high-skill scenarios.



a: Volumes of LV way repairs in a scenario with no planned replacements



b: Different skill levels ranging from 0 (no predictive skill in failure probabilities) to 1 (perfect predictions of failure probabilities).

Figure 9: Average volume of LV way repairs and replacements per year across all MC simulations

The average costs associated with each skill level and year is also plotted in Figure 10. The cost of CIs and CMLs — together making up the IIS cost of reactive repairs — dominate the total cost, but decrease through time in all scenarios as more LV ways are replaced and therefore the number of failures per year decreases. Consistently lower costs in both IIS and, though on a much lower scale, spending on reactive repairs, is seen for scenarios with greater skill in predicting failure rates. For the scenario with perfect prediction of failure rates, reactive repair spending actually decreases over time despite the increasing failure rates in the remaining unreplaced LV ways. The total proactive replacement spend is similar in all scenarios and follows the triangular trajectory of replacement volumes defined in Figure 2. This demonstrates that the real advantage to LV way replacement is in reduced IIS penalty costs: while there is some benefit in reduced spending on reactive repairs, these are generally much lower.

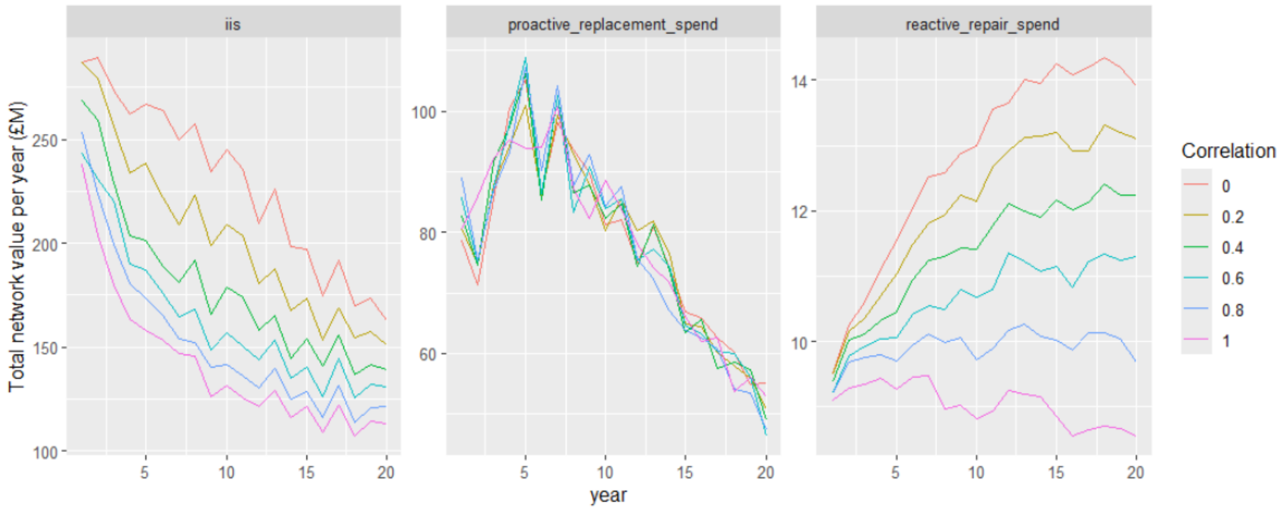
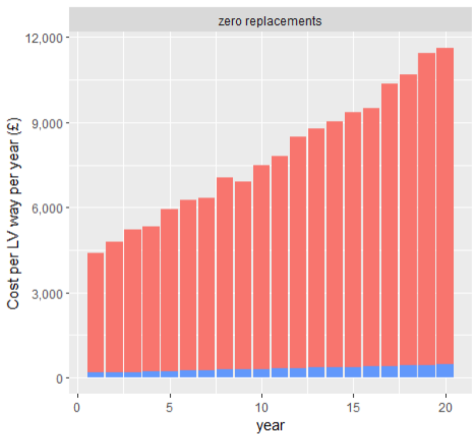
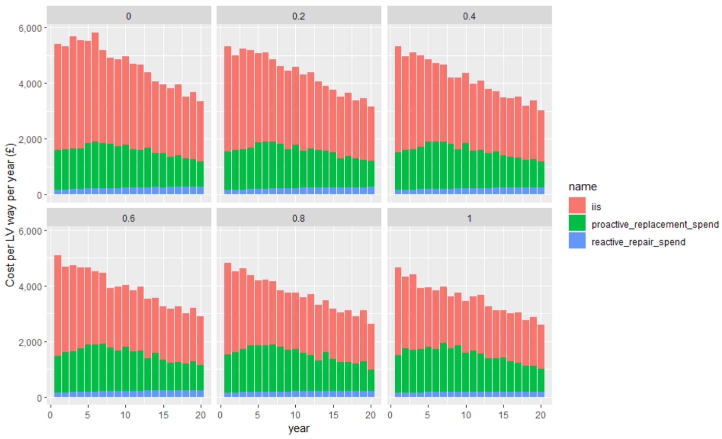


