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Low Voltage Monitoring

Primer and Guideline

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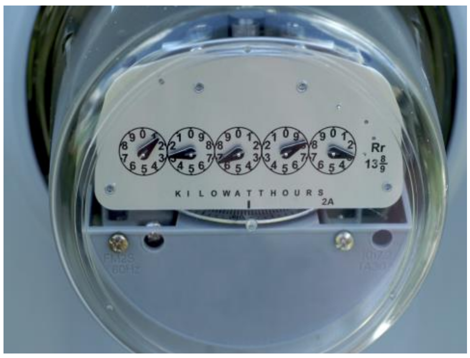

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Glossary

Abbreviation	Stands for
AC	Alternating Current
AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
AMP	Asset Management Plan
BAU	Business As Usual
CBD	Central Business District
DC	Direct Current
DER	Distributed Energy Resources
DERMS	Distributed Energy Resources Management System
DPP	Default Price Path
DSO	Distribution System Operator
EDB	Electricity Distribution Business
EV	Electric Vehicles
HP	Heat Pump
kVA	Kilo-volt-amperes
LV	Low Voltage
PLC	Power Line Communications
PQ	Power Quality
PV	Photovoltaics
RF	Radio Frequency
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SaaS	Software as a Service
THD	Total Harmonic Distortion
UK	United Kingdom
UPS	Uninterruptible Power Supplies
VoLL	Value of Lost Load

1. Introduction

We have been engaged to write a white paper giving guidance on when to use Low Voltage (LV) monitoring in the context of a changing electricity network with increased Distributed Energy Resources (DER), the type of monitoring to use under what circumstances with cost and benefit guidance.

In this first stage of our work we seek to identify the problems that are caused, or are likely to be caused, with increasing levels of DER penetration. Part of this is researching the national and international literature and part of it is seeking feedback from Working Group 2 on the problems New Zealand EDBs are concerned with.

This paper has three major parts after this introduction.

- The first part is a primer on LV monitoring experience internationally and its relevance to the New Zealand context – Section 2, Primer.
- The second part is general guidance on the use of LV monitoring – Section 3, General guidance on choosing LV monitoring technology.
- The third part has specific guidance for a range of scenarios where LV monitoring can be valuable – Section 4, Specific guidance on choosing LV monitoring technology.

2. Primer

2.1 LV networks background and context

The Low Voltage (LV) network refers to the assets of distribution companies which carry power from distribution transformers to the electricity meters of industrial, commercial and residential customers.

In New Zealand LV networks are operated at 230 volts (single-phase) and 400 volts (three-phase) plus or minus 6 per cent, at the frequency of 50 hertz.

2.1.1 LV network characteristics differ across the country

In rural areas LV networks tend to be mainly overhead, while LV networks in urban areas are more likely to be underground. Distribution transformers can be pole or ground-mounted. Pole-mounted transformers are generally smaller and supply fewer customers than ground-mounted transformers. Ground-mounted transformers are usually located in suburban areas and CBDs with underground LV networks, serving larger and more critical loads compared with pole-mounted transformers.

Electricity Distribution Businesses (EDBs) are responsible for maintaining and managing the LV networks to ensure supply is reliable, and voltage and frequency meet supply quality standards set out in the Electricity (Safety) Regulations 2010. LV networks have several attributes that make them worthy of special asset management attention:

- They transport electricity to almost all electricity customers.
- They consist of a significant portion of total network assets.
- Proximity to customers and general public makes management an important part of safety systems.
- LV networks are progressively needing to adapt to integrate a variety of high load consumer technologies, and host increased DER penetration, which can cause a variety of issues.

2.2 Monitoring data can be used to improve network performance and safety

Monitoring at the LV level provides EDBs with data that can identify issues and assist with planning, design and control of LV networks. The efficient use of monitoring data can reduce costs, optimise investment, and improve customer service and safety.

2.2.1 The LV network is currently invisible

While EDBs have visibility over high and medium-voltage networks, they typically do not have the same level of visibility into their LV networks. Historically, relatively high reliability compared to the potential cost of inspecting a considerable number of LV circuits meant that visibility was not a high priority. However, where expectations of increased reliability lift even as electricity costs are expected to be affordable, alongside the complicating addition of DER, then the benefits of increased visibility mount.

- The lack of visibility in LV networks leaves EDBs reliant on customer notification to identify faults or outages. With visibility the operator can detect and locate faults faster, potentially before customers are exposed to them.
- Monitoring provides visibility so EDBs can determine if the networks are performing within capability and are able to operate within regulatory limits. Monitoring data can inform actions that optimise network utilisation and reduce line losses.
- Measuring power quality in LV networks makes it possible to address issues as they are identified. Improved power quality reduces losses and thereby enhances the effective capacity in the networks so capital expense of additional network capacity can be avoided.
- Monitoring will provide data that could identify unknown issues and support new approaches to network and asset management.

2.2.2 Optimised network planning

Data enables new approaches to diagnosis, condition evaluation, maintenance and life assessment, ultimately optimising the life of existing assets. If planning, investment or operational decisions are to be made effectively, especially when the LV network is expecting an increase in DER, accurate data is required. LV transformer monitoring can measure relevant parameters for network planning, such as maximum, minimum and mean values of voltage and current, and real and reactive energy (Evans & MacLeman, 2013).

LV transformers play a role in ensuring a reliable power supply as failure will commonly result in unplanned outages. As a cost-intensive component of power systems, with labour-intensive maintenance and repair, LV transformer monitoring has significant cost-saving potential (Elanien & Salama, 2010).

Current practice largely relies on condition-based monitoring and maintenance that may result in selecting a transformer maintenance and replacement strategy which does not minimise costs. Monitoring could reduce the incidence of replacing LV assets both too soon and too late, delivering savings.

2.2.3 Safety issues identified

Customers expect affordability, security and safety as foundation requirements of the electricity systems. For many EDBs in New Zealand the low voltage network is approaching the time where replacement will be needed to meet hazard requirements (The Lines Company, 2016).

Since integrated photovoltaics (PV) power generation was not considered in network designs, if customers install PV generators with capacity higher than their consumption, the network's safety and reliability can be compromised, resulting in frequent outages, excessive overloading, and inability in fault current termination (Mohammadi & Mehraeen, 2017).

LV monitoring enables a shift to a safety-by-design approach, meaning EDBs can proactively detect deteriorating and broken neutral connections. Experience in Victoria has shown that near real-time LV monitoring has the capability to substantially lower safety risks to customers through actively monitoring real-time network parameters, detecting and alarming for neutral integrity failures before they cause customer shocks (Energy Queensland, 2019).

With bi-directional flow from unknown or undetected DER, a dual isolation approach may be required to eliminate the risk of electric shock when work is being performed on or near LV network infrastructure.

2.2.4 DER incidence exacerbates LV network issues

The expected adoption rate of new energy technologies – driven by falling costs and global carbon abatement measures – leaves a limited window for EDBs to adjust so they can continue to deliver efficient outcomes and quality of service to customers.

Growth in DER results in active networks, characterised by bi-directional power flow, variable voltage profiles and less predictable loads. This presents EDBs with new challenges as active networks have different dynamics from traditional, passive networks and require different sets of information, planning and management processes. A solution could be to use modelled "Hosting Capacity" but this approach is not necessarily accurate, especially in increasingly dynamic systems, and creates additional costs for consumers due to necessarily requiring higher margins for risk where there is uncertainty.

At high DER penetration a level of dynamic control is required to maintain the balance between load and generation and keep the network stable. To do so, real-time information on the current state of the network is likely required.

Understanding how demand profiles are changing and having clear visibility of power flows and quality across the LV distribution network enables companies to identify and locate technical and non-technical losses and quickly manage or resolve issues (Spearing, 2018).

2.3 LV monitoring technology deployed

There are myriad specifications and strategies being explored and increasingly adopted based on the outcomes of trials and tests of a range of LV network monitoring equipment and data management systems. Approaches vary significantly, with most EDBs initially using off-the-shelf systems offered by a range of commercial providers. There are, however, several projects developing customised solutions to drive down the per-unit monitoring device costs.

There is a significant risk of making the suboptimal choice in a rapidly changing environment. This could be getting locked into a proprietary system before having enough data to make optimal investment. Projects like OpenLV are addressing this risk by offering an open software platform operating on off-the-shelf commodity hardware and reducing the risk of lots of competing systems being deployed. The OpenLV project has trialled and demonstrated an open, flexible platform that could ultimately be deployed in every LV substation in the UK (Potter, 2017).

Data and device specification vary, depending on the objective, in terms of coverage, accuracy, periodicity and latency. Cheaper devices generally measure fewer parameters. Approaches range from temporary installation on a small number of feeders (with or without rotation) to create representative feeder profiles, to progressing towards permanent real-time monitoring across entire LV networks.

Trials and modelling increase understanding of data requirements

Trials are an important step to develop an understanding of the types of data, the expected use, and transfer and storage requirements, as these influence the design of expanded monitoring systems (Evans & MacLeman, 2013).

Trials have:

- developed methods and devices that can be installed without supply interruption
- demonstrated retrospectively installed equipment can provide meaningful data to assess the network impacts of DER penetration
- focused on characterising when network problems might occur with forecast uptake of DER, and on the development of monitoring solutions
- provided insight into the best individual metrics to explain the occurrence of problems in LV feeders (Initial Utilisation Level and the Total Path Impedance) (Electricity North West, 2014)
- Indicated real-time streamed data may only be justified when used for the control of smart devices (Barbato, et al., 2018).

Simple approaches generally underestimate the scale of network issues

The utilisation of single-phase (balanced) network and load representations was found to underestimate the impacts of DER in LV networks (Electricity North West, 2014). For example, at 60-minute sampling, the percentage of customers with voltage problems identified was about half the rate compared to five-minute sampling frequency (with high PV penetration). Less granular data (e.g., 15-minute, 30-minute and 60-minute sampling) for loads and generation profiles underestimates the impacts of DER.

More complex approaches available and technically feasible

If planning, investment or operational decisions are to be made effectively when the LV network is undergoing pressure to allow connection of DER, more accurate data is required regarding the resulting impacts on the network. At least in part, this data will need to come from detailed, accurate substation monitoring (Evans & MacLeman, 2013).

In terms of effectively managing the LV distribution network and the challenges presented by both electricity losses and renewable technologies, utilities need access to accurate, timely data and actionable information. Advanced LV monitoring systems can measure, transfer and store real-time data. Many offer automated data translation through a suite of analysis tools.

Systems can be safely retrofitted to LV feeders to include LV power flow monitoring, measurement at the LV side of the transformer (i.e. current, voltage, active and reactive power, voltage, harmonics, flicker, sags, swells, etc.), LV fault passage indication and LV fault location.

Maaß et al. (2015) describe a data processing network for LV, high-rate measurement devices capable of sending the full high-rate acquisition data for permanent storage in a large-scale database. The study integrates different dedicated interfaces for statistical evaluation, big data queries, comparative analysis and data integrity tests in order to provide a wide range of post-processing methods for smart grid analysis. Collected data can be transmitted to a database, where it can be analysed and presented to give operators situational analysis of the LV network. Analysis tools can easily provide daily load profiles and voltage level data to help utilities plan for 'stress points' and energy losses in the network and maintain statutory voltage levels (Spearing, 2018).

Metering equipment installed at customers' premises can play a key role

Barbato et al. (2018) describe the FP7 European project IDE4L, where an extensive analysis of the LV network has been performed using smart meters and the installation of sensors on the medium to low-voltage transformers.

Distributed measurements allow identification of local voltage deviations and implementation of control strategies to avoid power quality issues by regulating, for example, the reactive power exchange at the prosumer premises, as well as local active power curtailment. The availability of real-time measurements from the LV grid allows the EDBs to perform a deep analysis of the LV network state and, therefore, determines customer behaviours and power quality phenomena. Monitoring equipment used during the trial provided both half-hourly and real-time streamed data.

2.4 NZ context

Some local context is found in Watson et al.'s (2016) study of PV on the LV network in New Zealand. The study reviewed literature on PV impacts on distribution networks that had investigated voltage issues, losses, unbalance, overcurrent, harmonics, and neutral displacement. Then, by simulating the entire LV network, the authors found that some minor overvoltage problems can be expected in the future, particularly in urban areas, but they also found that in most cases overvoltage would not be much higher than the statutory limit.

- PV systems connected to the LV distribution network may cause overvoltage, particularly when high solar radiation coincides with times of low loading, as well as overloading of conductors and transformers.
- Urban networks were found to have the least capacity to host PV. Nevertheless, each LV network is different, and there is a wide variance as to how much a specific LV network can cope with.

The New Zealand system is often already operated close to its upper statutory voltage limit in order to allow for voltage drop across the network. This maximises the capacity of long feeders by maximising the available voltage drop but also affects the hosting capacity for PV (Watson, et al., 2016).

Access to AMI uncertain

AMI systems can be a source of both profile and network (local power quality) data however access to AMI data, other than for reconciliation purposes is uncertain. In New Zealand the responsibility and costs for meters rest with the retailer, and the ownership of data has been contentious for a long time.

Profile data is available and useful for some applications, but access for other purposes is not necessarily agreed. Network data is not currently accessible, and its availability is even more uncertain as it might require the reconfigurations of meters.

2.5 Expectations of future demand and DER uptake are critical to the business case for LV monitoring

LV networks are diverse, with numerous variables affecting operations and the ability to monitor. The case for monitoring the LV network depends on consumer demand, embedded generation, and active management of consumer assets expectations.

While spatial considerations are also important, factors like distribution, ratios of residential to non-residential connections and overhead and underground are considered less likely to change dramatically or have more visible and manageable impacts. Underground networks can be more difficult to fit LV monitoring to, but that is an issue around the choice of solution rather than a different scenario.

2.5.1 Critical parameters

While many factors and their interactions need consideration, the penetration and distribution of electric vehicles (EV), PV, energy storage, high-load consumer devices and home energy management systems are the core parameters that differ across scenarios.

We also consider decision-making under 'Business As Usual' (BAU), where network investment may be required due to underlying growth, generally through new connections.

2.5.1.1 High potential to contribute to peak

Distribution networks must be designed to supply peak loads to ensure acceptable reliability, despite peak loads typically only occurring for a small fraction of the year. This means that the overall electricity infrastructure cost is largely determined by the peak load on the network. Consequently, there is strong motivation to minimise peak load growth throughout the electricity network.

Core drivers of energy consumption such as population and income growth are less important than the growth in connections and where these connections occur. Strong power-consuming processes like electrical vehicle charging contribute to the need to change assumptions around load profiles with increased incidence of congestion possible as charging demand is likely to occur at same time. Other high-load consumer devices like heat pumps contribute to peak load and changing load profiles. Heat pumps are behaviour-changing; more households use heat pumps in the morning, and many leave them on continuously, which is much less common for other heating methods (Pollard, 2016).

2.5.1.2 Ability to inject power into network

The size and types of PV installations and the penetration or incidence in LV networks are important. Installations that include energy storage bring a different set of issues and opportunities than direct-to-grid connections.

Urban and rural networks have different capacity to absorb PV and can, therefore, support different penetration levels before major issues arise. However, even at low penetration, PV can reverse the flow of power in the LV network.

PV is growing quickly as a generation source, with residential use the key driver over the past five years, accounting for more than 80 per cent of installed capacity (MBIE, 2018). Regional concentration is likely to continue in the areas with good irradiation. The region with the largest number is New Zealand's largest population centre Auckland, with solar on 4,204 residential properties (EA, 2018).

2.5.1.3 Ability to be controlled based on current network conditions

To face the new constraints, distribution networks need to become intelligent. The incidence of smart devices on the LV network can enable load shifting, but initially it is important to understand what capability is in a network and how it can best be utilised.

EV currently represent a tiny fraction of the total fleet but have averaged 95 per cent year-on-year growth over the past six years. We assume the future growth in EVs is going to be directed towards models with smart charging and the efficiency gain will be a significant demand driver. Ownership is currently concentrated in Auckland, and with individuals rather than companies.

Advances in storage technology both for PV and EV have significant flow-on effects. The ongoing improved longevity and reduction in battery prices are driving the uptake. Distributed storage provides voltage stability and can consume excess power in light load conditions, helping to shift consumption to improve the local consumption/production balance.

Table 1 gives a high-level overview of the scenarios where LV monitoring can be useful in addressing common network issues.

Table 1: Scenarios and associated issues

Predominant form of growth	Level of growth	Concern	Safety concern
New connections (natural growth)	Moderate/high	Thermal loadings Low voltage Phase loading imbalance	Neutral currents and neutral voltage rise
High-load DER (EVs and/or heat pumps)	Moderate/high	Changing patterns of demand Thermal loadings Low voltage Voltage stability/power quality Phase loading imbalance	Neutral currents and neutral voltage rise
Injecting DER (PV solar, other DG, and batteries)	Moderate	Changing patterns of demand High voltage Voltage stability/power quality	Neutral currents and neutral voltage rise Backfeed

Predominant form of growth	Level of growth	Concern	Safety concern
		Phase loading imbalance Phase voltage imbalance	
Injecting DER (PV solar, other DG, and batteries)	High	Changing patterns of demand Thermal loadings High voltage Voltage stability/power quality Phase loading imbalance Phase voltage imbalance Harmonics	Neutral currents and neutral voltage rise Backfeed
All DER	High	Changing patterns of demand Thermal loadings High and low voltage Voltage stability/power quality Phase loading imbalance Phase voltage imbalance Harmonics	Neutral currents and neutral voltage rise Backfeed

2.6 Key specifications for LV monitoring

This section develops the how, where, when and what to monitor.

2.6.1 Parameters to monitor

There is a trade-off between high-specification monitoring that measures the most parameters and lower-cost units that do not measure parameters such as harmonics and transients.

The core parameters to monitor are voltage and current (3ϕ&N, split-ϕ&N, 1ϕ&N)

Both line-to-neutral voltages and phase currents (or active and reactive power) at the head of the feeders should be monitored. Voltages are of particular importance for PV systems, given that most LV networks are likely to experience voltage issues rather than congestion. For EVs and electric heat pumps, phase currents also need to be monitored as many feeders are likely to experience congestion before voltage issues (Electricity North West, 2014).

2.6.2 Sampling intervals

For performance evaluation of the LV network, the mean value of 10-minute sampling intervals (or close to this, e.g. 15 minutes) should be adopted to avoid underestimating impacts. Trials found no significant benefit in adopting shorter sampling intervals (e.g. one or five minutes). For the monitoring of currents (or active and reactive power), hourly values were deemed adequate (Electricity North West, 2014).

However, for transients and harmonics, much higher frequency can be required. A transient power problem can appear and disappear in a few millionths of a second. Meters that sample at a rate of 256 or 512 samples per cycle can sometimes detect oscillatory transients, which tend to occur at low to medium frequencies, 1 MHz or less. However, impulsive transients can peak and decay in microseconds. To capture the peak, the meter might have to sample at a rate of 2 MHz (33,333 samples per cycle) or faster. By sampling circuit activity at very high rates (up to 100,000 samples per cycle), fast transients can be identified (Eaton Cutler Hammer, 2006).

2.6.3 Locations to monitor

Generally, trials have looked at monitoring transformers/substations and individual feeders. There are clear benefits from incorporating smart meter or smart device data, but this is not necessary for most applications.

For voltage purposes, the end points of the corresponding feeders should be monitored, given that the busbar would only work as a proxy if some knowledge of the feeders exists. Mid points do not necessarily bring more critical information, although they increase certainty and observability. For congestion purposes, currents at the head of the feeders should be monitored (Electricity North West, 2014).

2.6.4 Data transfer and storage requirements

Equipment generally offers a range of storage and transfer options, from manual collection to almost real-time continuous transfer. Even at high-specification, the amount of data transfer involved does not look like a constraint, especially given the options available with 5G networks although patchy coverage and, therefore, use of 3G networks will be challenging.

Other technologies are also available but, in the most remote cases, EDBs may need to build their own communication networks

There are compression techniques that can significantly reduce the bandwidth and storage requirements for communication. It is worth considering using cloud services (including data storage) provided by equipment suppliers. Suppliers with cloud services have incentives to continually improve data compression while maintaining service specifications, which also helps with managing communications.

2.6.5 Data processing and analytics

For small-scale trials, the data has been handled with simple spreadsheet analysis (Electricity North West, 2014; Evans & MacLeman, 2013). Most commercial LV monitoring unit providers offer a suite of analytics options that can be adapted to fit specific requirements.

Table 2 outlines the parameters to be considered in choosing and designing an LV monitoring system.

Table 2: Specifications for LV monitoring

Design criteria	Attribute
Location	Transformer, feeder, branches, connection
Permanence	One-off, rotating, permanent, real-time
Inputs	Voltage and current – 3ϕ&N, split-ϕ&N, 1ϕ&N
Sample rate	Milliseconds, seconds, interval
Recording rate	Delta, milliseconds, seconds, interval
Record	Delta, instant, maximum, minimum, average, event, quality metadata, harmonic metadata, derived value
On board memory	Months, weeks, days
Communications	Cellular, RF mesh, PLC and backhaul, fibre
Polling rate	Milliseconds, seconds, minutes, hours
Database	Temporary, archived, permanent
Model	Simple capacity, DC thermal, DC voltage, AC simple, derived full AC static, derived full AC transient
Model accessibility	Ad-hoc, permanent periodic update, periodic dynamic update, real-time status
Analysis	Thermal capacity, voltage capacity, AC capacity, AC stability, AC transient/harmonic
AMI data	Included, excluded

2.7 Costs of preferred technologies and modelling approach

We have used two approached to costing. One scenario used information on the costs of trials and expanded rollout of LV monitoring extracted from United Kingdom and Australian examples, with the most recent examples preferred as significant cost reductions have occurred recently. The second approach adjusts categories where cost examples from New Zealand EDB experience are available. These examples have tended to use devices with quite slow sampling rates, which are not suitable for all monitoring purposes, so it may understate the data transmission and storage costs. We have not adjusted these as we expect costs to continue to reduce as monitoring technology is more widely adopted.

Cost per unit is expected to reduce significantly in the near term

There is evidence of significant cost savings from scale of deployment, and, as with many technologies each year, the costs are reducing while capabilities increase. The most recent projects had much lower costs than those at least five years old. There are also several research projects partnering with academics and industry that are attempting to drive the unit cost down and enable widespread adoption.

- Early trials of small number of units (<100) reported costs in magnitude of $10,000 per monitoring location.
- Scaling up of trialling and more recent experience reduces costs to range of $2,000 to $5,000 per location. This is aligns with recent high specification device cost ($4,500) reported by NZ EDBs.
- Research projects have been funded with the goal of bringing cost of unit and installation down to the $200 to $500 range.

We average available international estimates, convert to NZD and produce a range of costs based on the scale of deployment

By using the most recent examples and the best available category breakdown of costs, we have produced the following range of cost estimates. These are high-level and largely ignore the differences in installation location and device specification. No examples of data and project management costs at scale have been identified, so we have been forced to assume the same level of price change as has occurred in the shift from high to mid costs.

We expect the monitoring unit costs are overstated due to the rapid price reduction for devices with improved capability seen in the last seven years of trials. Data management and modelling costs also appear to be falling with the increased availability of integrated cloud-based solutions. Network specifics will impact installation, communication, and maintenance costs so EBDs can access more accurate cost estimates from discussions with equipment suppliers.

Table 3: High level cost estimation based on scale (NZD)

Cost components	Description	Low	Mid	High
Scale	Number of units	>1,000	<1,000 & >100	<100
Site surveys	Assess sites for installation and data transmission	$109	$209	$309
Monitoring equipment	Unit cost (assume 10-year life)	$1,995	$2,926	$4,244
Installation	Install cost per unit	$303	$394	$500
Maintenance	Assume 1% of unit cost	$20	$29	$42
Communication	Transfer of data from unit to database	$243	$437	$786
Data hub	Database infrastructure	$70	$450	$2,894
Data quality	Data management	$19	$73	$275
Project management	Modelling and administration	$317	$728	$1,674
Total		$3,541	$5,245	$10,724

Sources: (Evoenergy, 2018; Energy Queensland, 2019; SP Energy Networks, 2015; SA Power Networks, 2019)

Local cost estimates are in a narrower band for scale of deployment

Most notably we remove the site survey costs as we are told these are not required. The basis for this is that most sites will be relatively simple to install and a known portion of sites are not feasible or economically viable. We use a recent example of high-specification device cost and scale based on example of lower-specification devices. Installation costs are increased, maintenance cost for trial scale is increased, and data transfer and management costs are reduced for all scales of deployment.

Table 4: High level cost estimation based on scale (NZD)

Cost components	Description	Low	Mid	High
Scale	Number of units	>1,000	<1,000 & >100	<100
Site surveys	Assess sites for installation and data transmission	$-	$-	$-
Monitoring equipment	Unit cost (assume 10-year life)	$3,844	$4,183	$4,500
Installation	Install cost per unit	$400	$650	$850
Maintenance	Assume 1% of unit cost for large scale and 10% for trial	$38	$42	$450
Communication	Transfer of data from unit to database	$46	$50	$55
Data hub	Database infrastructure	$12	$13	$15
Data quality	Data management	$12	$13	$15
Project management	Modelling and administration	$317	$728	$1,674
Total		$4,669	$5,679	$7,559

Sources: Sapere analysis and communications with working group EDBs

2.8 Benefit assessment methodology

We identified five key areas of potential benefits and developed methods to estimate the level of these benefits based on the level of LV monitoring rollout, with publicly available data and evidence from international literature for four of these. The remaining category – safety benefits – is likely to only be fully realised once adoption of LV monitoring occurs.

Benefits will vary across EDBs depending on network characteristics. The specific characteristics of each EBD's case for LV monitoring will require them to quantify their own benefits separately. We give guidance on how this can be done.

The general benefits outlined below are assessed collectively for all EDBs.

Value of Lost Load (VOLL) benefit of $16 million per year

Based on a value of $20,000 per MWh and 2019 reported SAIDI levels across the whole industry, we estimate that LV monitoring could reduce 'cause unknown' by 50 per cent, and both 'defective equipment' and 'vegetation' by 10 per cent. As SAIDI figures do not cover the LV network, this is used illustratively rather than based on evidence. We use a reduction factor of 50 per cent for 'cause unknown' on the basis that being able to identify causes for these faults will both resolve faults more quickly and be more likely to result in repairs that prevent faults from occurring again.

Table 5: Estimated SAIDI reductions

SAIDI causes	2019	Reduction
Cause unknown	13.04	6.52
Defective equipment	33.43	3.34
Vegetation	34.95	3.49
Total		13.36

Source: Commerce Commission performance summaries 2019

The benefit is allocated evenly across EDBs based on number of transformers. Only 10 per cent of benefit is achieved at the 1 per cent of transformers trial-level deployment of monitoring equipment. 100 per cent of benefit is achievable at the expansion level - 10 per cent of transformers monitored.

Asset replacement and renewal savings of 10 per cent

Data has been extracted at the EDB level based on reported 2019 Asset Management Plans (AMPs). This means there is some bias introduced as some EDBs are known to be spending more now to make up for previous underinvestment. We recognise this, but, as these are high-level estimates, we do not see an issue with the aggregated benefit estimate.

With trial level deployment of LV monitoring, we allocate a conservative 1 per cent yearly saving on asset replacement and renewal. This is based on evidence that the data should enable EDBs to avoid replacing assets too soon. With further deployment of monitoring equipment, we model this benefit to rise to 10 per cent of yearly asset replacement and renewal forecasts.

System growth savings of $12 million per year

We translated the 39 kVa per transformer savings identified in SP Energy Networks (2015) to the New Zealand context. This produced a saving of 9.5 kVa per transformer or a total of 1.8 million kVa and saving of 8 per cent on 2019 forecast expenditure of $153 million. This translates to $12 million per year. We spread this evenly across the EDBs based on the number of transformers and consider that all this benefit is potentially achievable even with monitoring of just 1 per cent of transformers.

DER optimisation benefits increase with projected uptake

We draw on work looking at DER incentives, information and coordination to estimate in year 1 $1.8 million of potential benefits, which rises rapidly by year 5 to $14 million and $83 million by year 10. We spread the potential benefit evenly across EDBs based on the number of transformers, with 10 per cent of benefits realised with trial-scale deployment, 20 per cent with expanded monitoring, and 50 per cent with monitoring on all LV transformers.

Safety benefits are likely but cannot be estimated from available data

Trials are expected to reveal the level of safety benefit achievable at higher level of LV deployment.

3. General guidance on choosing LV monitoring technology

3.1 Getting started

There are four scenarios under which LV monitoring might be deployed:

1. Planning – Assisting decision-making for asset management.
2. Customer experience – General performance monitoring, especially relating to unknown faults or unresolved customer complaints.
3. DER hosting – Understanding the implications of significant load growth and/or customer power injections through new technology.
4. Diagnostics – Even where the cause of a problem or fault is generally known, there can still need to be a systemic process to discover the source, or sources, of problem or fault.

Most, if not all, EDBs will have used relatively simple loggers of power and voltage to help monitor demand, phase balance, and average voltage levels to plan for distribution transformer or LV feeder rationalisation, or even for the need for it. More advanced LV monitoring can help plan for more complex problems, especially if their LV networks are being transformed by the advent of new consumer technology.

LV monitoring has the potential to significantly improve the customer experience from their electricity supply, even as the LV network becomes more complex to manage. For example, investigating increasing incidence of transient disturbance will lead to the discovery of some faults before they ever occur. Even where faults do occur, LV monitoring should significantly reduce restoration times, potentially even pinpointing fault locations as they occur.

The third scenario – understanding the DER hosting capacity of the LV network – has been the driver for much investigation into LV monitoring internationally. In many of these jurisdictions, the LV utility has already been playing 'catch up'. This is not yet the case in New Zealand, but as Distributed Energy Resources (such as EVs, solar PV and batteries) may soon be deployed at significant scale, then the option value of DER hosting capacity monitoring is substantially increased.

Ideally, if EDBs are concerned with the potential for DER take-up on their networks, DER hosting capacity monitoring would be done early and well ahead of the take-up. This has two benefits. First, a baseline of the LV network monitored is established, which will make any new or increased problems caused by DER take-up easier to identify. Second, early signalling of the DER hosting capacity of specific distribution substations and LV feeders would create customer benefits by giving certainty about what they can and cannot do with new technology in their location.

There is leveraged benefit in LV monitoring that can also make it worth investing in higher-specification devices. For relatively static data, the findings from monitoring one LV feeder can be extrapolated to similar feeders. For example, the baseline of underlying harmonic levels for an LV feeder can be assumed to be similar for other LV feeders of similar construction, size, environment and customer type. This can be particularly useful for determining levels of DER hosting capacity in the whole LV network from the measurement of a few representative LV feeders.

Obviously, this does not work for problems or situations that are more dynamic. For example, the diagnosis of a transient fault in one LV feeder does not inform the location or specific context for a transient fault on another feeder, although it could generally indicate what types of faults are likely. Similarly, if an LV feeder is undergoing significant change, such as through customer activity, then comparisons to static feeders will not be useful.

3.2 Equipment selection

Obviously, before LV monitoring equipment can be deployed, the equipment must be selected and procured. The equipment selection decision spans across the field monitoring equipment, communications, data storage and analytical systems. Historically, even starting on higher-specification LV monitoring would have required making significant fixed cost decisions on the back-office systems and communications network, and would then often be restricted in the equipment that can work with it.

The technology has moved in a direction where there is not a technical reason for these large fixed cost decisions. Most LV monitoring technology today is available with its own webservices, including cloud storage and Software as a Service (SaaS) analytics. Communications are also flexible, with almost all LV monitoring devices offering multiple communication options as standard, which allows for connection to public systems or specialised services (existing or new). There are, however, still economies of scale that warrant consideration of the whole LV monitoring system for larger numbers of devices (i.e. from hundreds to thousands). While the number of devices in a fleet is small, maintaining flexibility causes no harm.

The choice of specification of devices for an EDB depends on the current need but also what the forecast needs are for the network. If investigating customer complaints and faults is one of the reasons for using LV monitoring, then devices that can sample three phases and the neutral at a rate of one per cycle to no more than a few seconds would be necessary, with PQ analytics (voltage sag/swell/flicker and THD). To investigate and diagnose difficult faults might warrant the highest specification of devices capable of event-recording transient disturbances.

Similarly, if an EDB was seeking to assess the DER hosting capability of its LV network, then establishing a baseline of voltage profile and individual harmonics would be warranted, which would use devices with high sample rates, e.g. 12,750 samples per second.

The number of devices held can also vary by purpose. For general investigations, usually one device can be used to get an idea of any underlying issues. However, general investigation can detect issues but may not give any guidance on where in the LV network the issue is. Once an investigation moves from general identification of a problem to diagnosis, then multiple devices may be needed to find the source of problems, or to at least speed the process up.

Determining some aspects of DER hosting capacity also requires multiple devices to be deployed at the same time. For example, determining the varying voltage profile on an LV feeder, or determining the harmonic attenuation performance, and estimating the predictive LV network models that can be derived.

3.3 Safety

LV monitoring potentially offers an increase in safety surveillance. Most LV monitoring devices can pick up reverse power and can potentially detect unexpected power injections from customers. Highly accurate and sensitive devices can reconcile phase and neutral currents to pick up residual earth currents and neutral voltage rise. Potentially, monitoring these characteristics would be able to detect changes in the conductivity of neutrals and earthing over time.

Monitoring safety is a dynamic activity and would require widespread deployment of permanent high-specification devices to be effective. This would be expensive. The incidence of life-threatening safety problems is low, but there is significant value in preventing any injury. The benefits of safety monitoring may increase if the number of customer-owned power injection devices increases significantly (e.g. solar PV and batteries).

3.4 Benefits of cooperation

Where LV monitoring is considered it is also worth considering coordinating investment and operational efforts across EDBs. This is because there are some potential savings through economies of scale, but also because the sharing of data and information and bigger asset samples are also beneficial.

Much of the initial value of LV monitoring is achieved through leveraging a smaller sample of LV feeders across the whole network. Overseas experience suggests a set of representative feeders (in the order of 10) can be applied across the whole network with most of the benefit of direct monitoring. By clubbing together, EDBs could better develop a statistically representative sample of LV feeders that can be extrapolated over a greater number of assets.

Later in the LV monitoring development, economies of scale may encourage common back-end systems, communication networks and eventual real-time monitoring across EDB groups. Even more beneficial may be the common development of advanced analytical techniques, such as artificial intelligence, which again can be leveraged across a larger asset base.

3.5 Other data sources

Other sources of data that can enhance LV monitoring are Advanced Metering Infrastructure (smart metering) and DER data. Although, EDBs do not necessarily have access rights to either of these data sources. Meters are the responsibility and cost of retailers, and the ownership of metering data has been controversial. This controversy spills over into the basis and the commercial terms by which data can be procured.

Distributed generators can be required to provide interval and cumulative metering data, and reactive power data if it has Category 2 metering, under Part 6 of the Code. However, this requirement does not apply more broadly to DER and does not apply to power quality data unless the EDB has a reason to specify this at the time of the DG application. The discussion about DER metering requirements and data provision where DER is actively participating in the industry is one the industry still needs to have.

AMI data can include profile data (interval power import and export, and reactive power import and export) or network data (voltage, power quality, THD, etc). DER with smart inverters can also provide network data. At present neither is required to measure or provide power quality data or has incentives to provide it.

Reconciling AMI data with LV monitoring allows for the detailed LV topology to be reverse engineered. This can be helpful for planning and forecasting transformer and LV feeder loadings for various scenarios of customer load growth or DER uptake.

AMI network data and DER data can help derive LV network models, potentially being able to derive accurate AC models of the LV feeders.

With the prevalence of AMI in New Zealand there is much that could be modelled in the LV network through only using AMI data, but that is not within the scope of our guidance. Nevertheless, measuring voltage and current and multiple points upstream and downstream on LV circuits is likely to make analysis easier and probably more accurate.

4. Specific guidance on choosing LV monitoring technology

The following specific guidance is based on generic scenarios related to the four general reasons given for potentially using LV monitoring given above.

These scenarios are:

Planning

- transformer replacement or concerns
- LV feeder review or concerns
- difficult discrimination problem or concern and/or protection maloperation.

Customer experience

- voltage or power quality complaint
- unknown intermittent faults
- customer reports sporadic electric shocks
- faster fault location and response.

DER hosting

- significant take-up of DER loads
- significant take-up of DER injection
- need to coordinate DER.

Diagnostic

- reverse power
- reactive power
- voltage range
- phase load balance
- neutral or earth voltage rise or residual earth current
- power quality (voltage sag, swell and flicker)
- transients
- harmonics.

4.1 Planning

4.1.1 Transformer replacement or concerns

When a transformer replacement is being considered, LV monitoring can assist better decision-making, potentially even concluding that a transformer change is not necessary. Measuring active, reactive and apparent power per phase will help highlight the actual power loading on the transformer and how much of the problem may be due to poor power factor or out-of-balance phase loadings.

4.1.1.1 Benefits

The expected benefits of LV monitoring on transformers are reduced expenditure through optimising replacement timing better, avoiding early failure and urgent replacement, and installing less transformer capacity on average.

There are two factors that can 'use' transformer capacity for no benefit—reactive power and out-of-balance phase loadings.

The reactive power problem is relatively well addressed where out-of-phase current loadings load up circuits and transformers without a commensurate production of useful power. All EDBs have pricing mechanisms and programmes to address power factor. Nevertheless, a transformer upgrade could be avoided through identifying an achievable improvement in power factor.

The out-of-balance phase loading problem can potentially yield greater benefits. The phase categorising convention is to colour code them red, yellow and blue, with red always being first. Single-phase colour coding convention for fixed wiring is red for phase, black for neutral and green for earth. Electrical workers are trained to avoid mixing colours, as the integrity of the neutral and earths is critical for safety. Add to this that colour coding for flexible cords allows the use of blue for neutral, and yellow and green for earth.

This seems like a subtle driver of behaviour, but there is a real bias to connecting single-phase appliances and installations to red phase. This can overload the red phase, potentially leading to failures, even while two-thirds of the transformer is underutilised. Replacing a transformer, even if planned, can mean sizing it for the red phase load because it is difficult to address a significant out-of-balance problem.

Table 6: Planning – Transformer replacement or concerns

Problem	Measurement Location	DER forecast	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Transformer replacement or concerns	LV busbars or LV feeders	Low take-up forecasted for this transformer	n/a	≤ 30 minute average, maximum and minimum 3ϕ voltage, current, power and reactive power	**Power/reverse power** **Reactive power** **Voltage range** **Phase load balance**	Comms optional, can be manually collected, target peak load periods	AMI profile data can help determine LV topology for loading predictions.
		High take-up possible for this transformer	Similar feeder has been measured and showed little power quality, transient or harmonic interference				
			No comparable baseline or similar feeder shows interference	<0.5ms 3ϕ & N amplitude and phase angle. Summarised data and configurable disturbance recording	As above plus **Reconcile 3ϕ & N currents (earth leakage)** **Power quality (sag/swell/ flicker)** **Transient disturbance** **Harmonics**	Few months of sampling, volume of data probably needs non-real-time data communication	n/a
Expected benefits	Reduced expenditure on transformers. Replacement timing optimised, avoid transformer failure, and less transformer capacity installed on average.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

4.1.1.2 Why LV monitoring?

At the simplest level, either temporary or permanent, LV monitoring of a transformer will show the level to which a transformer is utilised. For this to be effective, the transformer needs to be monitored for a reasonable time and definitely over periods of the highest expected loading. Although care needs to be taken over assuming too much prior to monitoring, what might be expected to be the period of heaviest loading may not be the key determinant of the transformer's duty if there is a significant out-of-balance and/or reactive load with an unusual load profile.

A simple monitoring approach can, at least, highlight opportunities to improve the utilisation of the transformer. To determine what to do may then require a follow-up diagnostic process. More advanced approaches, such as determining the LV topology, can then improve future monitoring of transformer loading.

Overseas experience suggests that leveraged benefits result from LV monitoring. The problems identified on one distribution transformer or LV circuit are often then found on transformers and circuits with similar characteristics of load types, number of loads and areas. Monitoring representative transformers then leads to the development of targeted monitoring programmes with optimally specified monitoring technology.

4.1.1.3 What LV monitoring equipment to choose?

Prior to determining which equipment to choose, particularly for the first time, it is worth considering the future needs and the current understanding of the LV network. Factors to consider are:

- Should the individual LV circuits be monitored rather than just the transformer?
- Should any potentially unknown problems be identified?
- Would determining the optimal specification for future monitoring be useful?
- Should the LV network be modelled to assist future analysis?
- What other data is accessible (e.g. AMI data)?
- Does the DER hosting capacity of the LV network need to be assessed?

If little is known of the LV network,

- about the underlying performance of the LV network with respect to power quality,
- future LV monitoring is likely to be pursued,
- the LV network is undergoing rapid change (e.g. growth),
- or there are concerns about the impact of new technology (e.g. EVs, heat pumps, PV solar, batteries, etc.)

then there is a case for deploying the highest specification of LV monitoring device.

Assuming that no previous assessments of LV monitoring specification have been done, the minimum level of LV monitoring for assessing the loading on a distribution transformer is at least 30-minute sampling of the voltage, current, reactive and active power on each phase at the transformer's LV terminals or the LV bus. Thirty minutes is somewhat arbitrary but aligns with the interval revenue metering standard in New Zealand and should be able to be reconciled to consumers' metered peak demand. However, 30 minutes is probably not short enough to derive the actual peak load, so the LV monitoring device should be of the type that records not just the integral over the sampling period but also the maximum and minimum values.

Shorter sampling periods will be more likely to indicate the peak loading per phase or, at least, be more representative of the heating effect in the transformer from the peak load.

As a matter of course, the simplest technology will indicate:

- peak power and any reverse power
- reactive power loading
- the voltage range at the transformer
- phase load balance.

If suitably higher specification LV monitoring is used, then measurement can also indicate:

- earth leakage
- power quality (voltage sag/swell/flicker)
- transient disturbances
- harmonic distortion (including by harmonic to high orders).

These could indicate previously unknown problems and/or establish baselines for assessing DER hosting capacity.

High-speed sampling can also be used to assess the desirable specification for future LV monitoring by:

- integrating the high-definition data into different periods (e.g. one minute, five minutes, 15 minutes, 30 minutes)
- analysing interpolation techniques to derive the phase loadings from the integrated data
- comparing the derived loadings to the high-definition data.

This allows the selection of the best sampling period, being the desired balance between accuracy and amount of data.

Alternatively, the heating effect of high-definition data over different periods can be compared to the averaged heating effect of each period, i.e. the average of the square of high-definition current over the period being analysed compared to the average of current squared. The desired level of accuracy can then be selected where the sampling period values are representative of the heat loading of the transformer.

It could be that different sampling specifications might be needed for different LV feeder characteristics (e.g. type of customer, number of connections and area).

A final thing that can be done is to determine the LV topology for the distribution substation. This becomes impracticable for substations with a large number of connections as you need close to an LV monitor per connection. However, this is practical with access to AMI profile data.

Some LV monitoring can do this automatically if it has real-time direct communication with the smart meters on the substation. However, it should also be possible to do this with advanced analytical techniques and a large enough historical set of data, even with different sampling rates.

Determining the LV topology means determining which phase or phases a customer is connected to and on what circuit and/or circuit branch. It can possibly also determine the relative distance from the substation for each connection. If analysis can solve the LV topology problem, then a quite accurate model can be developed for circuit and transformer loading, which can also:

- assess LV losses (technical and potentially non-technical)
- identify connections that may not actually be on that substation
- identify that connections are missing from the data
- compensate for any missing AMI data.

Although, if too much data is missing or wrong, the LV topology problem will not be able to be solved.