Figure 10: Trends in average cost of components over the years, per skill level. Note the differing scales on the y axis.

These costs are stacked in Figure 11 to show the total average cost per LV way, per year. In a scenario with no planned replacements, both IIS and repair costs rise year-on-year as failure rates increase. In contrast, total cost generally decreases year-on-year for all scenarios with planned replacements, with lower IIS costs where failure probability predictions are more skilful as this allows the riskiest LV ways to be targeted for replacement first.



a: Costs per LV way in a scenario with no planned replacements



b: Different skill levels ranging from 0 (no predictive skill in failure probabilities) to 1 (perfect predictions of failure probabilities).

Figure 11: Average cost per LV way per year. Note the different y axis scales.

The real insight from this CBA methodology comes from assessing the benefit, in terms of net present value, of different hypothetical levels of skill in predicting failure rates relative to a baseline. This determines at what level of predictive skill a proactive maintenance strategy is expected to provide material financial savings. Two different baselines have been used: one, the case of zero proactive replacements (i.e. the current status quo), and two, the case of proactive replacements but with zero skill (i.e. selecting LV ways for replacement at random). In both cases, 'benefit' is defined as the saving in NPV of the scenario, relative to the baseline scenario.

The first baseline shows the potential benefits relative to current practices. The average PV of each scenario with planned replacements is plotted in Figure 12, with the mean and central 90% range for the zero-replacements baseline scenario also displayed. There is clearly a positive benefit to introducing a LV way replacement strategy, even for scenarios where there is very little or no skill in predictions of failure probabilities.