An LV topology model can track substation loading potentially only using AMI profile data. It can also be used to predict substation loading for different assumptions of customer demand.

4.1.1.4 Communication and data storage

At the lowest level of specification, the data requirements for LV monitoring for transformer capacity are not high, although the volume of data can add up if a number of transformers or feeders are monitored. A year's worth of 30-minute data containing average, minimum and maximum values for each of voltage, current, power and reactive power for each phase is a text file of about 6MB in size. However, the volume of data increases dramatically for high-resolution data.

For temporary applications, communications are not necessary. LV monitoring devices can usually store data for at least a couple of months and the data can be manually downloaded by USB, Bluetooth and/or WiFi at least. Most LV monitoring devices also support a number of network communication interfaces and the selection will be driven by availability and cost.

Data storage and access should be considered before LV monitoring begins. Most vendors of LV monitoring (if the device(s) have an internet connection) offer webservices and cloud storage, which is a good starting option, at least. The direction of travel may well be towards cloud services and SaaS.

It may be a good idea to archive a certain amount of current data for more detailed analysis, but processed long-term data can potentially be stored more efficiently. For example, a statistical summary of aggregate and per phase loading per week, or even per month, would be an efficient way of storing useful data for managing substation capacity.

Alternatively, the data could be processed in an event-driven database, which records the values and timestamps data when it crosses predetermined thresholds (such as a certain amount of change). This can be a very data-efficient way of storing data where the profile over time is recorded to a desired level of accuracy.

4.1.1.5 Building the business case – cost

There are significant economies of scale in deploying LV monitoring technology, and costs are expected to fall dramatically over time as LV monitoring gets deployed widely around the world. Recent international examples indicate the total cost for less than 100 monitoring devices is expected to be around $11,000 per device for a high-specification device. Recent New Zealand examples indicate the costs of around $7,500 per high-specification device, so if the business case for monitoring stacks up at these prices, the case looks strong. Costs will be less for lower specification and if data is collected manually. Deploying up to 1,000 devices should reduce per-unit costs to around $5,500, and significantly more than 1,000 should yield per-unit costs down to around $3,500 to $4,500 per unit.

Economies of scale may drive further price reductions in the future with significant world scale and cloud service and SaaS options.

The full range of costs to be considered should include:

- site surveys
- monitoring equipment
- installation
- maintenance
- communication
- database infrastructure
- data management
- project management.

4.1.1.6 Building the business case – benefits

At its simplest, LV monitoring of distribution substations is about asset management and cost efficiency. By monitoring a few representative substations findings, perhaps 10 to 20, the findings can be extrapolated to other substations with similar characteristics or can help target a smaller LV monitoring programme.

There are three methods that could be applied here. The first is to liaise with EDBs that have already done some LV monitoring to seek their assessments of what is achievable in terms of substation cost savings.

The second is to use the rule of thumb of 9.5kVA per substation, on average, saving in capacity. This can be quantified by using the 9.5kVA per substation to assess the percentage reduction in forecast LV costs. It is reasonable to assume that the capacity learnings will also be applied to the LV network generally. It is worth considering doing the LV monitoring to the LV feeder level to ensure this benefit.

The third method is to establish the percentage of forecast saving on LV costs that would be needed to make LV monitoring economic and then qualify why these savings are achievable.

For each of these methods an EDB will need to qualify why these savings are potentially achievable on their network. The case can be made that savings of at least 10 per cent seem achievable, given:

- the bias of connecting single-phase loads to red phase
- the prudent allowance of capacity in the absence of measured capacity and growth trends
- prudent assumptions about power factor.

If higher-specification LV monitoring is added, then there are benefits related to customer experience, DER hosting and possibly safety.

By analysing for any underlying problems, LV monitoring creates the potential to identify faults before they cause outages. An assessment of LV faults, identifying the percentage of faults that could be avoided through LV monitoring, will give an indication of what impact LV monitoring could have on outages for customers.

This probably cannot be added to the quantified benefits of LV monitoring for an EDB, as LV is not included in SAIDI and SAIFI statistics, unless operating cost savings can be identified. The full benefit of fault avoidance would also require widespread, dynamic LV monitoring. Nevertheless, the potential for long-run benefit to consumers is useful context for a business case into exploring what underlying issues the LV network might have. The benefit to consumers can be generally quantified by multiplying the expected savings in lost load (roughly estimated by assessing outage time by load – number and type of customer) by the Electricity Authority's published Value of Lost Load (VoLL – around $20,000/MWh).

It is difficult to value the direct benefits to EDBs from using LV monitoring to assess DER hosting capacity, and it could be that there are not any. Nevertheless, EDBs are likely to come under increasing political pressure to permit DER injection and either socialise or absorb any costs incurred in doing so. High-specification LV monitoring will enable a baseline to be established against which the impact of new connections can be empirically demonstrated. This should give EDBs a robust basis on which to apply justified cost-reflective pricing of DER.

While the direct benefits of DER do not accrue to EDBs, there are public benefits and benefits to consumers. It is worth determining these benefits for context in the broader LV monitoring case. An indicative assessment of the gross public benefits can be determined through assessing the installed MWs of DER injection (i.e. solar PV) connected to substations that will be monitored, or analysed as a result of monitoring, and multiplying by $394/kW (Reeve, Comendant, & Stevenson, 2020).

4.1.1.7 Building the business case – management case

It needs to be recognised in the LV monitoring business case that LV monitoring in and of itself does not achieve anything. It is important, then, to lay out at a high level what will be done as a result of an LV monitoring project, which should include how the data will inform future cases for LV monitoring.

EDBs that discover actionable evidence from LV monitoring and look to transition the monitoring from innovation to business as usual will need to reflect the evidence and impact LV monitoring has on asset management. This will need to show a direct link between measured LV data, analysis, modelling, and extrapolation to better decision-making in their network.

4.1.2 LV feeder review or concern

When an LV feeder is being reviewed or there is concern around future capacity or congestion concerns, LV monitoring can assist better decision-making, potentially even concluding that feeder reinforcement is not necessary, or that acting early to increase capacity will be beneficial.

Measuring active, reactive and apparent power per phase will help highlight the actual power loading on the feeder or major branch and how much of the problem may be due to poor power factor or out-of-balance phase loadings.

4.1.2.1 Benefits

The expected benefits of LV monitoring on feeders are reduced expenditure through optimising investment, avoiding faults, failures and urgent replacement, and potentially installing less capacity on average.

There are two factors that can 'use' feeder capacity for no benefit—reactive power and out-of-balance phase loadings.

The reactive power problem is relatively well addressed where out-of-phase current loadings load up circuits and transformers without a commensurate production of useful power. All EDBs have pricing mechanisms and programmes to address power factor. Nevertheless, LV conductor upgrades could be avoided through identifying an achievable improvement in power factor.

The out-of-balance phase loading problem can potentially yield greater benefits. The phase categorising convention is to colour code them red, yellow and blue, with red always being first. Single phase colour coding convention for fixed wiring is red for phase, black for neutral and green for earth. Electrical workers are trained to avoid mixing colours, as the integrity of the neutral and earths is critical for safety. Add to this that colour coding for flexible cords allow the use of blue for neutral, and yellow and green for earth.

This seems like a subtle driver of behaviour, but there is a real bias to connecting single-phase appliances and installations to red phase. This can overload the red phase, potentially leading to failures, even while two-thirds of LV circuit capacity are underutilised. Replacing LV conductors, especially underground, even if planned, can mean sizing it for the red phase load because it is difficult to address a significant out-of-balance problem.

In some cases, loads may be able to be shifted across LV circuits, utilising unused capacity.

Table 7: Planning – LV feeder review or concern

Problem	Measurement Location	DER forecast	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
LV feeder review or concern	LV feeders, and major branches for large feeders	Low take-up forecasted for this feeder	n/a	Five-minute averages 3ϕ & N voltage and current	**Power/reverse power** **Reactive power** **Voltage range** **Phase load balance** **Reconcile 3ϕ & N currents (earth leakage)**	Comms optional, can be manually collected, target peak load periods	AMI profile data helpful
		High take-up possible for this feeder	Similar feeder has been measured and showed little power quality, transient or harmonic interference				
			No comparable baseline or similar feeder shows interference	<0.5ms 3ϕ & N amplitude and phase angle. Summarised data and configurable disturbance recording	As above plus **Power quality (sag/swell/ flicker)** **Transient disturbance** **Harmonics**	Few months of sampling, volume of data probably needs non-real-time data communication	AMI profile and AMI network data helpful
Expected benefits	Reduced expenditure on conductor upgrades. Replacement timing optimised, avoid circuit failure, reduced jointing and less LV network capacity installed on average.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

4.1.2.2 Why LV monitoring?

At the simplest level, either temporary or permanent, LV monitoring of LV feeders will show the level to which the circuits are utilised. For this to be effective the LV feeders needs to be monitored for a reasonable time and definitely over periods of the highest expected loading. Although care needs to be taken over assuming too much prior to monitoring, what might be expected to be the period of heaviest loading may not be the key determinant of the circuit's duty if there is a significant out-of-balance and/or reactive load with an unusual load profile.

A simple monitoring approach can, at least, highlight opportunities to improve the utilisation of the feeders. To determine what to do may then require a follow-up diagnostic process. More advanced approaches, such as determining the LV topology, can then improve future monitoring of circuit loading.

Overseas experience suggests that leveraged benefits result from LV monitoring. The problems identified on one distribution transformer or LV circuit are often then found on transformers and circuits with similar characteristics of load types, number of loads and areas. Monitoring representative LV circuits then leads to the development of targeted monitoring programmes with optimally specified monitoring technology.

4.1.2.3 What LV monitoring equipment to choose?

Prior to determining which equipment to choose, particularly for the first time, it is worth considering the future needs, and the current understanding, of the LV network. Factors to consider are:

- Should the transformer and other circuits on the transformer be monitored rather than just the LV feeder of concern?
- Should any potentially unknown problems be identified?
- Would determining the optimal specification for future monitoring be useful?
- Should the LV network be modelled to assist future analysis?
- What other data is accessible (e.g. AMI data)?
- Does the DER hosting capacity of the LV network need to be assessed?

If little is known of the LV network,

- about the underlying performance of the LV network with respect to power quality,
- future LV monitoring is likely to be pursued,
- the LV network is undergoing rapid change (e.g. growth),
- or there are concerns about the impact of new technology (e.g. EVs, heat pumps, PV solar, batteries, etc.)

then there is a case for deploying the highest specification of LV monitoring device.

Assuming that no previous assessments of LV monitoring specification have been done, the minimum level of LV monitoring for assessing the loading on an LV feeder is at least 30-minute sampling of the voltage, current, reactive and active power on each phase, probably at the transformer connection downstream of the fuses/breakers, but as far upstream of the first load on the circuit as practical. If downstream of the circuit fuses, then LV monitoring will also keep track of circuit outages and, in the case of high-speed monitoring, report the exact event that lead to any fuse/breaker activations.

Thirty minutes is somewhat arbitrary but aligns with the interval revenue metering standard in New Zealand and should be able to be reconciled to consumers' metered peak demand. However, 30 minutes is probably not short enough to derive the actual peak load, so the LV monitoring device should be of the type that records not just the integral over the sampling period but also the maximum and minimum values.

Shorter sampling periods will be more likely to indicate the peak loading per phase or, at least, be more representative of the heating effect in the conductors from the peak load.

As a matter of course the simplest technology will indicate:

- peak power and current and any reverse power
- reactive power and current loading
- the voltage range at the transformer
- phase load balance.

If suitably higher specification LV monitoring is used, then measurement can also indicate:

- earth leakage
- power quality (voltage sag/swell/flicker)
- transient disturbances
- harmonic distortion (including by harmonic to high orders).

These could indicate previously unknown problems and/or establish baselines for assessing DER hosting capacity.

High-speed sampling can also be used to assess the desirable specification for future LV monitoring, by:

- integrating the high-definition data into different periods (e.g. one minute, five minutes, 15 minutes, 30 minutes)
- analysing interpolation techniques to derive the phase loadings from the integrated data
- comparing the derived loadings to the high-definition data.

This allows the selection of the best sampling period, being the desired balance between accuracy and amount of data.

Alternatively, the heating effect of high-definition data over different periods can be compared to the averaged heating effect of each period, i.e. the average of the square of high-definition current over the period being analysed compared to the average of current squared. The desired level of accuracy can then be selected where the sampling period values are representative of the heat loading of the conductors.

It could be that different sampling specifications might be needed for different LV feeder characteristics (e.g. type of customer, number of connections and area).

A final thing that can be done is to determine the LV topology for the LV feeder. This becomes impracticable for circuits with a large number of connections or where there is a lack of practical monitoring points, as you need close to an LV monitor per connection. However, this is practical with access to AMI profile data.

Some LV monitoring can do this automatically if it has real-time direct communication with the smart meters on the substation. However, it should also be possible to do this with advanced analytical techniques and a large enough historical set of data, even with different sampling rates.

Determining the LV topology means determining which phase or phases a customer is connected to and on what circuit and/or circuit branch. It can possibly also determine the relative distance from the substation for each connection. If analysis can solve the LV topology problem, then a quite accurate model can be developed for circuit loading which can also:

- assess LV losses (technical and potentially non-technical)
- identify connections that may not actually be on that substation
- identify that connections are missing from the data
- compensate for any missing AMI data.

Although, if too much data is missing or wrong, the LV topology problem will not be able to be solved.

AN LV topology model can track LV feeder loading potentially only using AMI profile data. It can also be used to predict circuit loading for different assumptions of customer demand.

4.1.2.4 Communication and data storage

At the lowest level of specification, the data requirements for LV monitoring for feeder capacity are not high, although the volume of data can add up if a number of transformers or feeders are monitored. A year's worth of 30-minute data containing average, minimum and maximum values for each of voltage, current, power and reactive power for each phase is a text file of about 6MB in size. However, the volume of data increases dramatically for high-resolution data.

For temporary applications, communications are not necessary. LV monitoring devices can usually store data for at least a couple of months and the data can be manually downloaded by USB, Bluetooth and/or WiFi at least. Most LV monitoring devices also support a number of network communication interfaces and the selection will be driven by availability and cost.

Data storage and access should be considered before LV monitoring begins. Most vendors of LV monitoring (if the device(s) have an internet connection) offer webservices and cloud storage, which is a good starting option, at least. The direction of travel may well be towards cloud services and SaaS.

It may be a good idea to archive a certain amount of current data for more detailed analysis, but processed long-term data can potentially be stored more efficiently. For example, a statistical summary of aggregate and per phase loading per week, or even per month, would be an efficient way of storing useful data for managing substation capacity.

Alternatively, the data could be processed in an event-driven database, which records the values and timestamps data when it crosses predetermined thresholds (such as a certain amount of change). This can be a very data-efficient way of storing data where the profile over time is still recorded to a desired level of accuracy.

4.1.2.5 Building the business case – cost

There are significant economies of scale in deploying LV monitoring technology, and costs are expected to fall dramatically over time as LV monitoring gets deployed widely around the world. Recent international examples indicate the total cost for less than 100 monitoring devices is expected to be around $11,000 per device for a high-specification device. Recent New Zealand examples indicate the costs of around $7,500 per high-specification device, so if the business case for monitoring stacks up at these prices the case looks strong. Costs will be less for lower specification and if data is collected manually. Deploying up to 1,000 devices should reduce per-unit costs to around $5,500, and significantly more than 1,000 should yield per-unit costs down to around $3,500 to $4,500 per unit.

Economies of scale may drive further price reductions in the future with significant world scale and cloud service and SaaS options.

The full range of costs to be considered should include:

- site surveys
- monitoring equipment
- installation
- maintenance
- communication
- database infrastructure
- data management
- project management.

4.1.2.6 Building the business case – benefits

At its simplest, LV monitoring of LV feeders is about asset management and cost efficiency. By monitoring a few representative circuits, perhaps 10 to 20, the findings can be extrapolated to other circuits with similar characteristics or help target a smaller LV monitoring programme, although this may be best done by comparing all circuits of the representative substation.

There are three methods that could be applied here. The first is to liaise with EDBs that have already done some LV monitoring to seek their assessments of what is achievable in terms of LV network cost savings.

The second is to use the rule of thumb of 9.5kVA per substation, on average, saving in capacity with the proportional savings in the LV network. This can be quantified by using the 9.5kVA per substation to assess the percentage reduction in forecast LV costs. It is reasonable to assume that the capacity learnings will also be applied to the LV network generally. It is worth considering doing the LV monitoring of all LV circuits on representative distribution substations to ensure this benefit.

The third method is to establish the percentage of forecast saving on LV costs that would be needed to make LV monitoring economic and then qualify why these savings are achievable.

For each of these methods an EDB will need to qualify why these savings are potentially achievable on their network. The case can be made that savings of at least 10 per cent seem achievable, given:

- the bias of connecting single-phase loads to red phase
- the prudent allowance of capacity in the absence of measured capacity and growth trends
- prudent assumptions about power factor.

If higher-specification LV monitoring is added, then benefits relate to customer experience, DER hosting and possibly safety.

By analysing for any underlying problems, LV monitoring creates the potential to identify faults before they cause outages. An assessment of LV faults identifying the percentage of faults that could be avoided through LV monitoring will give an indication of what impact LV monitoring could have on outages for customers.

This probably cannot be added to the quantified benefits of LV monitoring for an EDB, as LV is not included in SAIDI and SAIFI statistics, unless operating cost savings can be identified. The full benefit of fault avoidance would also require widespread, dynamic LV monitoring. Nevertheless, the potential for long-run benefit to consumers is useful context for a business case into exploring what underlying issues the LV network might have. The benefit to consumers can be generally quantified by multiplying the expected savings in lost load (roughly estimated by assessing outage time by load – number and type of customer) by the Electricity Authority's published Value of Lost Load (VoLL – around $20,000/MWh).

It is difficult to value the direct benefits to EDBs from using LV monitoring to assess DER hosting capacity, and it could be that there are not any. Nevertheless, EDBs are likely to come under increasing political pressure to permit DER injection and either socialise or absorb any costs incurred in doing so. High-specification LV monitoring will enable a baseline to be established against which the impact of new connections can be empirically demonstrated. This should give EDBs a robust basis on which to apply justified cost-reflective pricing of DER.

While the direct benefits of DER do not accrue to EDBs, there are public benefits and benefits to consumers. It is worth determining these benefits for context in the broader LV monitoring case. An indicative assessment of the gross public benefits can be determined through assessing the installed MWs of DER injection (i.e. solar PV) connected to substations that will be monitored, or analysed as a result of monitoring, and multiplying by $394/kW (Reeve, Comendant, & Stevenson, 2020).

4.1.2.7 Building the business case – management case

It needs to be recognised in the LV monitoring business case that LV monitoring, in and of itself, does not achieve anything. It is important, then, to lay out at a high level what will be done as a result of an LV monitoring project, which should include how the data will inform future cases for LV monitoring.

EDBs that discover actionable evidence from LV monitoring and look to transition the monitoring from innovation to business as usual will need to reflect the evidence and impact LV monitoring has on asset management. This will need to show a direct link between measured LV data, analysis, modelling and extrapolation to better decision-making in their network.

4.1.3 Difficult discrimination problem or concern and/or protection maloperation

Generally, you would expect LV monitoring to lead to much quicker resolution of protection problems, not just in identifying the problem but also by informing protection reconfiguration and/or settings. LV monitoring could also show that protection is appropriate and there is an unanticipated network problem.

4.1.3.1 Benefits

Generally, the benefit from protection problems by LV monitoring is reduced customer interruption. However, in the worst case, there is a chance of reducing the risk of harm to people and property.

The potential problems, and therefore the benefits, increase when there are generating sources within the LV network, such as PV solar and batteries.

Table 8: Planning – Difficult discrimination problem or concern and/or protection maloperation

Problem	Measurement Location	DER forecast	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Difficult discrimination problem or concern and/or protection maloperation	As near as practical to devices of concern or maloperation	n/a	n/a	<0.5ms 3ϕ & N & E amplitude and phase angle. Summarised data and configurable disturbance recording	**Power/ reverse power** **Reactive power** **Voltage range** **Phase load balance** **Reconcile 3ϕ & N currents (earth leakage)** **Power quality (sag/swell/ flicker)** **Transient disturbance** **Harmonics**	Few months of sampling, volume of data probably needs non-real-time data communication	AMI profile and AMI network data helpful
Expected benefits	Reduced customer outages and, in the worst cases, improved safety.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

4.1.3.2 Why LV monitoring?

High-specification LV monitoring can monitor the events that cause protection operations or maloperations. The voltage and current waveforms can be directly assessed against the operating characteristics of the protection devices. Once events are recorded, the data should very quickly determine whether protection operates correctly or not or whether there are unexpected loads or faults on the LV network.

4.1.3.3 What LV monitoring equipment to choose?

Potentially, some problems, such as an issue with discrimination, could be assessed with lower-specification LV monitoring. However, as faults are relatively rare, and the specific fault that has caused concerns could be even rarer, it is advisable to use high-specification LV monitoring so that there is the best chance of diagnosing any problems when there has only been one event. Measuring underlying LV performance may also be helpful; for example, identifying harmonic interference that might cause protection problems.

A sampling rate of 0.5ms is fast enough to derive harmonics to the 10th order and should be able to give good detail of transient events. LV monitoring equipment that is even faster is readily available. In the most complex problems, as much detail as possible about transient events could be helpful. Even though it can be derived, for protection problems it is worth considering measuring earth currents directly, where applicable, and where extra measuring channels are available on the LV monitoring equipment. High-specification equipment should also have onboard analytical tools, such as event plots, harmonic breakdowns, and phasor diagrams. Having these on-board tools can be useful for on-site diagnostics.

Ideally, LV monitoring should be installed as close as possible to the protection devices being investigated so that the actual events that are affecting the protection are being measured as accurately as possible. Any solar or battery inverters should also be monitored. Non-linear characteristics of an inverter, or the impact of a single-phase generating source on asymmetric faults, could contribute to protection problems. It is also possible that inverters absorb and limit transients preventing or slowing protection operation.

As a matter of course, high-specification technology will indicate:

- peak power and current and any reverse power
- reactive power and current loading
- the voltage range at the transformer
- phase load balance
- earth leakage
- power quality (voltage sag/swell/flicker)
- transient disturbances
- harmonic distortion (including by harmonic to high orders).

In addition to diagnosing and assessing protection operation, measuring these characteristics could also indicate previously unknown problems and/or establish baselines for assessing DER hosting capacity.

Another thing that can be done is to determine the LV topology for the LV feeder, or even an approximate electrical model. High-specification LV monitoring should enable the electrical characteristics of lines between monitoring points to be calculated to a reasonable level of accuracy.

Even assessing LV topology becomes impracticable for circuits with a large number of connections or where there is a lack of practical monitoring points, as you need close to an LV monitor per connection. However, this is practical with access to AMI profile data.

Some LV monitoring can determine LV topology automatically if it has real-time direct communication with the smart meters on the substation. However, it should also be possible to do this with advanced analytical techniques and a large enough historical set of data, even with different sampling rates.

Determining the LV topology means determining which phase or phases a customer is connected to and on what circuit and/or circuit branch. It can possibly also determine the relative distance from the substation for each connection. If analysis can solve the LV topology problem, then a quite accurate model can be developed for circuit loading which can also:

- assess LV losses (technical and potentially non-technical)
- identify connections that may not actually be on that substation
- identify that connections are missing from the data
- compensate for any missing AMI data.

Although, if too much data is missing, or wrong, the LV topology problem will not be able to be solved.

An LV topology model can track LV feeder loading potentially only using AMI profile data. It can also be used to predict circuit loading for different assumptions of customer demand.

Even a simple electrical model of the feeder should allow modelling of voltage profiles, some power quality and protection performance for different forecasts of LV feeder loading and DER penetration.

4.1.3.4 Communication and data storage

At the highest resolutions of raw LV monitoring, data storage requirements can quickly build up to terabytes. Some form of data compression is necessary for long-term application of LV monitoring. Due to the technical complexity of compressing high-resolution data while preserving high-quality information, it is worth considering the cloud services and SaaS solutions that most suppliers offer.

Even for temporary applications, communications are probably necessary. Some LV monitoring devices may be able to store high-resolution data for a month or two and the data can be manually downloaded by USB, Bluetooth and/or WiFi at least. However, the sheer volume of data probably warrants more frequent download, and for analysing protection it is advisable to have alarms for events. Most LV monitoring devices also support a number of network communication interfaces and the selection will be driven by availability, bandwidth and cost.

Data storage and access should be considered before LV monitoring begins. Most vendors of LV monitoring (if the device(s) have an internet connection) offer webservices and cloud storage, which is an option that should be considered for high-resolution data. The direction of travel for high-resolution data seems to be towards cloud services and SaaS.

It is a good idea to archive raw event data around protection events and faults. This data is a small subset of total data and allows for future analysis of events and faults that can potentially be extrapolated to predictive tools for other LV feeders.

Probably the best way of compressing high-resolution data is by a combination of metadata and event-driven storage. Data can be processed in an event-driven database, which records the values and timestamps data when it crosses predetermined thresholds (such as a certain amount of change). This can be a very data-efficient way of storing data where the profile over time is still recorded to a desired level of accuracy. Metadata can be an efficient way of storing high-resolution information in combination with an event-driven database. For example, defining harmonic voltage and currents in terms of amplitude and phase angle, and describing asymmetric voltages and currents in terms of positive, negative and zero phase sequences, when they change by a certain amount and/or when they exceed a certain level.

4.1.3.5 Building the business case – cost

At its simplest level LV monitoring to identify known protection/discrimination problems is more diagnostic. However, there may be reason to deploy LV monitoring more widely to assess protection and discrimination requirements under changing conditions, such as increasing asymmetry of loading in LV circuits or deployment of solar PV and batteries.

There are significant economies of scale in deploying LV monitoring technology, and costs are expected to fall dramatically over time as LV monitoring gets deployed widely around the world. Recent international examples indicate the total cost for less than 100 monitoring devices is expected to be around $11,000 per device for a high-specification device. Recent New Zealand examples indicate the costs of around $7,500 per high-specification device so if the business case for monitoring stacks up at these prices the case looks strong. Costs will be less for lower specification and if data is collected manually. Deploying up to 1,000 devices should reduce per-unit costs to around $5,500, and significantly more than 1,000 should yield per-unit costs down to around $3,500 to $4,500 per unit.

Economies of scale may drive further price reductions in the future with significant world scale and cloud service and SaaS options.

The full range of costs to be considered should include:

- site surveys
- monitoring equipment
- installation
- maintenance
- communication
- database infrastructure
- data management
- project management.

4.1.3.6 Building the business case – benefits

Getting protection and discrimination working correctly is fundamentally about safety and minimising outages. Safety is, obviously, extremely important and should generally be met in the normal case. Therefore, in the normal case, the primary benefit from LV monitoring arises due to getting discrimination correct, ensuring that no more customers are de-energised than need to be to clear a fault without spending money needlessly. In the absence of LV monitoring network planners will need to be conservative and reconfigure protection settings when it may not necessary.

There can be a strong relationship between discrimination problems and managing LV feeder capacity generally. For example, if there is significant out-of-balance loading (say on red phase), then this can lead to protection acting upstream of protection that should have activated even though the generally configuration would have been correct for balanced load.

In the case where significant levels of DER installation start to inject into an LV circuit, the combination of reverse power, inverter impacts on fault current, and possibly harmonics, might call into question the correct and safe operation of protection.

By monitoring a few representative circuits, perhaps 10 to 20, the key problems for both protection and discrimination can be anticipated for other circuits with similar characteristics. However, where problems are anticipated based on previous LV monitoring, LV monitoring of the circuit in question is probably still required.

There are three methods that could be applied to valuing the benefit of LV monitoring to planning protection and discrimination. The first is to liaise with EDBs that have already done some LV monitoring to seek their assessments of protection and discrimination issues that have been discovered.

The second is to assess the costs of reconfiguring protection of LV feeders and assume that 10 per cent to 20 per cent of the costs could be saved through being able to measure the feeder loads rather than conservatively estimating them.

The third method is to establish the percentage of forecast saving on LV costs that would be needed to make LV monitoring economic and then qualify why these savings are achievable. As per the method above, the percentage required can be compared to a judgement of the level of conservatism in engineering estimates.

In the case where high levels of DER might influence the operation of protection equipment, there is a real benefit to safety from LV monitoring. With measurement, any problems can be expected to be resolved quicker and potentially without any maloperations. Again, other EDBs that have experience with LV monitoring in this context could be helpful. Otherwise, the EDB's approach to valuing health and safety can be used to assess the value of avoiding a maloperation of protection. Then the required number of maloperations to make the economic case for LV monitoring can be qualified. In the case where the effects of two-way flows and the performance of inverters are unknown in the context of the LV network, it is likely that, at least, one or two maloperations of protection could be avoided.

If higher-specification LV monitoring is added, then benefits relate to customer experience, DER hosting and possibly safety.

By analysing for any underlying problems, LV monitoring creates the potential to identify faults before they cause outages. An assessment of LV faults, identifying the percentage of faults that could be avoided through LV monitoring, will give an indication of what impact LV monitoring could have on outages for customers.

This probably cannot be added to the quantified benefits of LV monitoring for an EDB, as LV is not included in SAIDI and SAIFI statistics, unless operating cost savings can be identified. The full benefit of fault avoidance would also require widespread, dynamic LV monitoring. Nevertheless, the potential for long-run benefit to consumers is useful context for a business case into exploring what underlying issues the LV network might have. The benefit to consumers can be generally quantified by multiplying the expected savings in lost load (roughly estimated by assessing outage time by load – number and type of customer) by the Electricity Authority's published Value of Lost Load (VoLL – around $20,000/MWh).

It is difficult to value the direct benefits to EDBs from using LV monitoring to assess DER hosting capacity, and it could be that there are not any. Nevertheless, EDBs are likely to come under increasing political pressure to permit DER injection and either socialise or absorb any costs incurred in doing so. High-specification LV monitoring will enable a baseline to be established against which the impact of new connections can be empirically demonstrated. This should give EDBs a robust basis on which to apply justified cost-reflective pricing of DER.

While the direct benefits of DER do not accrue to EDBs, there are public benefits and benefits to consumers. It is worth determining these benefits for context in the broader LV monitoring case. An indicative assessment of the gross public benefits can be determined through assessing the installed MWs of DER injection (i.e. solar PV) connected to substations that will be monitored, or analysed as a result of monitoring, and multiplying by $394/kW.

4.1.3.7 Building the business case – management case

It needs to be recognised in the LV monitoring business case that LV monitoring in and of itself does not achieve anything. It is important, then, to lay out at a high level what will be done as a result of an LV monitoring project, which should include how the data will inform future cases for LV monitoring.

EDBs that discover actionable evidence from LV monitoring and look to transition the monitoring from innovation to business as usual will need to reflect the evidence and impact LV monitoring has on asset management. This will need to show a direct link between measured LV data, analysis, modelling, and extrapolation to better decision-making in their network.

4.2 Customer Experience

4.2.1 Voltage or power quality complaint

Voltage can swing between the limits when electricity demand fluctuates. Greater demand causes voltage to drop, following which various items of network equipment, including transformer tap-changers and voltage regulators, will operate to maintain voltage levels. This variation will be more pronounced in rural areas due to the greater impedance of relatively longer lines and may be particularly noticeable by customers near the edge of the network.

When line impedances are relatively high, voltage can fluctuate quickly for fast-changing loads. For customers, this can result in a high nuisance value, for example, through visible short-term changes in lighting, or even flickering lights, through to maloperation of devices and appliances. However, the problem is not necessarily the line impedance. Sometimes customers connect large loads that are poorly designed or bypass elements of the control system, such as soft-starters.

LV monitoring can help determine the explicit sources of voltage and current fluctuation and allow network engineers to balance the cost of LV feeder reinforcement with what customers can reasonably expect to be permitted to connect to an LV supply, to alternative solutions such as power line conditioners or even some DER capability.

Using AMI data should also help reduce the time to establish the causes of voltage and power quality problems. Any data available from DER (solar or battery inverters) will also help, especially for high voltage concerns.

Internationally, there is an expectation that power quality monitoring is expanding from a means to investigate customer complaints to an integral part of power system performance assessments.

4.2.1.1 Benefits

It is not uncommon for voltage and power quality problems to be intermittent in nature or to manifest during non-business hours. LV monitoring can improve customers' service by picking up intermittent problems and/or short-duration voltage exceedances with enough data to diagnose the issue. LV monitoring can also save costs by avoiding the need to repeatedly send staff to investigate problems, which may often be at inconvenient times.

Table 9: Customer experience – Voltage or power quality complaint

Problem	Measurement Location	DER forecast	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Voltage or power quality complaint	LV feeder and near customer (unless AMI network data available)	Low take-up forecasted for this feeder	n/a	≤1 sec 3ϕ & N voltage and current	**Power/ reverse power** **Reactive power** **Voltage range** **Phase load balance (on feeder only)** **Reconcile 3ϕ & N currents (earth leakage) on feeder only** **Power quality (sag/swell/ flicker)**	Few months of sampling, volume of data probably needs non-real-time data communication	AMI profile and AMI network data helpful
		High take-up possible for this feeder	Similar feeder has been measured and showed little transient or harmonic interference				
			No comparable baseline, or similar feeder shows interference	On feeder only <0.5ms 3ϕ & N amplitude and phase angle. Summarised data	As above plus **Transient disturbance** **Harmonics** LV feeder model		
Expected benefits	Improved customer service through picking up intermittent problems or short-duration events. Reduced costs through less repeated visits to investigate problems.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

4.2.1.2 Why LV monitoring?

Medium-specification LV monitoring can monitor voltage and power quality events. The LV monitoring equipment can be configured to highlight events where voltage exceeds prescribed levels or meets a definition of sag, swell or flicker. Events can be alarmed or logged, and event recorders can offer an efficient way of storing data where the entire series of medium-resolution data does not need to be stored.

4.2.1.3 What LV monitoring equipment to choose?

Lower-specification equipment can be used to analyse whether voltage is within designed ranges. Thirty-minute samples with average, minimum and maximum values are all that is required to ascertain whether voltage is within range. However, such low-resolution data may not assist in determining the factors that are affecting voltage.

To assess power quality concerns (not including harmonics or transients), a sampling time of one second is advisable. This sampling time will pick up the voltage and current fluctuations that cause sag, swell and flicker events.

If, in addition to assessing power quality,

- future LV monitoring is likely to be pursued,
- the LV network is undergoing rapid change (e.g. growth),
- or there are concerns about the impact of new technology (e.g. EVs, heat pumps, PV solar, batteries, etc.)

then there is a case for deploying the highest specification of LV monitoring device, i.e. a sampling rate of <0.5ms.

Ideally, LV monitoring should be installed near the location of the identified voltage or power quality problem. If the problem is at a customer's premises and loads at those premises are suspected of contributing to the problem, then monitoring should be done on the customer's service line. Otherwise, the LV monitoring should be installed on the main LV circuit near the premises, which will help identify if any loads contributing to the problem are upstream and/or downstream of the initial location. The main LV circuit near the distribution substation should also be monitored. An estimate of the line impedance will assist analysis of the voltage or power quality problem. If there is a high voltage issue, then any solar or battery inverters should also be monitored.

As a matter of course, medium-specification technology will indicate:

- peak power and current and any reverse power
- reactive power and current loading
- the voltage range at the transformer
- phase load balance
- earth leakage
- power quality (voltage sag/swell/flicker).

High-specification LV monitoring can also measure:

- transient disturbances
- harmonic distortion (including by harmonic to high orders).

In addition to identifying and assisting diagnose voltage and power quality problems, measuring these characteristics could also indicate previously unknown problems and/or establish baselines for assessing DER hosting capacity.

Another thing that can be done is to determine the LV topology for the LV feeder, or even an approximate electrical model. High-specification LV monitoring should enable the electrical characteristics of lines between monitoring points to be calculated to a reasonable level of accuracy.

Even assessing LV topology becomes impracticable for circuits with a large number of connections or where there is a lack of practical monitoring points, as you need close to an LV monitor per connection. However, this is practical with access to AMI profile data.

Some LV monitoring can determine LV topology automatically if it has real-time direct communication with the smart meters on the substation. However, it should also be possible to do this with advanced analytical techniques and a large enough historical set of data, even with different sampling rates.

Determining the LV topology means determining which phase or phases a customer is connected to and on what circuit and/or circuit branch. It can possibly also determine the relative distance from the substation for each connection. If analysis can solve the LV topology problem, then a quite accurate model can be developed for circuit loading which can also:

- assess LV losses (technical and potentially non-technical)
- identify connections that may not actually be on that substation
- identify that connections are missing from the data
- compensate for any missing AMI data.

However, if too much data is missing or wrong, the LV topology problem will not be able to be solved.

An LV topology model can track LV feeder loading potentially only using AMI profile data. It can also be used to predict circuit loading for different assumptions of customer demand.

Even a simple electrical model of the feeder should allow modelling of voltage profiles, some power quality and protection performance for different forecasts of LV feeder loading and DER penetration.

4.2.1.4 Communication and data storage

Medium resolutions of raw LV monitoring data storage requirements can quickly build up to significant, but manageable, levels of data storage, although this does depend on how many points in the LV network are monitored. A year's worth of medium-resolution data for one monitor is in the order of 10GB of data. Some form of data compression is necessary for the long-term application of high-resolution LV monitoring. Due to the technical complexity of compressing high-resolution data while preserving high-quality information, it is worth considering the cloud services and SaaS solutions that most suppliers offer.

For temporary applications, communications are not necessary. Some LV monitoring devices will be able to store medium-resolution data for months and the data can be manually downloaded by USB, Bluetooth and/or WiFi at least. For longer-term applications or if alarms are to be set up, then most LV monitoring devices also support a number of network communication interfaces and the selection will be driven by availability, bandwidth and cost.

Data storage and access should be considered before LV monitoring begins. Most vendors of LV monitoring (if the device(s) have an internet connection) offer webservices and cloud storage, which is an option that should be considered for high-resolution data. The direction of travel for high-resolution data seems to be towards cloud services and SaaS.

It is a good idea to archive raw data at least until any voltage or power quality problems are resolved. After this, data can be compressed and information about voltage levels and power quality events can be described statistically. This data is a small subset of total data and allows for future analysis of events and faults that can potentially be extrapolated to predictive tools for other LV feeders.

Voltage and power quality data can be described in terms of distributions of levels or histograms of events, while profile data can be held in a compressed form. Data can be processed in an event-driven database that records the values and timestamps data when it crosses predetermined thresholds (such as a certain amount of change). This can be a very data-efficient way of storing data where the profile over time is still recorded to a desired level of accuracy.

4.2.1.5 Building the business case – cost

At its simplest level, LV monitoring to identify known protection/discrimination problems is more diagnostic. However, there may be reason to deploy LV monitoring more widely to assess protection and discrimination requirements under changing conditions, such as increasing asymmetry of loading in LV circuits or deployment of solar PV and batteries.

There are significant economies of scale in deploying LV monitoring technology, and costs are expected to fall dramatically over time as LV monitoring gets deployed widely around the world. Recent international examples indicate the total cost for less than 100 monitoring devices is expected to be around $11,000 per device for a high-specification device. Recent New Zealand examples indicate the costs of around $7,500 per high-specification device so if the business case for monitoring stacks up at these prices the case looks strong. Costs will be less for lower specification and if data is collected manually. Deploying up to 1,000 devices should reduce per-unit costs to around $5,500, and significantly more than 1,000 should yield per-unit costs down to around $3,500 to $4,500 per unit.

Economies of scale may drive further price reductions in the future with significant world scale and cloud service and SaaS options.

The full range of costs to be considered should include:

- site surveys
- monitoring equipment
- installation
- maintenance
- communication
- database infrastructure

- data management
- project management.

4.2.1.6 Building the business case – benefits

The benefits from LV monitoring for voltage and power quality problems are a mixture of customer service and reduced costs. LV monitoring can reduce time spent trying to detect issues and can result in more cost-effective solutions. In the worst case, where voltage problems are undiagnosed, the final solution may be the installation of a new distribution substation. Intermittent power quality problems may result in consumers 'self-medicating', i.e. purchasing their own power line conditioning or Uninterruptible Power Supplies (UPS). In many cases this may be a cost-effective solution, but it would improve the image of the EDB if it played an active role in assisting a customer with the solution. An EDB may also require a customer to upgrade their service line, which may not have been the most cost-effective solution, or, even worse, may not end up fixing the problem.

By monitoring a few representative circuits, perhaps 10 to 20, the key problems for voltage and power quality can possibly be anticipated for other circuits with similar characteristics. However, where problems are anticipated based on previous LV monitoring, LV monitoring of the circuit in question will still be required.

There are two methods that could be applied to valuing the benefit of LV monitoring for assessing voltage and power quality issues. The first is to liaise with EDBs that have already done some LV monitoring to seek their assessments of voltage and power quality issues that have been discovered.

The second is to estimate the costs of attending to voltage and power quality issues, which might include:

- responding to customer complaints
- investigating issues
- new or upgraded distribution substations
- new or upgraded LV lines, or upgrades to high-voltage lines.

The percentage of savings that would justify the cost of LV monitoring can then be qualified. Savings of 10 per cent to 20 per cent should be relatively easily achievable, given the inefficiency of applying assumed solutions to undiagnosed problems. Even higher percentages could be considered reasonable, especially if there are examples of problems continuing after solutions have been deployed.

If the financial case is still marginal, then it is also worth considering customer impacts. While EDBs do not directly benefit from improving customers' service on the LV network, this is compelling context. The private cost to customers from upgrading service lines for suspected voltage problems can be added to the financial case for context. However, if customers respond to a voltage or power quality problem, then they have incurred part of the economic loss from a supply interruption. Where customers are known to have responded to a voltage or power quality problem – e.g. through raising a complaint – then this can be considered equivalent to a 10-minute power outage at the Authority's VoLL. This will be approximately $3 per customer event, and it may be reasonable to assume that others on the same substation have similar losses.

If higher-specification LV monitoring is used, then benefits related to customer experience, DER hosting and possibly safety could also be achieved.

By analysing for any underlying problems, LV monitoring creates the potential to identify faults before they cause outages. An assessment of LV faults, identifying the percentage of faults that could be avoided through LV monitoring, will give an indication of what impact LV monitoring could have on outages for customers.

This probably cannot be added to the quantified benefits of LV monitoring for an EDB, as LV is not included in SAIDI and SAIFI statistics, unless operating cost savings can be identified. The full benefit of fault avoidance would also require widespread, dynamic LV monitoring. Nevertheless, the potential for long-run benefit to consumers is useful context for a business case into exploring what underlying issues the LV network might have. The benefit to consumers can be generally quantified by multiplying the expected savings in lost load (roughly estimated by assessing outage time by load – number and type of customer) by the Electricity Authority's published Value of Lost Load (VoLL – around $20,000/MWh).

It is difficult to value the direct benefits to EDBs from using LV monitoring to assess DER hosting capacity, and it could be that there are not any. Nevertheless, EDBs are likely to come under increasing political pressure to permit DER injection and either socialise or absorb any costs incurred in doing so. High-specification LV monitoring will enable a baseline to be established against which the impact of new connections can be empirically demonstrated. This should give EDBs a robust basis on which to apply justified cost-reflective pricing of DER.

While the direct benefits of DER do not accrue to EDBs, there are public benefits and benefits to consumers. It is worth determining these benefits for context in the broader LV monitoring case. An indicative assessment of the gross public benefits can be determined through assessing the installed MWs of DER injection (i.e. solar PV) connected to substations that will be monitored, or analysed as a result of monitoring, and multiplying by $394/kW.