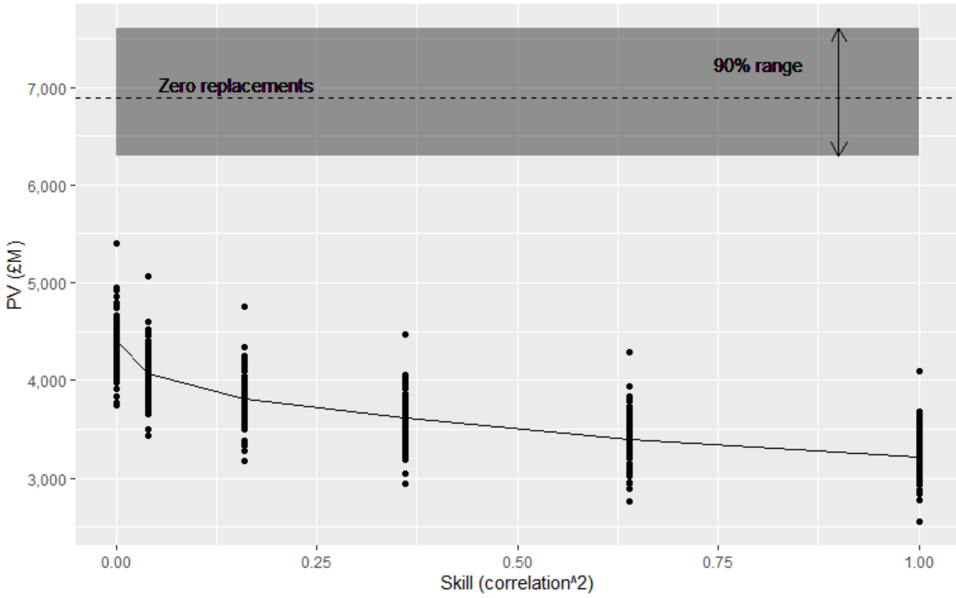


Figure 12: Total PV per skill level

The benefit itself is calculated for every LV way and Figure 13 shows the distribution of this benefit across the set of 1000 LV ways, with positive values for all LV ways across all scenarios and generally increasing benefit as predictive skill increases. Figure 14 shows this same information as a trend in average benefit as predictive skill increases (on the x-axis).

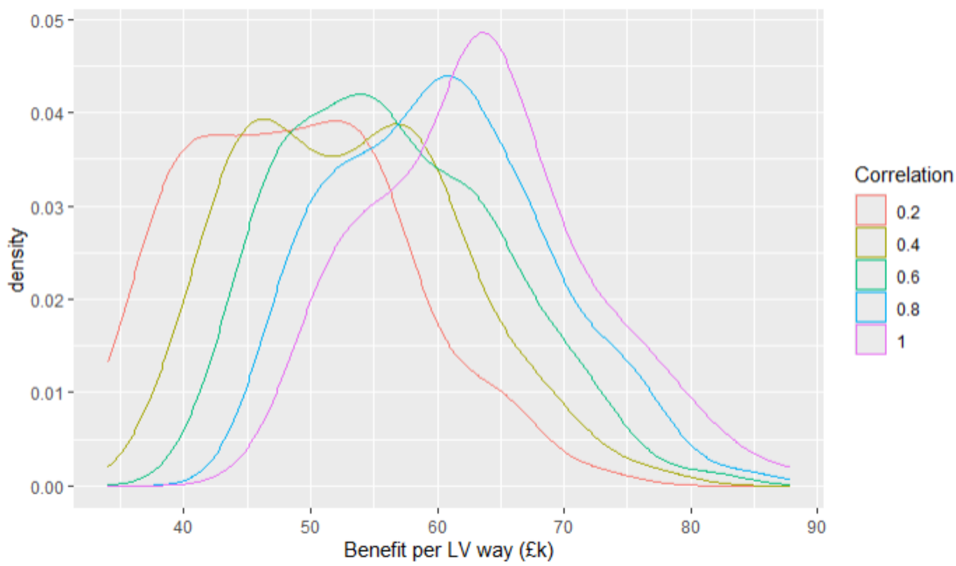


Figure 13: Distribution of total PV benefit relative to no proactive replacements, per skill level

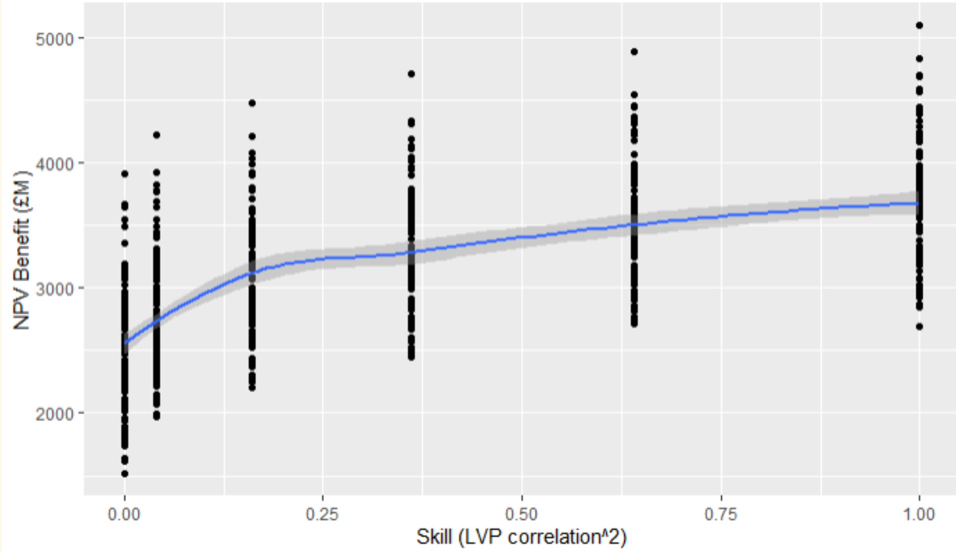


Figure 14: Fitted relationship between skill level and total NPV benefit, relative to no proactive replacements