4.2.1.7 Building the business case – management case

It needs to be recognised in the LV monitoring business case that LV monitoring, in and of itself, does not achieve anything. It is important, then, to lay out at a high level what will be done as a result of an LV monitoring project, which should include how the data will inform future cases for LV monitoring.

EDBs that discover actionable evidence from LV monitoring and look to transition the monitoring from innovation to business as usual will need to reflect the evidence and impact LV monitoring has on asset management. This will need to show a direct link between measured LV data, analysis, modelling, and extrapolation to better decision-making in their network.

4.2.2 Unknown intermittent faults

Unknown intermittent faults can be quite harmless, apart from their inconvenience factor to customers and costs to attend to, or indicators of larger problems. Often unknown faults are one-off faults probably caused by lightning, birds, animals or vegetation. When unknown faults recur, this can be a problem that will steadily get worse.

There is a large range of potential causes for unknown faults, and so the use of LV monitoring to ascertain if there is an underlying problem will generally need to measure everything.

AMI data and data from any distributed generation, solar or battery inverters may also help diagnose unknown intermittent problems.

4.2.3 Benefit

The benefit of using LV monitoring to investigate unknown faults is the potential to avoid costly catastrophic failures and reduce the number of outages for customers. Faults can be identified before they become catastrophic or cause more outages.

Table 10: Customer experience – Unknown intermittent faults

Problem	Measurement Location	DER forecast	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Unknown intermittent faults	LV feeder and on any major circuit branches	n/a	n/a	<0.5ms 3ϕ & N amplitude and phase angle. Summarised data and configurable disturbance recording	**Power/ reverse power** **Reactive power** **Voltage range** **Phase load balance** **Reconcile 3ϕ & N currents (earth leakage)** **Power quality (sag/swell/ flicker)** **Transient disturbance** **Harmonics** LV feeder model	Few months of sampling, volume of data probably needs non-real-time data communication	AMI profile and AMI network data helpful
Expected benefits	Reduced cost of faults and reduced outages for customers.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

4.2.3.1 Why LV monitoring?

High-specification LV monitoring can monitor LV circuits and pick up when unknown faults occur. By collecting high-resolution data, the nature of fault can be determined and a course of diagnosis begun.

4.2.3.2 What LV monitoring equipment to choose?

To investigate unknown faults, it will almost certainly be critical to pick up transient events. It is also possible that harmonic distortion could cause non-linear response in either network or customer equipment that leads to faults. Therefore, high-resolution data is recommended.

A sampling rate of 0.5ms is fast enough to derive harmonics to the 10th order and should be able to give good detail of transient events. LV monitoring equipment that is even faster is readily available. In the most complex problems, as much detail as possible about transient events could be helpful. High-specification equipment should also have onboard analytical tools, such as event plots, harmonic breakdowns and phasor diagrams. Having these on-board tools can be useful for on-site diagnostics.

Ideally, LV monitoring should be installed as close as possible to the protection device or devices that activate for the unknown intermittent fault. Other points on the LV circuit could also be monitored and AMI data will also be useful. However, in the first instance, the purpose of LV monitoring will be to establish the nature of the fault to inform a path of diagnosis.

As a matter of course, high-specification technology will indicate:

- peak power and current and any reverse power
- reactive power and current loading
- the voltage range at the transformer
- phase load balance
- earth leakage
- power quality (voltage sag/swell/flicker)
- transient disturbances
- harmonic distortion (including by harmonic to high orders).

In addition to establishing the underlying nature of unknown intermittent faults, measuring these characteristics can help establish baselines for assessing DER hosting capacity.

Another thing that can be done is to determine the LV topology for the LV feeder, or even an approximate electrical model. High-specification LV monitoring should enable the electrical characteristics of lines between monitoring points to be calculated to a reasonable level of accuracy.

Even assessing LV topology becomes impracticable for circuits with a large number of connections, or where there is a lack of practical monitoring points, as you need close to an LV monitor per connection. However, this is practical with access to AMI profile data.

Some LV monitoring can determine LV topology automatically if it has real-time direct communication with the smart meters on the substation. However, it should also be possible to do this with advanced analytical techniques and a large enough historical set of data, even with different sampling rates.

Determining the LV topology means determining which phase or phases a customer is connected to and on what circuit and/or circuit branch. It can possibly also determine the relative distance from the substation for each connection. If analysis can solve the LV topology problem, then a quite accurate model can be developed for circuit loading which can also:

- assess LV losses (technical and potentially non-technical)
- identify connections that may not actually be on that substation
- identify that connections are missing from the data
- compensate for any missing AMI data.

However, if too much data is missing or wrong, the LV topology problem will not be able to be solved.

An LV topology model can track LV feeder loading potentially only using AMI profile data. It can also be used to predict circuit loading for different assumptions of customer demand.

Even a simple electrical model of the feeder should allow modelling of voltage profiles, some power quality and protection performance for different forecasts of LV feeder loading and DER penetration.

4.2.3.3 Communication and data storage

At the highest resolutions of raw LV monitoring, data storage requirements can quickly build up to terabytes. Some form of data compression is necessary for long-term application of LV monitoring. Due to the technical complexity of compressing high-resolution data while preserving high quality information, it is worth considering the cloud services and SaaS solutions that most suppliers offer.

Even for temporary applications, communications are probably necessary. Some LV monitoring devices may be able to store high-resolution data for a month or two and the data can be manually downloaded by USB, Bluetooth and/or WiFi at least. However, the sheer volume of data probably warrants more frequent download, and for analysing faults it is advisable to have alarms for events. Most LV monitoring devices also support a number of network communication interfaces, and the selection will be driven by availability, bandwidth, and cost.

Data storage and access should be considered before LV monitoring begins. Most vendors of LV monitoring (if the device(s) have an internet connection) offer webservices and cloud storage, which is an option that should be considered for high-resolution data. The direction of travel for high-resolution data seems to be towards cloud services and SaaS.

It is a good idea to archive raw event data around unknown intermittent faults. This data is a small subset of total data and allows for future analysis of events and faults that can potentially be extrapolated to predictive tools for other LV feeders.

Probably the best way of compressing high-resolution data is by a combination of metadata and event-driven storage. Data can be processed in an event-driven database, which records the values and timestamps data when it crosses predetermined thresholds (such as a certain amount of change). This can be a very data-efficient way of storing data where the profile over time is still recorded to a desired level of accuracy. Metadata can be an efficient way of storing high-resolution information in combination with an event-driven database. For example, defining harmonic voltage and currents in terms of amplitude and phase angle, and describing asymmetric voltages and currents in terms of positive, negative and zero phase sequences, when they change by a certain amount and/or when they exceed a certain level.

4.2.3.4 Building the business case – cost

At its simplest level, LV monitoring to identify unknown intermittent faults is more diagnostic. However, there may be reason to deploy LV monitoring more widely to assess fault requirements under changing conditions, such as increasing asymmetry of loading in LV circuits or deployment of solar PV and batteries.

There are significant economies of scale in deploying LV monitoring technology, and costs are expected to fall dramatically over time as LV monitoring gets deployed widely around the world. Recent international examples indicate the total cost for less than 100 monitoring devices is expected to be around $11,000 per device for a high-specification device. Recent New Zealand examples indicate the costs of around $7,500 per high-specification device, so if the business case for monitoring stacks up at these prices the case looks strong. Costs will be less for lower specification and if data is collected manually. Deploying up to 1,000 devices should reduce per-unit costs to around $5,500, and significantly more than 1,000 should yield per-unit costs down to around $3,500 to $4,500 per unit.

Economies of scale may drive further price reductions in the future with significant world scale and cloud service and SaaS options.

The full range of costs to be considered should include:

- site surveys
- monitoring equipment
- installation
- maintenance
- communication
- database infrastructure
- data management
- project management.

4.2.3.5 Building the business case – benefits

The key benefit of LV monitoring is the potential to avoid more expensive failures, especially catastrophic failures that can sometimes occur when unknown intermittent faults get progressively worse. There is also the opportunity to detect faults earlier and prevent customer outages.

There are two methods that could be applied to valuing the benefit of LV monitoring to unknown intermittent faults. The first is to liaise with EDBs that have already done some LV monitoring to seek their assessments of unknown intermittent faults that have been discovered and resolved.

The second is to do a statistical analysis of unknown intermittent faults and the frequency by which such faults eventually lead to costly damage. The probability derived from the frequency assessment applied to the costs incurred from eventual failure can give an expected value of cost savings from applying LV monitoring to unknown intermittent faults.

The same statistical approach can also be applied to assessing the expected duration of outages for customers from ongoing unknown intermittent faults. This can be converted to a value by multiplying the duration by a reasonable assessment of average customer loading and the Electricity Authority's published estimate of VoLL (around $20,000/MWh). EDBs do not directly benefit from reduced outages on the LV network, but the customer benefit is an important context for the business case.

As a matter of course, higher-specification LV monitoring can yield additional benefits related to customer experience, DER hosting and possibly safety.

By analysing for any underlying problems, LV monitoring creates the potential to identify other faults before they cause outages. An assessment of LV faults, identifying the percentage of faults that could be avoided through LV monitoring, will give an indication of what impact LV monitoring could have on outages for customers.

This probably cannot be added to the quantified benefits of LV monitoring for an EDB, as LV is not included in SAIDI and SAIFI statistics, unless operating cost savings can be identified. The full benefit of fault avoidance would also require widespread, dynamic LV monitoring. Nevertheless, the potential for long-run benefit to consumers is useful context for a business case into exploring what underlying issues the LV network might have. The benefit to consumers can be generally quantified by multiplying the expected savings in lost load (roughly estimated by assessing outage time by load – number and type of customer) by the Electricity Authority's published Value of Lost Load (VoLL – around $20,000/MWh).

It is difficult to value the direct benefits to EDBs from using LV monitoring to assess DER hosting capacity, and it could be that there are not any. Nevertheless, EDBs are likely to come under increasing political pressure to permit DER injection and either socialise or absorb any costs incurred in doing so. High-specification LV monitoring will enable a baseline to be established against which the impact of new connections can be empirically demonstrated. This should give EDBs a robust basis on which to apply justified cost-reflective pricing of DER.

While the direct benefits of DER do not accrue to EDBs, there are public benefits and benefits to consumers. It is worth determining these benefits for context in the broader LV monitoring case. An indicative assessment of the gross public benefits can be determined through assessing the installed MWs of DER injection (i.e. solar PV) connected to substations that will be monitored, or analysed as a result of monitoring, and multiplying by $394/kW.

4.2.3.6 Building the business case – management case

It needs to be recognised in the LV monitoring business case that LV monitoring, in and of itself, does not achieve anything. It is important, then, to lay out at a high level what will be done as a result of an LV monitoring project, which should include how the data will inform future cases for LV monitoring.

EDBs that discover actionable evidence from LV monitoring and look to transition the monitoring from innovation to business as usual will need to reflect the evidence and impact LV monitoring has on asset management. This will need to show a direct link between measured LV data, analysis, modelling and extrapolation to better decision-making in their network.

4.2.4 Customer reports sporadic electric shocks

There are a number of faults that can develop in the LV network that can lead to the potential for phase to earth contact. These faults are quite rare but can also be extremely dangerous. These faults are just as likely to occur in a customer's installation or appliances but can also occur in the EDB's network.

Benefits

In the worst case, for an EDB, there could be liability arising from a network fault that causes fire, property damage or injury to people or livestock. However, even if the EDB has no direct liability, there are obvious public benefits from improving the safety of electricity supply.

Table 11: Customer experience – Customer reports sporadic electric shocks

Problem	Measurement Location	DER forecast	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Customer reports sporadic electric shocks	LV feeder and on customer's connection	n/a	n/a	<0.5ms 3ϕ & N amplitude and phase angle. Summarised data and configurable disturbance recording	**Power/ reverse power** **Reactive power** **Voltage range** **Phase load balance** **Reconcile 3ϕ & N currents (earth leakage)** **Power quality (sag/swell/ flicker)** **Transient disturbance** **Harmonics** LV feeder model	Few months of sampling, volume of data probably needs non-real-time data communication	AMI profile and AMI network data helpful
Expected benefit	Reduced injury to people and livestock and reduced property damage.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

4.2.4.1 Why LV monitoring?

High-specification LV monitoring can monitor earth leakage, high neutral or earth impedance and potential rise from neutral to earth. This can quickly ascertain whether there is a fault and the nature of the fault. This may even indicate where the fault is likely to be.

4.2.4.2 What LV monitoring equipment to choose?

Because the nature of an earth fault could be transient, it is ideal to use high-specification LV monitoring, although medium-specification LV monitoring may also be able to pick up earth leakage.

A sampling rate of 0.5ms is fast enough to derive harmonics to the 10^{th} order and should be able to give good detail of transient events. Even though it can be derived, for detecting earth leakage, it is worth measuring earth currents directly, where applicable and where extra measuring channels are available on the LV monitoring equipment. If there are a limited number of channels, then it may be worth using one of the channels to measure the earthing rather than a phase if this can be done. High-specification equipment should also have onboard analytical tools, such as event plots, transient fault analysis and phasor diagrams. Having these on-board tools can be useful for on-site diagnostics.

Ideally, LV monitoring should be installed as close as possible to the area where shocks are reported. LV monitoring on the LV substation would also be warranted to prove that there is no earth leakage if the other monitoring does not detect anything. If earth leakage is detected, then a diagnostic process can be followed. If diagnosis is going to take a while, then the LV monitoring can indicate the benefit of temporary protection to make the situation safer while diagnosis proceeds.

As a matter of course, high-specification technology will indicate:

- peak power and current and any reverse power
- reactive power and current loading
- the voltage range at the transformer
- phase load balance
- earth leakage
- power quality (voltage sag/swell/flicker)
- transient disturbances
- harmonic distortion (including by harmonic to high orders).

In addition to diagnosing and assessing protection operation, measuring these characteristics could also indicate previously unknown problems and/or establish baselines for assessing DER hosting capacity.

Another thing that can be done is to determine the LV topology for the LV feeder, or even an approximate electrical model. High-specification LV monitoring should enable the electrical characteristics of lines between monitoring points to be calculated to a reasonable level of accuracy.

Even assessing LV topology becomes impracticable for circuits with a large number of connections, or where there is a lack of practical monitoring points, as you need close to an LV monitor per connection. However, this is practical with access to AMI profile data.

Some LV monitoring can determine LV topology automatically if it has real-time direct communication with the smart meters on the substation. However, it should also be possible to do this with advanced analytical techniques and a large enough historical set of data, even with different sampling rates.

Determining the LV topology means determining which phase or phases a customer is connected to and on what circuit and/or circuit branch. It can possibly also determine the relative distance from the substation for each connection. If analysis can solve the LV topology problem, then a quite accurate model can be developed for circuit loading which can also:

- assess LV losses (technical and potentially non-technical)
- identify connections that may not actually be on that substation
- identify that connections are missing from the data
- compensate for any missing AMI data.

Although, if too much data is missing, or wrong, the LV topology problem will not be able to be solved.

An LV topology model can track LV feeder loading potentially only using AMI profile data. It can also be used to predict circuit loading for different assumptions of customer demand.

Even a simple electrical model of the feeder should allow modelling of voltage profiles, some power quality and protection performance for different forecasts of LV feeder loading and DER penetration.

4.2.4.3 Communication and data storage

At the highest resolutions of raw LV monitoring, data storage requirements can quickly build up to terabytes. Some form of data compression is necessary for long-term application of LV monitoring. Due to the technical complexity of compressing high-resolution data while preserving high-quality information, it is worth considering the cloud services and SaaS solutions that most suppliers offer.

Even for temporary applications, communications are probably necessary. Some LV monitoring devices may be able to store high-resolution data for a month or two and the data can be manually downloaded by USB, Bluetooth and/or WiFi at least. However, the sheer volume of data probably warrants more frequent download, and for analysing earth leakage faults it is advisable to have alarms for events. Most LV monitoring devices also support a number of network communication interfaces and the selection will be driven by availability, bandwidth and cost.

Data storage and access should be considered before LV monitoring begins. Most vendors of LV monitoring (if the device(s) have an internet connection) offer webservices and cloud storage, which is an option that should be considered for high-resolution data. The direction of travel for high-resolution data seems to be towards cloud services and SaaS.

It is a good idea to archive raw event data around protection events and faults. This data is a small subset of total data and allows for future analysis of events and faults that can potentially be extrapolated to predictive tools for other LV feeders.

Probably the best way of compressing high-resolution data is by a combination of metadata and event-driven storage. Data can be processed in an event-driven database, which records the values and timestamps data when it crosses predetermined thresholds (such as a certain amount of change).

This can be a very data-efficient way of storing data where the profile over time is still recorded to a desired level of accuracy. Metadata can be an efficient way of storing high-resolution information in combination with an event-driven database. For example, defining harmonic voltage and currents in terms of amplitude and phase angle, and describing asymmetric voltages and currents in terms of positive, negative and zero phase sequences, when they change by a certain amount and/or when they exceed a certain level.

4.2.4.4 Building the business case – cost

At its simplest level, LV monitoring to identify phase to earth faults is more diagnostic. However, there may be reason to deploy LV monitoring more widely to assess phase to earth requirements under changing conditions, such as increasing asymmetry of loading in LV circuits or deployment of solar PV and batteries.

There are significant economies of scale in deploying LV monitoring technology, and costs are expected to fall dramatically over time as LV monitoring gets deployed widely around the world. Recent international examples indicate the total cost for less than 100 monitoring devices is expected to be around $11,000 per device for a high-specification device. Recent New Zealand examples indicate the costs of around $7,500 per high-specification device, so if the business case for monitoring stacks up at these prices the case looks strong. Costs will be less for lower specification and if data is collected manually. Deploying up to 1,000 devices should reduce per-unit costs to around $5,500, and significantly more than 1,000 should yield per-unit costs down to around $3,500 to $4,500 per unit.

Economies of scale may drive further price reductions in the future with significant world scale and cloud service and SaaS options.

The full range of costs to be considered should include:

- site surveys
- monitoring equipment
- installation
- maintenance
- communication
- database infrastructure
- data management
- project management.

4.2.4.5 Building the business case – benefits

These kinds of earth faults where there is a risk to safety are rare. WorkSafe accident reports suggest perhaps one of these types of faults per year, which may not even be indicated by preceding electric shocks. However, the consequences of a fault of this type are high.

It could be that the best way of using LV monitoring for improving safety might be as a routine testing programme. It should be feasible to use LV monitoring equipment to replace standard substation earth testing. A programme of using LV monitoring to assess earthing performance over a period of time would yield a more robust earthing test than current methods and has the advantage of also being able to monitor earth leakage. Currently, LV monitoring is probably too expensive to replace substation earth testing but could be a marginal benefit if LV monitoring is being installed for other purposes.

As these kinds of faults are so rare, there is no really reliable method of valuing the benefit. It is probably best to apply the EDB's approach to high-impact, low-probability events. Even then LV monitoring may not be justifiable on any basis but as a public service. However, potentially offsetting some maintenance costs, such as transformer earth testing, can be considered in the case.

If higher-specification LV monitoring is used, then there are further potential benefits related to customer experience, DER hosting and possibly safety.

By analysing for any underlying problems, LV monitoring creates the potential to identify faults before they cause outages. An assessment of LV faults, identifying the percentage of faults that could be avoided through LV monitoring, will give an indication of what impact LV monitoring could have on outages for customers.

This probably cannot be added to the quantified benefits of LV monitoring for an EDB, as LV is not included in SAIDI and SAIFI statistics, unless operating cost savings can be identified. The full benefit of fault avoidance would also require widespread, dynamic LV monitoring. Nevertheless, the potential for long-run benefit to consumers is useful context for a business case into exploring what underlying issues the LV network might have. The benefit to consumers can be generally quantified by multiplying the expected savings in lost load (roughly estimated by assessing outage time by load – number and type of customer) by the Electricity Authority's published Value of Lost Load (VoLL – around $20,000/MWh).

It is difficult to value the direct benefits to EDBs from using LV monitoring to assess DER hosting capacity, and it could be that there are not any. Nevertheless, EDBs are likely to come under increasing political pressure to permit DER injection and either socialise or absorb any costs incurred in doing so. High-specification LV monitoring will enable a baseline to be established against which the impact of new connections can be empirically demonstrated. This should give EDBs a robust basis on which to apply justified cost-reflective pricing of DER.

While the direct benefits of DER do not accrue to EDBs, there are public benefits and benefits to consumers. It is worth determining these benefits for context in the broader LV monitoring case. An indicative assessment of the gross public benefits can be determined through assessing the installed MWs of DER injection (i.e. solar PV) connected to substations that will be monitored, or analysed as a result of monitoring, and multiplying by $394/kW.

If EDBs are expecting high take-up of DER, then it is worth considering LV monitoring early. The data requirements and analysis are greatest for establishing a baseline for DER, and EDBs will need to be cognisant of new challenges that haven't had to be considered before. The learning curve for this shouldn't be underestimated.

4.2.4.6 Building the business case – management case

It needs to be recognised in the LV monitoring business case that LV monitoring, in and of itself, does not achieve anything. It is important, then, to lay out at a high level what will be done as a result of an LV monitoring project, which should include how the data will inform future cases for LV monitoring.

EDBs that discover actionable evidence from LV monitoring and look to transition the monitoring from innovation to business as usual will need to reflect the evidence and impact LV monitoring has on asset management. This will need to show a direct link between measured LV data, analysis, modelling and extrapolation to better decision-making in their network.

4.2.5 Faster fault location and response

Faster fault location cannot be delivered by a simple LV monitoring deployment. It requires the deployment of an LV monitoring system with real-time communications. High-specification LV monitoring is required at key points but can be augmented with lower specification devices, such as line fault indicators and/or other sources of data – i.e. AMI data and DER data – to substantially improve performance.

Automatic sectionalise and reclose functionality can also be added to such LV systems, substantially reducing power restoration times for customers generally.

4.2.5.1 Benefits

The key benefit of using LV fault location and response is reduced customer outage time, but substantial reductions in fault management costs should also be achievable.