The same analysis can be carried out for the second baseline of proactive replacements but with no predictive skill. This shows, again, increasing benefit for increasing predictive skill with the scenario with perfect predictive skill providing the greatest benefit. When measured against correlation as a measure of predictive skill, the relationship between NPV benefit and correlation is roughly linear. However, it is important to note that forecast skill is generally expressed in terms of metrics like R^2, the proportion of *variance* explained by the predictions. The variance explained by the models is proportional to the *square* of the correlation displayed in these plots: this means that the square of correlation could closer proxy when linking to and measuring forecast performance. While the improvement in NPV is linearly proportional to correlation, the relationship between NPV and a measure such as R^2 would be quadratic, with decreasing marginal improvements in benefit for higher R^2. This means that an improvement in R^2 from 0.1 to 0.2 would be expected to give a greater increase in benefit than an increase from 0.6 to 0.7.

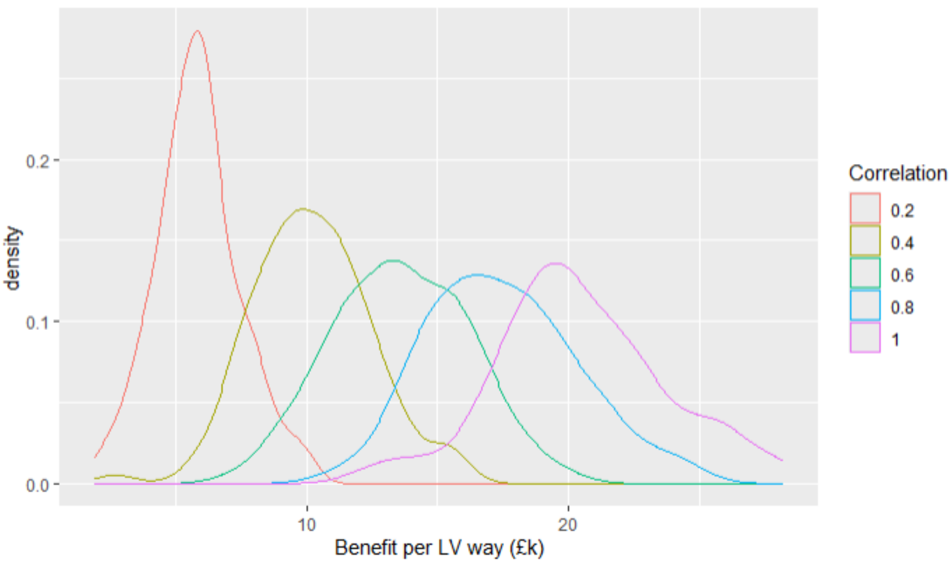


Figure 15: Distribution of total PV benefit relative to no predictive skill, per skill level