Table 12: Customer experience – Faster fault location and response

Problem	Measurement Location	DER history	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Faster fault location and response	Most likely u/g LV feeder, major branches, distributed through customer load clusters (ideally each customer's connection)	If take-up is widespread and haven't had much experience yet with LV monitoring, consider starting with small trials	n/a	<0.5ms 3ϕ & N amplitude and phase angle Central system customisable for multiple purposes. Dynamic LV feeder model assessment Specialised LV monitoring equipment can be used in conjunction, e.g. line fault indicators	**Power/ reverse power** **Reactive power** **Voltage range** **Phase load balance** **Reconcile 3ϕ & N currents (earth leakage)** **Power quality (sag/swell/ flicker)** **Transient disturbance** **Harmonics** LV feeder model LV SAIDI, SAIFI and CAIDI	Permanent high bandwidth for data generally, real-time for alarms	AMI profile and AMI network data greatly improves performance
Expected benefits	Reduced customer outages, reduced fault management costs.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

4.2.5.2 Why LV monitoring?

An LV monitoring system that can integrate many data sources such as medium to high-resolution monitoring devices, line fault indicators, AMI data and DER data can assist with fault management. As AI modelling improves, it is theoretically possible that such a system could pinpoint the location of a fault, both electrically and, potentially, geographically.

In the short term these systems can notify of faults quickly and determine their nature. With the use of line fault indicators, which can indicate whether a fault is upstream or downstream and the nature of the fault, fault locations can be determined down to a section of line.

Such systems can also integrate sectionalisers and reclosers to help restore customers safely while keeping faults isolated.

4.2.5.3 What LV monitoring equipment to choose?

High-resolution LV monitoring devices with real-time communications, at least for alarms, installed on LV circuits at distribution substations can do a lot to notify of faults and the nature of faults. It may also be worth installing LV monitoring on the major branches on key LV feeders. They will also be able to anticipate some faults before they occur where the incidence of transients increases. In conjunction with line fault indicators, the location of faults can also be narrowed down.

In conjunction with AMI data, possibly DER data, and advanced analytical techniques, LV monitoring can determine the LV topology and, increasingly accurately, derive the electrical models of the LV circuits. This should enable increasingly accurate predictions about the exact location and nature of a fault. As there is yet quite a lot that could be done in fault management, it would be worth considering cloud services for the back-end system, or, for a standalone system, a licence that entitles fault management and predictive analytics upgrades.

For the key LV monitoring devices, a sampling rate of 0.5ms is fast enough to derive harmonics to the 10^{th} order and should be able to give good detail of transient events. LV monitoring equipment that is even faster is readily available. In the most complex problems, as much detail as possible about transient events could be helpful. High-specification equipment should also have on-board analytical tools, such as event plots, harmonic breakdowns, and phasor diagrams. Having these on-board tools can be useful for on-site diagnostics.

Ideally, LV monitoring should be installed on the LV feeder at the distribution substation and on any major circuit branches. On large circuits, line fault indicators may also be warranted.

As a matter of course, high-specification technology will indicate:

- peak power and current and any reverse power
- reactive power and current loading
- the voltage range at the transformer
- phase load balance
- earth leakage
- power quality (voltage sag/swell/flicker)
- transient disturbances

- harmonic distortion (including by harmonic to high orders).

In addition to diagnosing and assessing protection operation, measuring these characteristics could also indicate previously unknown problems and/or establish baselines for assessing DER hosting capacity.

Another thing that can be done is to determine the LV topology for the LV feeder, or even an approximate electrical model. High-specification LV monitoring should enable the electrical characteristics of lines between monitoring points to be calculated to a reasonable level of accuracy.

Even assessing LV topology becomes impracticable for circuits with a large number of connections or where there is a lack of practical monitoring points, as you need close to an LV monitor per connection. However, this is practical with access to AMI profile data.

Some LV monitoring can determine LV topology automatically if it has real-time direct communication with the smart meters on the substation. However, it should also be possible to do this with advanced analytical techniques and a large enough historical set of data, even with different sampling rates.

Determining the LV topology means determining which phase or phases a customer is connected to and on what circuit and/or circuit branch. It can possibly also determine the relative distance from the substation for each connection. If analysis can solve the LV topology problem, then a quite accurate model can be developed for circuit loading which can also:

- assess LV losses (technical and potentially non-technical)
- identify connections that may not actually be on that substation
- identify that connections are missing from the data
- compensate for any missing AMI data.

Although, if too much data is missing or wrong, the LV topology problem will not be able to be solved.

An LV topology model can track LV feeder loading potentially only using AMI profile data. It can also be used to predict circuit loading for different assumptions of customer demand.

Even a simple electrical model of the feeder should allow modelling of voltage profiles, some power quality and protection performance for different forecasts of LV feeder loading and DER penetration.

4.2.5.4 Communication and data storage

At the highest resolutions of raw LV monitoring, data storage requirements can quickly build up to terabytes. Some form of data compression is necessary for long-term application of LV monitoring. The technical complexity of compressing high-resolution data while preserving high-quality information is another reason it is worth considering the cloud services and SaaS solutions that most suppliers offer.

For fault management, at least, real-time alarms are required with fast data access. Suitable LV monitoring devices support a number of network communication interfaces, and the selection will be driven by availability, bandwidth and cost.

Data storage and access should be considered before LV monitoring begins. Most vendors of LV monitoring (if the device(s) have an internet connection) offer webservices and cloud storage, which is an option that should be considered for high-resolution data. The direction of travel for high-resolution data seems to be towards cloud services and SaaS.

It is a good idea to archive raw event data around protection events and faults. This data is a small subset of total data and allows for future analysis of events and faults that can potentially be extrapolated to predictive tools for other LV feeders.

Probably the best way of compressing high-resolution data is by a combination of metadata and event-driven storage. Data can be processed in an event-driven database, which records the values and timestamps data when it crosses predetermined thresholds (such as a certain amount of change). This can be a very data-efficient way of storing data where the profile over time is still recorded to a desired level of accuracy. Metadata can be an efficient way of storing high-resolution information in combination with an event-driven database. For example, defining harmonic voltage and currents in terms of amplitude and phase angle, and describing asymmetric voltages and currents in terms of positive, negative and zero phase sequences, when they change by a certain amount and/or when they exceed a certain level.

4.2.5.5 Building the business case – cost

The technology that will be deployed for fault management can measure other aspects of the LV network as well. It is likely that the cost of monitoring one feeder or substation in real-time, especially in the short-term, will make real-time monitoring unlikely to be widely deployed despite economies of scale.

There are significant economies of scale in deploying LV monitoring technology, and costs are expected to fall dramatically over time as LV monitoring gets deployed widely around the world. Recent international examples indicate the total cost for less than 100 monitoring devices is expected to be around $11,000 per device for a high-specification device. Recent New Zealand examples indicate the costs of around $7,500 per high-specification device so if the business case for monitoring stacks up at these prices the case looks strong. Costs will be less for lower specification and if data is collected manually. Deploying up to 1,000 devices should reduce per-unit costs to around $5,500, and significantly more than 1,000 should yield per-unit costs down to around $3,500 to $4,500 per unit.

Economies of scale may drive further price reductions in the future with significant world scale and cloud service and SaaS options.

The full range of costs to be considered should include:

- site surveys
- monitoring equipment
- installation
- maintenance
- communication
- database infrastructure

- data management
- project management.

4.2.5.6 Building the business case – benefits

Fault management is fundamentally about reducing outage times for customers. EDBs should also expect to be able to reduce fault management costs. As LV monitoring for fault management is applied permanently, probably to larger feeders, there may not be much leveraged benefit. It may be by monitoring a few representative circuits, perhaps 10 to 20, some key lessons can be learned for other circuits with similar characteristics.

EDBs do not directly benefit from reducing customer outages. However, the significant positive impact LV monitoring could have on customers is a compelling case for considering the case.

There are three methods that could be applied to valuing the benefit of LV monitoring to fault management. The first is to liaise with EDBs that have already done some LV monitoring to seek their assessments of fault management benefits they have identified.

The second is to do a simple assessment of LV fault outage durations for an average substation and do an assessment of the reduction in duration of expected outages if fault staff were notified immediately of faults, the LV feeder, and a good idea of the nature, and possibly location, of the fault. All outages will need to be assessed because the sample size for individual substations will likely be too small.

Approximate potential cost savings can be assessed by

$$Cost\ savings = \frac{Expected\ outage\ savings}{Current\ LV\ outage\ duration}\ X\ \frac{Monitored\ substation\ capacity}{Total\ substation\ capacity}\ X\ Costs$$

The costs considered should be at least the variable costs of LV fault management. Fixed costs may need to be explicitly considered for whether there would be any cost savings through reduced fault management work.

Customer outage benefits can be assessed by multiplying the duration of minutes estimated to be saved for the substations to be monitored by an estimate of the typical customer loads for those transformers by the Electricity Authority’s published VoLL (around $20,000/MWh).

The third method is to establish the percentage of forecast saving on LV fault management costs that would be needed to make LV monitoring economic and then qualify why these savings are achievable. Significant reductions in at least the variable costs of fault management should be justifiable. The reduction in the value of customer outages can also be considered in this context.

As the LV monitoring will be high-specification, then other benefits related to customer experience, DER hosting and possibly safety should also be realised.

By analysing for any underlying problems, LV monitoring creates the potential to identify faults before they cause outages. An assessment of LV faults, identifying the percentage of faults that could be avoided through LV monitoring, will give an indication of what impact LV monitoring could have on outages for customers.

This probably cannot be added to the quantified benefits of LV monitoring for an EDB, as LV is not included in SAIDI and SAIFI statistics, unless operating cost savings can be identified. The full benefit of fault avoidance would also require widespread, dynamic LV monitoring. Nevertheless, the potential for long-run benefit to consumers is useful context for a business case into exploring what underlying issues the LV network might have. The benefit to consumers can be generally quantified by multiplying the expected savings in lost load (roughly estimated by assessing outage time by load – number and type of customer) by the Electricity Authority's published Value of Lost Load (VoLL – around $20,000/MWh).

It is difficult to value the direct benefits to EDBs from using LV monitoring to assess DER hosting capacity, and it could be that there are not any. Nevertheless, EDBs are likely to come under increasing political pressure to permit DER injection and either socialise or absorb any costs incurred in doing so. High-specification LV monitoring will enable a baseline to be established against which the impact of new connections can be empirically demonstrated. This should give EDBs a robust basis on which to apply justified cost-reflective pricing of DER.

While the direct benefits of DER do not accrue to EDBs, there are public benefits and benefits to consumers. It is worth determining these benefits for context in the broader LV monitoring case. An indicative assessment of the gross public benefits can be determined through assessing the installed MWs of DER injection (i.e. solar PV) connected to substations that will be monitored, or analysed as a result of monitoring, and multiplying by $394/kW. (Reeve, Comendant, & Stevenson, 2020, p. 40).

4.2.5.7 Building the business case – management case

It needs to be recognised in the LV monitoring business case that LV monitoring, in and of itself, does not achieve anything. It is important, then, to lay out at a high level what will be done as a result of an LV monitoring project, which should include how the data will inform future cases for LV monitoring.

EDBs that discover actionable evidence from LV monitoring and look to transition the monitoring from innovation to business as usual will need to reflect the evidence and impact LV monitoring has on asset management. This will need to show a direct link between measured LV data, analysis, modelling and extrapolation to better decision-making in their network.

4.3 DER hosting

4.3.1 Significant take-up of DER loads

Policies and initiatives to decarbonise the economy are expected to significantly increase distribution loads. Fast load growth brings its own challenges, but the nature of the load growth may add to the complexity. It is expected that decarbonisation will focus on the electrification of transport and industrial process heat. However, there will also continue to be an emphasis on efficiency for all loads, as well as a continuing trend of moving to electricity for heating generally. New tenancy rules for landlords may also increase the number and size of heat pumps in the residential housing stock.

Most industry and large commercial heating conversions should be three-phase. However, smaller industrial and commercial conversions may lead to sizeable single-phase loads being installed. Take-up of EVs will almost certainly mean many larger single-phase loads in the LV network. This could lead to significant out-of-balance loading on LV feeders.

More of these loads are also likely to be digitally controlled using inverters, which has implications for the transient and harmonic performance of the LV network.

4.3.1.1 Benefits

EDBs will be expected to manage the take-up of decarbonising technology, even if that take-up is rapid. LV monitoring will greatly assist any response to fast take-up of high load technology and help prioritise. It can also quickly reduce some uncertainty. For example, there is a concern about the peak demand impacts of a substantial number of EVs charging in the LV network at the same time. Diversity will also have an impact on that peak. Measuring LV feeders with advanced take-up of EVs will help determine how individual charging behaviour and natural diversity will combine to result in peak demand needs.

LV monitoring can also facilitate experiments with distribution charging regimes and measure the actual response quickly.

Benefits accrue in three ways:

- Reduced conservatism, mistakes and, therefore, cost in responding to fast take-up of high-load DER technology.
- Improved pricing, and particularly the ability to identify the causers of marginal distribution investment.
- Maximum DER hosting capability.

Technically, the third value does not accrue to EDBs, but there will be significant political pressure to permit EV chargers and heat pumps quickly. Resisting this pressure will be assisted by empirically demonstrating the limits of the LV network to absorb new technology loads and the point at which investment becomes required.

Table 13: DER hosting – Significant take-up of DER loads

Problem	Measurement Location	DER history	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Significant take-up of DER loads, large single-phase electronic loads, e.g. EVs, heat pumps, etc.	LV feeders, and near DER loads	If take-up is wide spread and haven't had much experience yet with LV monitoring, consider starting with small trials	Similar feeder has been measured and showed little power quality, transient or harmonic interference	5 minute averages 3ϕ & N voltage and current	**Power/ reverse power** **Reactive power** **Voltage range** **Phase load balance** **Reconcile 3ϕ & N currents (earth leakage)**	Permanent while significant DER growth occurring, high bandwidth communications, real-time alarms	DER data helpful AMI profile and AMI network data helpful
			No comparable baseline or similar feeder shows interference	<0.5ms 3ϕ & N amplitude and phase angle. Summarised data and configurable disturbance recording	As above plus **Power quality (sag/swell/ flicker)** **Transient disturbance** **Harmonics**		
Expected benefits	Reduced costs responding to new technology up-take, improved pricing, increased DER technology hosting capacity.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

4.3.1.2 Why LV monitoring?

LV monitoring of LV feeders with early adoption of new technology loads, such as EV chargers, will inform the problems that might be expected in the future. At the simplest level, either temporary or permanent, LV monitoring of LV feeders will show the level to which the circuits are utilised or become over-utilised as new technology loads increase. For this to be effective, the LV feeders needs to be monitored for a reasonable time and definitely over periods of the highest expected loading. Although care needs to be taken over assuming too much prior to monitoring, what might be expected to be the period of heaviest loading may not be the key determinant of the circuit's duty if there is a significant out-of-balance and/or reactive load with an unusual load profile. EV chargers, in particular, could lead to quite different loading profiles and out-of-balance loadings.

A simple monitoring approach can, at least, highlight opportunities to improve the utilisation of the feeders. To determine what to do may then require a follow up diagnostic process. More advanced approaches, such as determining the LV topology, can then improve future monitoring of circuit loading.

Overseas experience suggests that leveraged benefits result from LV monitoring. The problems identified on one distribution transformer or LV circuit are often then found on transformers and circuits with similar characteristics of load types, number of loads and areas. Monitoring representative LV circuits then leads to the development of targeted monitoring programmes with optimally specified monitoring technology.

4.3.1.3 What LV monitoring equipment to choose?

Assuming that no previous assessments of LV monitoring specification have been done, the minimum level of LV monitoring for assessing the loading on an LV feeder is at least 30-minute sampling of the voltage, current, reactive and active power on each phase, probably at the transformer connection downstream of the fuses/breakers, but as far upstream of the first load on the circuit as practical. If downstream of the circuit fuses, then LV monitoring will also keep track of circuit outages and, in the case of high-speed monitoring, report the exact event that lead to any fuse/breaker activations.

Thirty minutes is somewhat arbitrary but aligns with the interval revenue metering standard in New Zealand and should be able to be reconciled to consumers' metered peak demand. However, 30 minutes is probably not short enough to derive the actual peak load, and so the LV monitoring device should be of the type that records not just the integral over the sampling period but also the maximum and minimum values.

Shorter sampling periods will be more likely to indicate the peak loading per phase or, at least, be more representative of the heating effect in the conductors from the peak load. There should not be a reason to be concerned about harmonics if EV chargers and any digitally controlled heat pumps meet NZ standards. However, as an even greater proportion of LV loads will be electronic, it would be a good idea to use high-specification LV monitoring at least in the first instance. It might also be necessary to use medium to high-specification monitoring to quickly and robustly determine diversity factors for these loads.

As a matter of course the simplest technology will indicate:

- peak power and current and any reverse power
- reactive power and current loading
- the voltage range at the transformer
- phase load balance.

If suitably higher specification LV monitoring is used, then measurement can also indicate:

- earth leakage
- power quality (voltage sag/swell/flicker)
- transient disturbances
- harmonic distortion (including by harmonic to high orders).

These could indicate previously unknown problems and/or establish baselines for assessing DER hosting capacity.

High-speed sampling can also be used to assess the desirable specification for future LV monitoring by:

- integrating the high-definition data into different periods (e.g. one minute, five minutes, 15 minutes, 30 minutes)
- analysing interpolation techniques to derive the phase loadings from the integrated data
- comparing the derived loadings to the high-definition data.

This allows the selection of the best sampling period, being the desired balance between accuracy and amount of data.

Alternatively, the heating effect of high-definition data over different periods can be compared to the averaged heating effect of each period, i.e. the average of the square of high-definition current over the period being analysed compared to the average of current squared. The desired level of accuracy can then be selected where the sampling period values are representative of the heat loading of the conductors.

It could be that different sampling specifications might be needed for different LV feeder characteristics, e.g. (type of customer, number of connections and area).

A final thing that can be done is to determine the LV topology for the LV feeder. This becomes impracticable for circuits with a large number of connections or where there is a lack of practical monitoring points, as you need close to an LV monitor per connection. However, this is practical with access to AMI profile data.

Some LV monitoring can do this automatically if it has real-time direct communication with the smart meters on the substation. However, it should also be possible to do this with advanced analytical techniques and a large enough historical set of data, even with different sampling rates.

Determining the LV topology means determining which phase or phases a customer is connected to and on what circuit and/or circuit branch. It can possibly also determine the relative distance from the substation for each connection. If analysis can solve the LV topology problem, then a quite accurate model can be developed for circuit loading which can also:

- assess LV losses (technical and potentially non-technical)
- identify connections that may not actually be on that substation
- identify that connections are missing from the data
- compensate for any missing AMI data.

However, if too much data is missing, or wrong, the LV topology problem will not be able to be solved.

An LV topology model can track LV feeder loading potentially only using AMI profile data. It can also be used to predict circuit loading for different assumptions of customer demand. The value of an LV topology model may be greatly increased with the potential take-up of significant single-phase EV charger or heat pump loading as out-of-balance loadings could be problematic. However, this can only work if a robust diversity factor has been established for these loads.

4.3.1.4 Communication and data storage

At the lowest level of specification, the data requirements for LV monitoring for feeder capacity are not high, although the volume of data can add up if a number of transformers or feeders are monitored. A year's worth of 30-minute data containing average, minimum and maximum values for each of voltage, current, power and reactive power for each phase is a text file of about 6MB in size. However, the volume of data increases dramatically for high-resolution data.

For temporary applications, communications are not necessary. LV monitoring devices can usually store data for at least a couple of months and the data can be manually downloaded by USB, Bluetooth and/or WiFi at least. Most LV monitoring devices also support a number of network communication interfaces, and the selection will be driven by availability and cost.

Data storage and access should be considered before LV monitoring begins. Most vendors of LV monitoring (if the device(s) have an internet connection) offer webservices and cloud storage, which is a good starting option, at least. The direction of travel may well be towards cloud services and SaaS.

It may be a good idea to archive a certain amount of current data for more detailed analysis, but processed long-term data can potentially be stored more efficiently. For example, a statistical summary of aggregate and per phase loading per week, or even per month, would be an efficient way of storing useful data for managing substation capacity. A statistical assessment for the diversity factor for the new technology loads would be imperative.

Alternatively, the data could be processed in an event-driven database, which records the values and timestamps data when it crosses predetermined thresholds (such as a certain amount of change). This can be a very data-efficient way of storing data where the profile over time is still recorded to a desired level of accuracy.

4.3.1.5 Building the business case – cost

There are significant economies of scale in deploying LV monitoring technology, and costs are expected to fall dramatically over time as LV monitoring gets deployed widely around the world. Recent international examples indicate the total cost for less than 100 monitoring devices is expected to be around $11,000 per device for a high-specification device. Recent New Zealand examples indicate costs of around $7,500 per high-specification device, so if the business case for monitoring stacks up at these prices the case looks strong. Costs will be less for lower specification and if data is collected manually. Deploying up to 1,000 devices should reduce per-unit costs to around $5,500, and significantly more than 1,000 should yield per-unit costs down to around $3,500 to $4,500 per unit.

Economies of scale may drive further price reductions in the future with significant world scale and cloud service and SaaS options.

The full range of costs to be considered should include:

- site surveys
- monitoring equipment
- installation
- maintenance
- communication
- database infrastructure
- data management
- project management.

4.3.1.6 Building the business case – benefits

There is a substantial likelihood that significantly large digital loads are connected into LV networks quite quickly. If this were to occur, engineering and investment decisions would have to be made very quickly and conservatively. The potential of over-investment is significant. There is also a small chance that engineering assessments are too conservative, which would lead to the curtailment of the new technology loads. These are costs that would directly affect the EDB.

There are three methods that could be applied to assessing these costs. The first is to liaise with EDBs that have already done some LV monitoring to seek their assessments of what has already been identified in terms of diversity of these new technology loads.