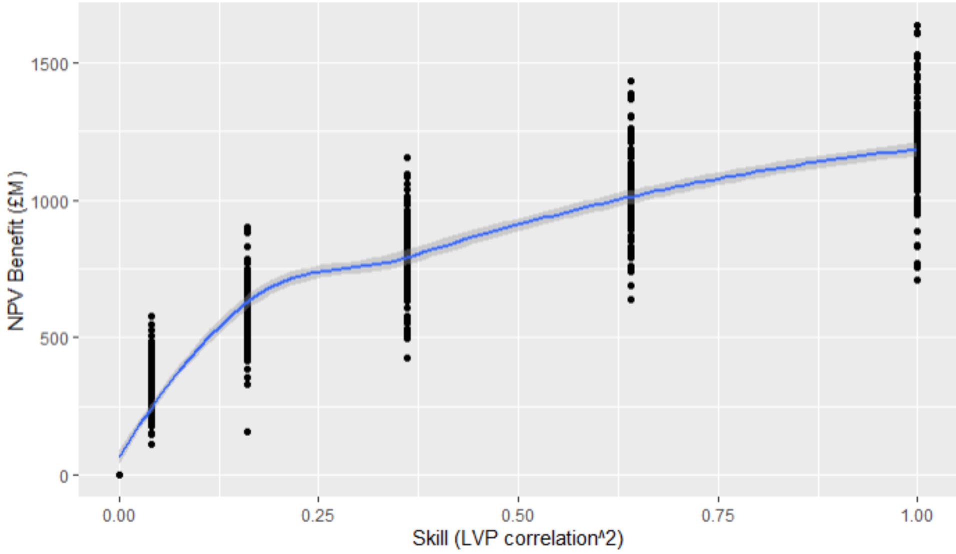


Figure 16: Fitted relationship between skill level and total NPV benefit, relative to no predictive skill

Finally, all the previous analysis has assumed a fixed profile and volume of LV way replacements in all scenarios. A sensitivity to the total proportion of LV ways replaced was also undertaken, for a fixed skill level where the correlation between real and estimated failure probabilities is 0.6. Figure 17 shows the result of this sensitivity, and indicates that replacing around 40% of all LV ways appears to be optimal under the assumed skill level and repair, replacement and CI and CML costs. In other words, 60% of cables aren't worth replacing because they are not likely enough to fail, and/or the number of customers affected by faults is too low for the avoided IIS penalties to offset the cost of replacement.

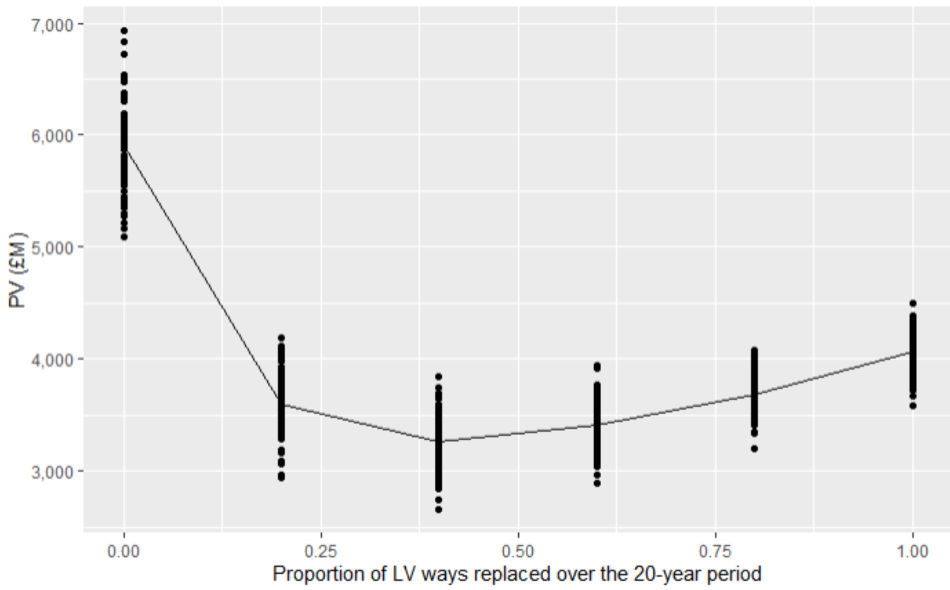


Figure 17: Sensitivity of PV to proportion of LV ways replaced over the simulated period

9 Conclusions and Recommendations

9.1 Methodology Findings

The CBA methodology presented in this report sets out how SP ENW could determine the net financial benefit of adopting a proactive maintenance strategy and investing in in-house fault prediction capabilities. The demonstration shows some interesting and informative results across different levels of skill in predicted annual failure probabilities. Two baseline scenarios are included: the case of no planned replacements, and the case of planned replacements but no skill in fault prediction. Some key findings include:

- Given the reasonable estimates used for input parameters, in a scenario where 50% of LV ways are replaced over the next 20 years, the CBA demonstration shows that IIS costs from unplanned outages caused by faults are by far the largest contributor to cost. Thus, proactive replacement reduces cost primarily by reducing the volume and length of customer outages, with the reduction in fault repair costs being much smaller.
- The no planned replacements baseline shows increasing overall costs over time, which exceed the costs for any scenario that includes some planned replacement.
- Greater skill in failure probability predictions always leads to greater cost benefit and this is linearly proportional to the correlation between the estimated and true failure probabilities. When assessing models in terms of R^2, the improvement is more marginal at higher skill levels: increasing prediction skill from an R^2 of 0.1 to 0.2 would give much greater benefit than increasing from $R^2 = 0.7$ to 0.8.
- Under the assumed inputs, and assuming a prediction system where the correlation between predicted and true failure probabilities is 0.6, replacement of approximately 40% of LV ways over the next 20 years is optimal, balancing higher fault costs from under-investment and higher replacement costs in the case of over-investment.

9.2 Implementation Considerations

The actual implementation of a proactive maintenance strategy requires only skilful *ranking* of LV way failure probabilities (i.e. a model that assigns the highest predicted failure probability to the LV way with the highest actual failure probability, regardless of the magnitude of the value predicted). However, it is important to note that the results of the CBA itself – and therefore the calculated financial benefit – requires accurate inputs for the *level* of failure probabilities to assess the balance of costs for reactive repairs vs proactive replacements.

The main CBA methodology is based around an assessment of the cost benefit of adopting a proactive maintenance strategy, given any level of skill in prioritising LV ways for replacement. This gives the flexibility to calculate the benefit of potential improvements to predictive models before they are implemented, and therefore informs the financial feasibility of such an investment. However, this CBA methodology does not directly set out how per-joint damage predictions would translate into a proactive maintenance strategy in practice. The key data missing to enable this is the calibration of predictions to observed fault data, including the relationship between faults at different locations on the same LV way. If this were available, the process would include the following preparatory steps:

- Gather data on the total number of customers for each LV way on SP ENW's network.
- Gather data on or estimate the expected replacement cost for each LV way on SP ENW's network.

- Generate (probabilistic) predictions of damage for every joint on every LV way, from statistical models demonstrated in the methodology report [1].
- Calculate a proxy for LV way failure rate from the predicted damage of the joints, the number of joints and existing asset condition. However, this step relies heavily on the availability of asset condition data and ideally historic fault records for calibration and verification.

The relative size of failure probabilities is the only property needed for ranking and prioritisation of LV way replacements when using the CBA methodology's strategy to conduct proactive maintenance, but the actual values of failure probabilities do affect the results of the CBA methodology since the number and cost of reactive repairs is dependent on this. Because of this, it is important that predictions are calibrated against historic data to ensure alignment with real world fault rates. This should account for the relationship between predicted damage and observed faults, calibrating the damage predictions, as well as accounting for correlations between faults at joints on the same LV way as these are expected to have some dependence.

From this point, the CBA methodology could be used to test varying proportions of total cable replacement for the specific LV ways on SP ENW's network and determine the optimal total number of replacements according to SP ENW's preferred trajectory of cable replacement (i.e. specifying which year replacements should peak in, and how 'peaky' this distribution should be). When the replacement volumes per year have been set, the CBA methodology would be implemented in the following way for each year:

- Use the predictions of fault probabilities per LV way along with number of customers and estimated replacement cost to calculate the value of the merit metric M for each LV way, as in Equation 3.
- Order LV ways by decreasing merit and select the first n_y - these are the ways earmarked for proactive replacement in year y.

The implementation of the actual LV way prioritisation and selection process is relatively simple; the most complex part of this process to implement would be the mapping of predicted damage per joint to a failure probability per LV way. This requires either assumptions about the link between joint damage and overall LV way failure probability, or calibration to fault data that is currently not consistently available. A system to record this data would be an important first step towards implementation of a proactive maintenance strategy, increasing visibility and understanding of faults on the network.

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