The second is to make some rough estimates based on the EDBs' forecasts of these new loads and some reasonable assumptions about diversity. It is reasonable to assume that new technology loads are unlikely to be less than prevailing diversity and are also unlikely to have a diversity of 100 per cent, i.e. no diversity. A reasonable assumption might be, for example, that underlying diversity is 15 per cent and that a prudent diversity factor for these new loads is 85 per cent. In the absence of empirical data, it would be reasonable to assume that all outcomes of diversity are equally likely. Therefore, in this example, the expected diversity is 50 per cent but the prudent assumption for diversity is 85 per cent. This means that an EDB would expect, in the absence of data, that overinvested capacity would be about 40 per cent of the prudent capacity investment.

Based on an assumption of, for example, EV chargers in an area, then a prudent capacity can be derived and, therefore, the prudent cost, of which 40 per cent could be saved.

Obviously, this could lead to quite large benefits but based on some significant uncertainty. Therefore, it may be better to use the third method, which is to perform a similar calculation as above but use the percentage of savings in investment that would just make the LV monitoring economic. Anything less than 40 per cent should be justifiable using the prudent versus uncertainty comparison as above.

The opportunity to improve pricing is probably best left to a qualitative argument. It is a self-evident argument that improved cost-reflective pricing relies on being able to identify the drivers of cost. It can be expected that EDBs will be under political and regulatory pressure to not apply prices to new technology that they cannot justify.

As the EDB is directly benefiting from the cost savings from LV monitoring above, it cannot also claim a benefit for the EV and HP hosting capability. However, to the extent that the EDB can increase the ability to accommodate EVs and HPs from the existing network, then the EDB can claim this as a benefit. This benefit does not accrue directly to the EDB but is useful context.

The same prudent versus expected diversity approach can be used here. By assessing the prudent hosting capacity of the existing network, it can be assumed – using the above example of 85 per cent prudent diversity versus 50 per cent expected diversity (in the absence of data) – there is the potential to host 70 per cent more capacity of EV chargers or HPs.

Using an expected carbon savings of 1.7 tonnes per year for each EV purchased (Concept Consulting Group Ltd, 2016) and the NZTA social cost of carbon updated to 2020 dollar terms, the carbon benefits for each EV charger can be assumed to around $121 per year (NZTA, 2016).

If higher-specification LV monitoring is added, then benefits relate to customer experience, DER injection hosting and possibly safety.

By analysing for any underlying problems, LV monitoring creates the potential to identify faults before they cause outages. An assessment of LV faults, identifying the percentage of faults that could be avoided through LV monitoring, will give an indication of what impact LV monitoring could have on outages for customers.

This probably cannot be added to the quantified benefits of LV monitoring for an EDB, as LV is not included in SAIDI and SAIFI statistics, unless operating cost savings can be identified. The full benefit of fault avoidance would also require widespread, dynamic LV monitoring. Nevertheless, the potential for long-run benefit to consumers is useful context for a business case into exploring what underlying issues the LV network might have. The benefit to consumers can be generally quantified by multiplying the expected savings in lost load (roughly estimated by assessing outage time by load – number and type of customer) by the Electricity Authority's published Value of Lost Load (VoLL – around $20,000/MWh).

It is difficult to value the direct benefits to EDBs from using LV monitoring to assess DER hosting capacity, and it could be that there are not any. Nevertheless, EDBs are likely to come under increasing political pressure to permit DER injection and either socialise or absorb any costs incurred in doing so. High-specification LV monitoring will enable a baseline to be established against which the impact of new connections can be empirically demonstrated. This should give EDBs a robust basis on which to apply justified cost-reflective pricing of DER.

While the direct benefits of DER do not accrue to EDBs, there are public benefits and benefits to consumers. It is worth determining these benefits for context in the broader LV monitoring case. An indicative assessment of the gross public benefits can be determined through assessing the installed

MWs of DER injection (i.e. solar PV) connected to substations that will be monitored, or analysed as a result of monitoring, and multiplying by $394 kW (Reeve, Comendant, & Stevenson, 2020).

4.3.1.7 Building the business case – management case

It needs to be recognised in the LV monitoring business case that LV monitoring, in and of itself, does not achieve anything. It is important, then, to lay out at a high level what will be done as a result of an LV monitoring project, which should include how the data will inform future cases for LV monitoring.

EDBs that discover actionable evidence from LV monitoring and look to transition the monitoring from innovation to business as usual will need to reflect the evidence and impact LV monitoring has on asset management. This will need to show a direct link between measured LV data, analysis, modelling and extrapolation to better decision-making in their network.

4.3.2 Significant take-up of DER injection

The take-up of DER injection changes the nature of the LV network fundamentally. Significant levels of solar PV and/or battery systems can reduce demand dramatically, significantly changing the historic dynamic of distribution networks. However, not only can DER injection reduce demand significantly, but it can also dramatically influence voltage.

If there is significant injection, DER injecting surplus power net of load, then the changes are even more dramatic. Two-way flows and distributed digital voltage and reactive power sources can affect voltage, protection operation and possibly harmonics. DER injection can reduce demand on the LV network, but it could also increase the injection demand above the available capacity of the LV network in some cases.

Despite the above challenges, EDBs will face political pressure to enable maximum DER contribution, which will mean understanding both the hosting capacity of the LV network for DER injecting capacity and net injections back into the network.

Where an EDB is concerned with the potential for significant DER injection, it should also be aware that the dynamic hosting capacity could be higher than the static hosting capacity. By coordinating DER injection – for example, in managing voltage profiles and adjusting transformer tap settings for such coordination – an LV network may be able to host more capacity than if there is no coordination or adjustment. It is probably useful to be aware of both limits.

4.3.2.1 Benefits

Being able to empirically demonstrate the DER injection hosting capacity of the EDB's LV network will reduce political pressure and help manage the costs associated with significant DER injection. LV monitoring can also assist with cost-reflective pricing and maximise the use of DER injection.

Table 14: DER Hosting – Significant take-up of DER injection

Problem	Measurement Location	DER history	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Significant take-up of DER injection, e.g. solar PV, batteries, etc.	LV feeder, near DER injection/load centres and if possible, based on analysis, move near to any null points	If take-up is widespread and haven't had much experience yet with LV monitoring, consider starting with small trials	Any previous baseline data will help assess the marginal impact of DER	<0.5ms 3ϕ & N amplitude and phase angle. Summarised data and configurable disturbance recording	**Power/ reverse power** **Reactive power** **Voltage range** **Phase load balance** **Reconcile 3ϕ & N currents (earth leakage)** **Power quality (sag/swell/ flicker)** **Transient disturbance** **Harmonics** LV feeder model	Permanent while significant DER growth occurring, high bandwidth communications, real-time alarms	DER data greatly improves performance
Expected benefits	Reduced costs responding to DER injection take-up, improved cost-reflective pricing, increased DER injection hosting capacity.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

4.3.2.2 Why LV monitoring?

There are many aspects of assessing the hosting capacity of the network for DER injection that can only be done with LV monitoring. For example, the potential phenomenon where there are null fundamental current points (where DER injection completely matches and offsets demand), but where there is limited harmonic attenuation, can only be assessed by measuring the LV circuits near the null points. Even determining where these null points will be will need measurement. Similarly, assessing the voltage profile along an LV feeder requires measurement at many points on the feeder.

4.3.2.3 What LV monitoring equipment to choose?

Due to the potential technical complexity of the LV network with significant DER injection, high-specification LV monitoring will be desirable in the first instance. Previous LV monitoring might reduce the need for high-specification monitoring. For example, if the THD concentration at null points phenomenon is shown to not be an issue, then this reduces the need for high-speed sampling. However, if harmonics or transients are shown to be potential issues, then, as the range of ratios of DER injection to load and locations is large, this is likely to mean that each LV feeder anticipated to have significant DER injection may warrant measurement. At least medium-specification monitoring will be required as the voltage implications of potentially rapid changes in solar output, for example, will need to be considered.

A sampling rate of 0.5ms is fast enough to derive harmonics to the 10^{th} order and should be able to give good detail of transient events. LV monitoring equipment that is even faster is readily available. As much detail as possible about harmonics and transient events could be helpful. High-specification equipment should also have onboard analytical tools, such as event plots, harmonic breakdowns and phasor diagrams. Having these on-board tools can be useful for on-site diagnostics.

Ideally, LV monitoring should be installed on the LV feeder at the distribution substation and on any major circuit branches. Some experimentation may be required to work where null points occur so that these can be monitored. The early development of an LV circuit electrical model, or a topology model at least, might be helpful in predicting the ideal points to apply LV monitoring. The use of any AMI and DER data would be helpful here.

As a matter of course high-specification technology will indicate:

- peak power and current and any reverse power
- reactive power and current loading
- the voltage range at the transformer
- phase load balance
- earth leakage
- power quality (voltage sag/swell/flicker)
- transient disturbances
- harmonic distortion (including by harmonic to high orders).

In addition to assessing DER injection hosting capacity, measuring these characteristics could also indicate previously unknown problems.

Another thing that can be done is to determine the LV topology for the LV feeder, or even an approximate electrical model. High-specification LV monitoring should enable the electrical characteristics of lines between monitoring points to be calculated to a reasonable level of accuracy.

Even assessing LV topology becomes impracticable for circuits with a large number of connections, or where there is a lack of practical monitoring points, as you need close to an LV monitor per connection. However, this could be practical with access to AMI profile data.

Some LV monitoring can determine LV topology automatically if it has real-time direct communication with the smart meters on the substation. However, it should also be possible to do this with advanced analytical techniques and a large enough historical set of data, even with different sampling rates.

Determining the LV topology means determining which phase or phases a customer is connected to and on what circuit and/or circuit branch. It can possibly also determine the relative distance from the substation for each connection. If analysis can solve the LV topology problem, then a quite accurate model can be developed for circuit loading which can also:

- assess LV losses (technical and potentially non-technical)
- identify connections that may not actually be on that substation
- identify that connections are missing from the data
- compensate for any missing AMI data.

However, if too much data is missing or wrong, the LV topology problem will not be able to be solved.

An LV topology model can track LV feeder loading potentially only using AMI profile data. It could also be used to predict circuit loadings, and particularly any null points, for DER injection once more is known about the net injection profiles. If there is access to DER data, then this becomes more accurate.

Even a simple electrical model of the feeder should allow modelling of voltage profiles, some power quality and protection performance for different forecasts of LV feeder loading and DER injection.

4.3.2.4 Communication and data storage

At the highest resolutions of raw LV monitoring, data storage requirements can quickly build up to terabytes. Some form of data compression is necessary for long-term application of LV monitoring. The technical complexity of compressing high-resolution data while preserving high-quality information is another reason it is worth considering the cloud services and SaaS solutions that most suppliers offer.

Suitable LV monitoring devices support a number of network communication interfaces, and the selection will be driven by availability, bandwidth and cost.

Data storage and access should be considered before LV monitoring begins. Most vendors of LV monitoring (if the device(s) have an internet connection) offer webservices and cloud storage, which is an option that should be considered for high-resolution data. The direction of travel for high-resolution data seems to be towards cloud services and SaaS.

It is a good idea to archive raw event data around protection events and faults. This data is a small subset of total data and allows for future analysis of events and faults that can potentially be extrapolated to predictive tools for other LV feeders.

Probably the best way of compressing high-resolution data is by a combination of metadata and event-driven storage. Data can be processed in an event-driven database, which records the values and timestamps data when it crosses predetermined thresholds (such as a certain amount of change). This can be a very data-efficient way of storing data where the profile over time is still recorded to a desired level of accuracy. Metadata can be an efficient way of storing high-resolution information in combination with an event-driven database. For example, defining harmonic voltage and currents in terms of amplitude and phase angle, and describing asymmetric voltages and currents in terms of positive, negative and zero phase sequences, when they change by a certain amount and/or when they exceed a certain level.

4.3.2.5 Building the business case – cost

There are significant economies of scale in deploying LV monitoring technology, and costs are expected to fall dramatically over time as LV monitoring gets deployed widely around the world. Recent international examples indicate the total cost for less than 100 monitoring devices is expected to be around $11,000 per device for a high-specification device. Recent New Zealand examples indicate the costs of around $7,500 per high-specification device so if the business case for monitoring stacks up at these prices the case looks strong. Costs will be less for lower specification and if data is collected manually. Deploying up to 1,000 devices should reduce per-unit costs to around $5,500, and significantly more than 1,000 should yield per-unit costs down to around $3,500 to $4,500 per unit.

Economies of scale may drive further price reductions in the future with significant world scale and cloud service and SaaS options.

The full range of costs to be considered should include:

- site surveys
- monitoring equipment
- installation
- maintenance
- communication
- database infrastructure
- data management
- project management.

4.3.2.6 Building the business case – benefits

There is a substantial chance that significantly large digital loads and/or injections could be connected into some LV networks quite quickly. If this were to occur, engineering and investment decisions would have to be made very quickly and conservatively. The chance of over-investment is significant. It is also likely that engineering assessments of the existing LV network will be, prudently, too conservative, which would lead to the curtailment of the new technology loads.

The value of benefits depends on context and timing. If the point is reached where DER injection is significant, then LV monitoring may become critical to decision-making and the deployment of LV monitoring may be unavoidable. There is some merit in monitoring LV feeders before any DER injection deployment, but there is limited value in this as assumptions about the DER injection itself will need to be made. Probably the point at which there is the most discretionary benefit in LV monitoring on LV feeders that are forecasted to have high take-up of DER injection is when there are one to a few sites already installed. Of course, there would also be value in liaising with EDBs that have already done some LV monitoring to seek their findings and learnings with respect to DER injection.

Even having just a few sites may not give enough information to extrapolate to higher levels. It may be necessary to work with the solar PV and/or battery system owners to form experimental conditions; for example, setting up net DER injection with predominantly digital loads. To the extent possible with the installed technology, it would also be worth experimenting with the voltage characteristics of any inverters. It is worth considering, even with solar PV installations, testing overnight scenarios with inverters connected versus disconnected.

Defining the counterfactual for what would be done to manage DER injection in the absence of data is problematic. There are two approaches, both of which have issues. We could assume that EDBs will invest prudently to manage forecasted DER injection, which, with uncertainty, would result in overinvestment. However, the investments in capacity that would normally be done by EDBs will not necessarily work, or be prudent, for DER injection. DER injection will not necessarily increase the need for thermal capacity, and it may cause high voltage rather than low voltage problems.

The second approach to the counterfactual is to assume that once DER injection starts to become significant, EDBs will need to require that there be no net injection back into the LV network. This is also problematic as there could still be issues with high levels of DER injection even without export. This is also problematic as Part 6 of the Code is intended for the connection of DG to be permissive, with EDBs able to recover generation driven investment costs. However, in a situation where there is rapid deployment of DER injection, an EDB could easily have to invoke Clause 11 of Schedule 6.2 – Regulated terms for distributed generation – of the Code. While Clause 11 anticipates temporary disconnection of DG to manage to an EDB’s congestion management policy or to prevent damage to other consumers, in a highly dynamic environment of significant DER injection an EDB would be prudent to limit DER injection in the first instance. This is a debatable counterfactual but with more certain assumptions than might be made about prudent investments in the LV network for high voltages. Overseas experience suggests the first response to problems caused by solar PV was to curtail output.

This counterfactual creates the risk for EDBs that this reduces the utilisation of the LV network, and maybe more of the distribution network. The push to cost-reflective pricing, with DER assets that can respond to such price signals, could lead to under-recovery of revenue. Where costs can be reallocated then, for those that bear these extra costs, there are stronger incentives to invest in solar PV and battery systems to avoid them, the so-called death spiral. By working to cost-effectively enable net DER injection, an EDB can give access to DER investors to arbitrage energy markets and maintain utilisation of the LV network.

The only reasonable way to assess the benefit here is, for LV feeders where high take-up of DER injection is forecasted, to determine the probability of LV feeder write-down that would make LV monitoring economic. That risk can then be considered in the context of the confidence in the DER injection forecasts. As the likelihood of significant DER injection increases, the case for LV monitoring will become more compelling.

The opportunity to improve pricing is probably best left to a qualitative argument. It is a self-evident argument that improved cost-reflective pricing relies on being able to identify the drivers of cost. EDBs are likely to come under increasing political pressure to permit DER injection and either socialise or absorb any costs incurred in doing so. High-specification LV monitoring will enable a baseline to be established against which the impact of new connections can be empirically demonstrated. This should give EDBs a robust basis on which to apply justified cost-reflective pricing of DER injection.

While the direct benefits of DER do not accrue to EDBs, there are public benefits and benefits to consumers. It is worth determining these benefits for context in the broader LV monitoring case. An indicative assessment of the gross public benefits can be determined through assessing the installed MWs of DER injection (i.e. solar PV) connected to substations that will be monitored, or analysed as a result of monitoring, and multiplying by $394/kW.

As high-specification LV monitoring will be used, then other benefits are achievable related to customer experience and possibly safety.

By analysing for any underlying problems, LV monitoring creates the potential to identify faults before they cause outages. An assessment of LV faults, identifying the percentage of faults that could be avoided through LV monitoring, will give an indication of what impact LV monitoring could have on outages for customers.

This probably cannot be added to the quantified benefits of LV monitoring for an EDB, as LV is not included in SAIDI and SAIFI statistics, unless operating cost savings can be identified. The full benefit of fault avoidance would also require widespread, dynamic LV monitoring. Nevertheless, the potential for long-run benefit to consumers is useful context for a business case into exploring what underlying issues the LV network might have. The benefit to consumers can be generally quantified by multiplying the expected savings in lost load (roughly estimated by assessing outage time by load – number and type of customer) by the Electricity Authority's published Value of Lost Load (VoLL – around $20,000/MWh).

4.3.2.7 Building the business case – management case

It needs to be recognised in the LV monitoring business case that LV monitoring, in and of itself, does not achieve anything. It is important, then, to lay out at a high level what will be done as a result of an LV monitoring project, which should include how the data will inform future cases for LV monitoring.

EDBs that discover actionable evidence from LV monitoring and look to transition the monitoring from innovation to business as usual will need to reflect the evidence and impact LV monitoring has on asset management. This will need to show a direct link between measured LV data, analysis, modelling and extrapolation to better decision-making in their network.

4.3.3 Need to coordinate DER

If the deployment of DER – and especially injecting DER such as solar PV and/or battery systems – reaches a certain level, then there will be a need to coordinate the DER to manage capacity and voltage, at least. Without coordination, the hosting capacity of the LV network could be substantially less.

It is important to note that coordination, in the context of LV monitoring, does not mean the commercial coordination or operation of DER like what might be done by a DERMS or DSO, but rather the signalling of dynamic operating limits of the LV network. LV monitoring can also monitor the performance of DER providers against those operating limits, either individually or in aggregate.

4.3.4 Benefits

By signalling LV feeder operating limits and monitoring the performance of DER against those limits, an EDB can increase its ability to host DER. Being able to empirically demonstrate that the DER injection hosting capacity of the EDB's LV network is being actively managed will reduce political pressure and help manage the costs associated with significant DER injection. LV monitoring can also assist with cost-reflective pricing and maximising the use of DER injection.

Table 15: DER Hosting – Need to coordinate DER

Problem	Measurement Location	DER history	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Need data to operate LV network and coordinate DER	LV feeder, near DER injection/load centres and if possible, based on analysis, move near to any null points	If take-up is widespread and haven't had much experience yet with LV monitoring, consider starting with small trials	Any previous baseline data will help assess the marginal impact of DER	<0.5ms 3ϕ & N amplitude and phase angle. Central system customisable for multiple purposes.	**Power/ reverse power** **Reactive power** **Voltage range** **Phase load balance** **Reconcile 3ϕ & N currents (earth leakage)** **Power quality (sag/swell/ flicker)** **Transient disturbance** **Harmonics** LV network model LV SAIDI, SAIFI and CAIDI	Permanent, high bandwidth real-time communications and ability to share data with other systems (e.g. DERMS, DSO)	DER data greatly improves performance
Expected benefits	Reduced costs responding to DER injection take-up, improved cost-reflective pricing, increased DER injection hosting capacity.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

4.3.4.1 Why LV monitoring?

There are many aspects of assessing the hosting capacity of the network for DER injection that can only be done with LV monitoring. For example, the potential phenomenon where there are null fundamental current points (where DER injection completely matches and offsets demand), but where there is limited harmonic attenuation, can only be assessed by measuring the LV circuits near the null points. Even determining where these null points will be will need measurement. Similarly, assessing the voltage profile along an LV feeder requires measurement at many points on the feeder.

Signalling the dynamic limits of LV feeders, in conjunction with monitoring DER response, will assist managing the LV network while allowing maximum DER hosting.

4.3.4.2 What LV monitoring equipment to choose?

Due to the potential technical complexity of the LV network with significant DER injection with the requirement to be able to signal LV constraints, high-specification LV monitoring will be desirable in the first instance. Previous LV monitoring might reduce the need for high-specification monitoring. For example, if the THD concentration at null points phenomenon is shown to not be an issue, then this reduces the need for high-speed sampling. However, at least medium-specification monitoring will be required as the voltage implications of potentially rapid changes in solar output, for example, will need to be considered and will change the operating limits of the LV feeder.

A sampling rate of 0.5ms is fast enough to derive harmonics to the 10th order and should be able to give good detail of transient events. LV monitoring equipment that is even faster is readily available. As much detail as possible about harmonics and transient events could be helpful. High-specification equipment should also have onboard analytical tools, such as event plots, harmonic breakdowns and phasor diagrams. Having these on-board tools can be useful for on-site diagnostics.

Ideally, LV monitoring should be installed on the LV feeder at the distribution substation, and on any major circuit branches. Some experimentation may be required to work where null points occur so that these can be monitored. The best points to monitor the voltage profile will also need to be considered, but this could be made easier using AMI and DER data. The early development of an LV circuit electrical model, or a topology model at least, might be helpful in predicting the ideal points to apply LV monitoring. The use of any AMI and DER data would also be helpful here.

As a matter of course, high-specification technology will indicate:

- peak power and current and any reverse power
- reactive power and current loading
- the voltage range at the transformer
- phase load balance
- earth leakage
- power quality (voltage sag/swell/flicker)
- transient disturbances
- harmonic distortion (including by harmonic to high orders).

In addition to assessing DER injection hosting capacity, measuring these characteristics could also indicate previously unknown problems.

Another thing that can be done is to determine the LV topology for the LV feeder, or even an approximate electrical model. High-specification LV monitoring should enable the electrical characteristics of lines between monitoring points to be calculated to a reasonable level of accuracy.

Even assessing LV topology becomes impracticable for circuits with a large number of connections, or where there is a lack of practical monitoring points, as you need close to an LV monitor per connection. However, this could be practical with access to AMI profile data.

Some LV monitoring can determine LV topology automatically if it has real-time direct communication with the smart meters on the substation. However, it should also be possible to do this with advanced analytical techniques and a large enough historical set of data, even with different sampling rates.

Determining the LV topology means determining which phase or phases a customer is connected to and on what circuit and/or circuit branch. It can possibly also determine the relative distance from the substation for each connection. If analysis can solve the LV topology problem, then a quite accurate model can be developed for circuit loading which can also:

- assess LV losses (technical and potentially non-technical)
- identify connections that may not actually be on that substation
- identify that connections are missing from the data
- compensate for any missing AMI data.

However, if too much data is missing or wrong, the LV topology problem will not be able to be solved.

An LV topology model can track LV feeder loading potentially only using AMI profile data. It could also be used to predict circuit loadings, and particularly any null points, for DER injection once more is known about the net injection profiles. If there is access to DER data, then this becomes more accurate.

Even a simple electrical model of the feeder should allow modelling of voltage profiles, some power quality and protection performance for different forecasts of LV feeder loading and DER injection.

4.3.4.3 Communication and data storage

At the highest resolutions of raw LV monitoring, data storage requirements can quickly build up to terabytes. Some form of data compression is necessary for long-term application of LV monitoring. The technical complexity of compressing high-resolution data while preserving high quality information is another reason it is worth considering the cloud services and SaaS solutions that most suppliers offer. Supplier-provided cloud services should also mean that web APIs are available to provide data to DER operators, DERMS and/or a DSO.

Even if the system is to be hosted by the EDB, it would be worth doing this as a private cloud service rather than trying to achieve interoperability through a dedicated or bespoke system.

Suitable LV monitoring devices support a number of network communication interfaces, and the selection will be driven by availability, bandwidth and cost.

Data storage and access should be considered before LV monitoring begins. Most vendors of LV monitoring (if the device(s) have an internet connection) offer webservices and cloud storage, which is an option that should be considered for high-resolution data. The direction of travel for high-resolution data seems to be towards cloud services and SaaS.

It is a good idea to archive raw event data around protection events and faults. This data is a small subset of total data and allows for future analysis of events and faults that can potentially be extrapolated to predictive tools for other LV feeders.

Probably the best way of compressing high-resolution data is by a combination of metadata and event-driven storage. Data can be processed in an event-driven database, which records the values and timestamps data when it crosses predetermined thresholds (such as a certain amount of change). This can be a very data-efficient way of storing data where the profile over time is still recorded to a desired level of accuracy. Metadata can be an efficient way of storing high-resolution information in combination with an event-driven database. For example, defining harmonic voltage and currents in terms of amplitude and phase angle, and describing asymmetric voltages and currents in terms of positive, negative and zero phase sequences, when they change by a certain amount and/or when they exceed a certain level.

4.3.4.4 Building the business case – cost

There are significant economies of scale in deploying LV monitoring technology, and costs are expected to fall dramatically over time as LV monitoring gets deployed widely around the world. Recent international examples indicate the total cost for less than 100 monitoring devices is expected to be around $11,000 per device for a high-specification device. Recent New Zealand examples indicate the costs of around $7,500 per high-specification device, so if the business case for monitoring stacks up at these prices the case looks strong. Costs will be less for lower specification and if data is collected manually. Deploying up to 1,000 devices should reduce per-unit costs to around $5,500, and significantly more than 1,000 should yield per-unit costs down to around $3,500 to $4,500 per unit.

Economies of scale may drive further price reductions in the future with significant world scale and cloud service and SaaS options.

The full range of costs to be considered should include:

- site surveys
- monitoring equipment
- installation
- maintenance
- communication
- database infrastructure
- data management
- project management.

4.3.4.5 Building the business case – benefits

Logically, an EDB cannot be concerned about needing to coordinate significant levels of DER without first being concerned about the potential for significant levels of DER. If an EDB does have this concern for an LV substation, or group of substations, then the first step would be to assess the capability of the LV network to host DER injection. The key criteria for then also being able to assist with the coordination of DER would be to ensure the system chosen can provide data to third parties through standard data exchange; for example, web API.

In this case the EDB would also need to consider what role it should play in the coordination of DER insofar as who should define the operating limits and constraints of the LV network. The EDB may also want to specify that the LV monitoring system can also define the limits and constraints.

Generally, the case for the LV system is primarily justified by assessing the hosting capacity of DER injection.

There is a substantial chance that significant large digital loads and/or injections could be connected into some LV networks quite quickly. If this were to occur, engineering and investment decisions across the network would have to be made very quickly and conservatively. The chance of over-investment is significant. It is also likely that engineering assessments of the existing LV network will be, prudently, too conservative, which would lead to the curtailment of the new technology loads.

The value of benefits depends on context and timing. If the point is reached where DER injection is significant, then LV monitoring may become critical to decision-making and the deployment of LV monitoring may be unavoidable. There is some merit in monitoring LV feeders before any DER injection deployment, but there is limited value in this as assumptions about the DER injection itself will need to be made. Probably the point at which there is the most discretionary benefit in LV monitoring on LV feeders that are forecasted to have high take-up of DER injection is when there are one to a few sites already installed. Of course, there would also be value in liaising with EDBs that have already done some LV monitoring to seek their findings and learnings with respect to DER injection.

Even having just a few sites may not give enough information to extrapolate to higher levels. It may be necessary to work with the solar PV and/or battery system owners to form experimental conditions; for example, setting up net DER injection with predominantly digital loads. To the extent possible with the installed technology, it would also be worth experimenting with the voltage characteristics of any inverters. It is worth considering, even with solar PV installations, testing overnight scenarios with inverters connected versus disconnected.

Defining the counterfactual for what would be done to manage DER injection in the absence of data is problematic. There are two approaches, both of which have issues. We could assume that EDBs will invest prudently to manage forecasted DER injection which, with uncertainty, would result in overinvestment. However, the investments in capacity that would normally be done by EDBs will not necessarily work, or be prudent, for DER injection. DER injection will not necessarily increase the need for thermal capacity, and it may cause high voltage rather than low voltage problems.

The second approach to the counterfactual is to assume that once DER injection starts to become significant, EDBs will need to require that there be no net injection back into the LV network. This is also problematic as there could still be issues with high levels of DER injection even without export.

However, this is a more likely counterfactual than assumptions that might be made about prudent investments in the LV network for high voltages. Overseas experience suggests the first response to problems caused by solar PV was to curtail output.

The risk for EDBs is that this reduces the utilisation of the LV network, and maybe more of the distribution network. The push to cost-reflective pricing, with DER assets that can respond to such price signals, could lead to under-recovery of revenue. Where costs can be re-allocated then, for those that bear these extra costs, there are stronger incentives to invest in solar PV and battery systems to avoid them, the so-called death spiral. By working to cost-effectively enable net DER injection, an EDB can give access to DER investors to arbitrage energy markets and maintain utilisation of the LV network.

The only reasonable way to assess the benefit here is – for LV feeders where high take-up of DER injection is forecasted – to determine the probability of LV feeder write-down that would make LV monitoring economic. That risk can then be considered in the context of the confidence in the DER injection forecasts. As the likelihood of significant DER injection increases, the case for LV monitoring will become more compelling.

The opportunity to improve pricing is probably best left to a qualitative argument. It is a self-evident argument that improved cost-reflective pricing relies on being able to identify the drivers of cost. EDBs are likely to come under increasing political pressure to permit DER injection and either socialise or absorb any costs incurred in doing so. High-specification LV monitoring will enable a baseline to be established against which the impact of new connections can be empirically demonstrated. This should give EDBs a robust basis on which to apply justified cost-reflective pricing of DER injection.

While the direct benefits of DER do not accrue to EDBs, there are public benefits and benefits to consumers. It is worth determining these benefits for context in the broader LV monitoring case. An indicative assessment of the gross public benefits can be determined through assessing the installed MWs of DER injection (i.e. solar PV) connected to substations that will be monitored, or analysed as a result of monitoring, and multiplying by $394/kW.

As high-specification LV monitoring will be used, then other benefits are achievable related to customer experience and possibly safety.

By analysing for any underlying problems, LV monitoring creates the potential to identify faults before they cause outages. An assessment of LV faults, identifying the percentage of faults that could be avoided through LV monitoring, will give an indication of what impact LV monitoring could have on outages for customers.

This probably cannot be added to the quantified benefits of LV monitoring for an EDB, as LV is not included in SAIDI and SAIFI statistics, unless operating cost savings can be identified. The full benefit of fault avoidance would also require widespread, dynamic LV monitoring. Nevertheless, the potential for long-run benefit to consumers is useful context for a business case into exploring what underlying issues the LV network might have. The benefit to consumers can be generally quantified by multiplying the expected savings in lost load (roughly estimated by assessing outage time by load – number and type of customer) by the Electricity Authority’s published Value of Lost Load (VoLL – around $20,000/MWh).

4.3.4.6 Building the business case – management case

It needs to be recognised in the LV monitoring business case that LV monitoring, in and of itself, does not achieve anything. It is important, then, to lay out at a high level what will be done as a result of an LV monitoring project, which should include how the data will inform future cases for LV monitoring.

EDBs that discover actionable evidence from LV monitoring and look to transition the monitoring from innovation to business as usual will need to reflect the evidence and impact LV monitoring has on asset management. This will need to show a direct link between measured LV data, analysis, modelling and extrapolation to better decision-making in their network.

4.4 Diagnostic

4.4.1 General

The case for diagnostic LV monitoring equipment is probably best considered when first making the case for any LV monitoring, especially high-specification LV monitoring. The risk of not considering diagnostics early is that LV monitoring deployed for other purposes may detect problems which then the EDB is obligated to follow up on. In many cases the only way to diagnose problems would be to use LV monitoring. For example, if LV monitoring picked up unacceptable levels of THD, then LV monitoring is likely to be the best way to diagnose the problem. However, there is a fine line between what might be considered LV monitoring and what might be considered technician's diagnostic equipment.

One way might be to include extra LV monitoring equipment when any case is made for LV monitoring. The extra equipment can be used for more general monitoring or can be redeployed for diagnostics, if required.

Benefits

Even where LV monitoring equipment is not the only way to diagnose a problem, it is still likely to be the fastest way to diagnose problems. There is the potential to collect enough data that a problem can be diagnosed after one occurrence of an event or problem. Other approaches may require more testing of more events as hypotheses about the problem are narrowed down.

Table 16: Diagnostic – Reverse Power

Problem	DER forecast	Measurement Location	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Unexpected/ unregistered reverse power detected or suspected (SAFETY ISSUE)	n/a	Move down the feeder from point of detection or at substation to major branches and down to customer connections.	Reverse power could have been picked up during active power monitoring. It could take a while to detect using measurement.	<1s 3ϕ & N amplitude and phase angle	Isolate source of reverse power	Few weeks of sampling, volume of data probably needs non-real-time data communication.	AMI profile data could speed up detection.
			Could also have been detected as very low voltage and currents during outages. This could indicate faulty no volt DER protection injecting through a current limiter.	<1s 3ϕ & N amplitude and phase angle. Accurate measuring very low voltages and currents.	Isolate source of no-volt injections (URGENT)	Portable, with on-site polling by technicians. Probably need LV circuit de-energised.	AMI profile data could speed up detection.
Expected benefits	Faster diagnosis time, could pick up minor injections that might otherwise be missed.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

Table 17: Diagnostic – Reactive power

Problem	DER forecast	Measurement Location	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Source of reactive power leading to low power factor or voltage issues	n/a	Move down the feeder from point of detection or at substation to major branches and down to customer connections.	If poor power factor detected during LV monitoring, assess times of reactive power contribution for targeted analysis.	5-30 minute 3ϕ active, apparent, reactive power or energy meter.	Isolate source of reactive power.	Few weeks of sampling or targeted portable testing.	AMI network data could speed up detection.
Expected benefits	Potentially faster diagnosis.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

Table 18: Diagnostic – Voltage range

Problem	DER forecast	Measurement Location	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Voltage outside regulated range detected or suspected • Voltage range set too high or low	n/a	Monitor at substation, any major branches and load centres, and end of circuits.	If low or high voltages detected during LV monitoring, assess times of low or high voltage for targeted analysis.	5min 3ϕ voltage averages	Identify voltage profile	As long as possible up to a few months of sampling, could be manually collected.	AMI network and DER data would improve the result.
• Line impedance or loading too high	Low take-up forecasted for this feeder.			<1s 3ϕ & N voltage and current amplitude and phase angle.	LV feeder model	As long as possible up to a few months of sampling, volume of data probably needs non-real-time data communication.	AMI profile data would assist identifying LV topology for model.
• DER injection has changed voltage profile	High take-up forecasted for this feeder.				Above plus Predictive LV feeder model		
Expected benefits	Faster diagnosis. Able to analyse the changing voltage profile. Can inform new design and configuration for LV circuits.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

Table 19: Diagnostic – Phase load balance

Problem	DER forecast	Measurement Location	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Phase loadings on feeder or transformer out of balance	Low take-up forecasted for this feeder.	Monitor at substation, any major branches and customer connections.	Out-of-balance loadings could be a historic problem or a result of fast changes of consumption, such as EVs or heat pumps.	5min 3ϕ & N voltage and current averages	Identify LV topology and customer demand	As long as possible up to a few months of sampling, could be manually collected.	AMI profile data would speed up and improve the result.
	High take-up forecasted for this feeder.				As above plus Dynamic LV topology model	Consider permanent monitoring while demand patterns are changing with non-real-time data communication.	
Expected benefits	Potentially faster balancing. Will catch changes in load balance over time to enable best compromise on balance.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

Table 20: Diagnostic – Neutral or earth voltage rise or residual earth current

Problem	DER forecast	Measurement Location	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Phase and neutral voltages and currents don't reconcile (SAFETY ISSUE) • Broken or high impedance neutral or earth • Faulty appliance, or installation • Uncleared phase to earth fault	Low take-up forecasted for this feeder	Monitor at location detected or substation move to any major branches and then customer connection	Issues need to be investigated as quickly as possible but may be intermittent. Longer monitoring may be necessary to pick up intermittent problem	<1s 3ϕ & N voltage and current amplitude and phase angle with on-board analytics and configurable alarms	Identify source of neutral or earth voltage rise, or earth leakage (URGENT)	As long as it takes with focus on locating issue, can use non-real-time data communication with real-time alarms for neutral or earth voltage rise or leakage current	AMI network data and DER data could assist analysis
	High take-up forecasted for this feeder	Monitor at substation, major branches, and sample of connections at same time			As above plus Predictive LV network model for assessing DER hosting capacity		AMI profile data would improve the result
Expected benefits	Faster, and therefore safer, diagnosis. Better information about any design and/or configuration changes.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

Table 21: Diagnostic – Power quality (voltage sag, swell and flicker)

Problem	DER forecast	Measurement Location	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Problems, concerns, or complaints about voltage sag, swell or flicker	Low take-up forecasted for this feeder	Monitor at location detected or substation move to any major branches and then customer connection	Problems may be intermittent. Longer monitoring may be necessary to pick up intermittent problem	<1s 3ϕ & N voltage and current amplitude and phase angle	Identify any volatile, or rapidly ramping loads Potentially identify LV feeder impedance for PQ calculations	As long as it takes with focus on locating issue, can use non-real-time data communication	AMI network data may speed up and improve result
	High take-up forecasted for this feeder	Monitor at substation, major branches, and sample of connections at same time			As above plus Predictive LV network model for assessing DER hosting capacity		AMI profile data would improve the result
Expected benefits	Faster diagnosis. Better information about any design and/or configuration changes.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

Table 22: Diagnostic – Transients

Problem	DER forecast	Measurement Location	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Transient or intermittent faults identified or suspected	Low take-up forecasted for this feeder	Monitor at location detected or substation move to any major branches and then customer connection	Problems may be intermittent. Longer monitoring may be necessary to pick up intermittent problem	<0.5ms 3ϕ & N voltage and current amplitude and phase angle with on-site analytics including transient disturbance event plots	Identify any interference or developing faults	As long as it takes with focus on locating issue, can use non-real-time data communication	DER data may help with transient analysis
	High take-up forecasted for this feeder	Monitor at substation, major branches, and sample of connections at same time			As above plus Predictive LV network model for assessing faults and protection for DER hosting capacity		
Expected benefits	Possibly only way to diagnose problems. Faster diagnosis.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

Table 23: Diagnostic – Harmonics

Problem	DER forecast	Measurement Location	Baseline	Data sampling specification	Analysis	Permanence Communication	Additional data
Exceedance or near exceedance of THD limits identified or suspected	Low take-up forecasted for this feeder	Monitor at substation, major branches, any line capacitors, and sample of connections at same time. May need to monitor many connections at the same time.	Problems may be intermittent. Longer monitoring may be necessary to pick up intermittent problem. Multiple factors may contribute to the problem which may require extensive monitoring.	<0.5ms 3ϕ & N voltage and current amplitude and phase angle with on-site analytics including waveform plots	Identify any high harmonic voltages and currents either at points of resonance or sources	As long as it takes with focus on locating issue, can use non-real-time data communication, data requirements may make it necessary to only communicate harmonic summary data	AMI network data may speed up and improve result
	High take-up forecasted for this feeder				As above plus Predictive LV harmonic attenuation model for assessing DER hosting capacity		
Expected benefits	Possibly only way to diagnose problems. Faster diagnosis. Better informed solutions.						

Orange denotes the analysis designed for addressing the concern, black denotes other analysis that can be done, **bold (orange or black) denotes analysis that might find unexpected problems**

4.4.1.1 Why LV monitoring?

LV monitoring is likely to speed up diagnosis in most cases. In some cases, LV monitoring could be the only way to determine the sources of problems.

4.4.1.2 What LV monitoring equipment to choose?

The LV monitoring equipment selected for diagnosis should be equivalent to the highest specification LV monitoring that is deployed elsewhere. Anything less may not be able to diagnose problems that other LV monitoring can detect. However, there is also no point in having diagnosis equipment for problems that cannot be detected by other means. In this context, the capability of other data should be considered, e.g. AMI data and/or DER data, which may be able to detect complicated problems, such as harmonics.

The other thing to consider for equipment that is to be used for diagnosis is the ability to rapidly deploy and move the LV monitoring equipment. Multiple potential sensor types for the input channels would increase the flexibility of use of the diagnostic equipment.

4.4.1.3 Communication and data storage

If LV monitoring data storage and modelling is already used, then the data from the diagnostic equipment can be added to this. However, consideration should be given to keeping the raw data for longer, until issues have definitely been resolved. This may make it desirable to use a supplier's web services even if the EDB has its own data storage.

Even for temporary applications communications are probably necessary. Some LV monitoring devices may be able to store high-resolution data for a month or two and the data can be manually downloaded by USB, Bluetooth and/or WiFi at least. However, the sheer volume of data probably warrants more frequent download, and for analysing faults it is advisable to have alarms for events. Most LV monitoring devices also support a number of network communication interfaces, and the selection will be driven by availability, bandwidth and cost.

4.4.1.4 Building the business case – cost

The case for diagnostic LV monitoring equipment would most likely be as an extension of LV monitoring for other purposes, in which case the cost of diagnostic LV monitoring would be marginal on another business case.

There are significant economies of scale in deploying LV monitoring technology, and costs are expected to fall dramatically over time as LV monitoring gets deployed widely around the world. Recent international examples indicate the total cost for less than 100 monitoring devices is expected to be around $11,000 per device for a high-specification device. Recent New Zealand examples indicate the costs of around $7,500 per high-specification device, so if the business case for monitoring stacks up at these prices the case looks strong. Costs will be less for lower specification and if data is collected manually. Deploying up to 1,000 devices should reduce per-unit costs to around $5,500, and significantly more than 1,000 should yield per-unit costs down to around $3,500 to $4,500 per unit.

Economies of scale may drive further price reductions in the future with significant world scale and cloud service and SaaS options.

The full range of costs to be considered should include:

- site surveys
- monitoring equipment
- installation
- maintenance
- communication
- database infrastructure
- data management
- project management.

4.4.1.5 Building the business case – benefits

One of the risks for the case for LV monitoring for other purposes is that problems are uncovered which then the EDB will need to respond to. Although, the risk could be greater for not uncovering problems. A way of mitigating the risk would be to include extra LV monitoring equipment in the associated proposal for diagnostic equipment.

Outside of risk management, the key benefit of LV monitoring for diagnostics is faster resolution of problems. There is also the potential to avoid more expensive failures, especially catastrophic failures that can sometimes occur when unknown problems get progressively worse. There is also the opportunity to detect faults earlier and prevent customer outages.

There are two methods that could be applied to valuing the benefit of LV monitoring to diagnostics. The first is to liaise with EDBs that have already done some LV monitoring to seek their assessments of the value of LV monitoring for diagnostics they have discovered.

The second is to do a statistical analysis of the range of problems and faults and the frequency by which such problems or faults eventually lead to costly damage. The probability derived from the frequency assessment applied to the costs incurred from eventual failure can give an expected value of cost savings from applying LV monitoring to unknown intermittent faults.

The same statistical approach can also be applied to assessing the expected duration of outages for customers. This can be converted to a value by multiplying the duration by a reasonable assessment of average customer loading and the Electricity Authority's published estimate of VoLL (around $20,000/MWh). EDBs do not directly benefit from reduced outages on the LV network, but the customer benefit is an important context for the business case.

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